Voluntary Clean Water Guidance for Agriculture Chapters

A phased approach is being used to develop these guidelines. During the first phase an overview of the guidance was produced along with its initial chapter which examines tillage and residue management practices. Additional chapters not completed though anticipated for inclusion in the overall guidance are listed below. These chapters will be completed in the following several years. Producers who are interested water quality guidance related to practices not yet addressed can contact Ecology's Agriculture and **Water Quality Planner Ron Cummings at ron.cummings@ecy.wa.gov or (360) 407-6600.**

Chapter 1 Cropping Methods: Tillage & Residue Management-Completed (December 2020)

Chapter 2 Cropping Methods: Crop System-***In development***

Chapter 3 Nutrient Management-***In development***

Chapter 4 Pesticide Management-***In development***

Chapter 5 Sediment Control: Soil Stabilization & Sediment Capture (Vegetative)-***In development***

Chapter 6 Sediment Control: Soil Stabilization & Sediment Capture (Structural)-Completed (December 2022)

Chapter 7 Water Management: Irrigation Systems & Management-***In development***

Chapter 8 Water Management: Field Drainage & Drain Tile Management-***In development***

Chapter 9 Water Management-Stormwater Control & Diversion-***In development***

Chapter 10 Livestock Management-Pasture & Rangeland Grazing-Completed (December 2022)

Chapter 11 Livestock Management-Animal Confinement, Manure Handling & Storage-***In development***

Chapter 12 Riparian Areas & Surface Water Protection-Completed (December 2022)

Chapter 13 Suites of Recommended Practices-***In development***

This report is available on the Department of Ecology's website at https://apps.ecology.wa.gov/publications/SummaryPages/2010008.html

Chapter 12

Riparian Areas & Surface Water Protection

Voluntary Clean Water Guidance for Agriculture

Prepared by:
Washington State Department of Ecology
Water Quality Program

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Acronyms

Acronym	Definition
CD	Conservation District
BMPs	Best management practices
EPA	Environmental Protection Agency
EQIP	Environmental Quality Incentives Program
FOTGs	Field Office Technical Guides
NPS	Nonpoint Source Pollution
NRCS	Natural Resources Conservation Service
RMZ	Riparian Management Zone
TMDL	Total Maximum Daily Load
WSDA	Washington State Department of Agriculture
WSU	Washington State University

Table of Units

Abbreviation	Meaning
Kg/M^3	Kilogram per cubic meter
Mg/ha	Mega-gram (10^6 grams) per hectare. (A mega-gram is equivalent to a metric ton.)
Mg/ha-yr	Mega-gram (10^6 grams) per hectare per year
mm/yr	Millimeter per year

Recommendations for Riparian Areas & Surface Water Protection

The Voluntary Clean Water Guidance introduction[1] provides overall goals and objectives, as well as information on how the guidance will be used. Readers are encouraged to read the Introduction before this chapter.

Introduction

The goal for this chapter is to develop guidelines for riparian management zones that, when implemented, will help restore and protect Washington State waters from agricultural pollution and facilitate the achievement of water quality standards.

Objective 1: summarize the effectiveness of riparian buffers at preventing surface water pollution from sediment, temperature, nitrogen, phosphorous, pathogens, pesticides and toxics.

Objective 2: formulate guidelines based on the attributes of riparian buffers that effectively prevent surface water pollution at the parcel scale.

Objective 3: produce guidelines that agricultural producers and technical assistance providers can use to determine the appropriate riparian buffer on an individual parcel.

While an appropriately designed and implemented riparian buffers are a key practice, they are not intended to treat any and all pollutants generated in up gradient areas. Suites of

[1] https://apps.ecology.wa.gov/publications/documents/2010008.pdf

agricultural BMPs need to be implemented with riparian buffers to minimize the generation and transport of pollutants and protect water quality.

Scope of Guidance

This guidance focuses of the effectiveness of riparian buffers at protecting water quality from agricultural pollutants. For a comprehensive overview of the functions and values of riparian ecosystems in Washington State, refer to the Washington Dept. of Fish & Wildlife's Riparian Ecosystems, Volume I: Science Synthesis and Management Implications (Quinn et al, 2020).[2]

The hydrologic scope of the riparian buffer effectiveness evaluation includes perennial, intermittent and ephemeral streams and rivers. This includes channels that were historically streams with riparian areas but were modified for agricultural purposes. Hydrologic features that are not included in this part of the guidance: wetlands; marine/lake/reservoir/pond shorelines; irrigation canals/ditches, field drainage ditches, and roadside ditches where no channel riparian area existed prior to agriculture.

Definitions as Used in this Document

Agroforestry: a land use management system in which crops, or pastureland are integrated among stands of trees or shrubs.

Channel migration zone (CMZ): areas in a floodplain where a stream or river channel can be expected to move naturally over time in response to gravity and topography.

Channel Width: The average width of the stream at the bankfull channel elevation in straight sections of a stream reach.

Concentrated Flow: Any surface runoff that is not shallow overland or sheetflow. For the purposes of this guidance, concentrated flow is any surface flow with a depth exceeding 1.2 inches (NRCS, 2010).

Eastern Washington: All counties east of the Cascade Mountain Range crest.

Ephemeral Stream Reach: a reach that does not intersect the water table for any part of the year; flows only in direct response to surface and shallow subsurface runoff following rain or snowmelt events; flow generally occurs for less than 10% of a typical water year (Hedman and Osterkamp, 1982).

Intermittent Stream Reach: a reach that intersects the water table for only part of the year; may have discontinuous sections of surface flow or may become entirely dry during the dry

[2] https://wdfw.wa.gov/publications/01987

season; continuous flow conditions generally occur for 10 to 80% of a typical water year (Hedman and Osterkamp, 1982).

Minimally Managed Riparian Vegetation: a native vegetation community with a species mixture and density that is within the range of natural variability for the site's ecological potential. The native vegetation community potential should be based on current NRCS ecological site descriptions and/or an equivalent assessment of the potential natural vegetation community. The dominant native tree species in sites with riparian forest should be managed in a way that promotes a trend towards an "old growth" condition over the long-term. "Minimally managed" includes activities such as: supplemental vegetation plantings; thinning from below (i.e. taking out the smaller trees in an over-dense stand) that is intended to increase growth of remaining plants (e.g. where tree growth is suppressed in a densely crowded stand); minimal harvest of trees for personal use (largest/tallest trees should not be harvested); control of invasive/noxious plant species, preferably through non-chemical means. It does not include commercial harvesting of trees (or other vegetation), removal of fallen trees, growing crops, or grazing.

Perennial stream reach: a reach that has year-round flow in a typical year; the channel intersects the water table for most of the year; continuous flow generally occurs for more than 80% of a typical water year (Hedman and Osterkamp, 1982).

Riparian area (a.k.a. **riparian "ecosystem" or "ecotone"**): the terrestrial environment that is transitional between aquatic and upland environments. A key defining characteristic is the presence of soils which tend to have greater moisture availability for plant communities than in the adjacent uplands. This area is delineated by features of the natural environment rather than management actions.

Riparian management zone (RMZ): Land adjacent to surface waters for which management actions are tailored to maintain specific resource objectives, in particular, water quality protection and the provision of aquatic and riparian habitat for fish and wildlife.

An RMZ may be wider or narrower than the entire riparian area. For example, in arid regions or in steeper terrain, the RMZ is often wider than the riparian area, but in wetter regions, the RMZ may be narrower than the riparian area.

In this guidance, the total width of the RMZ for streams with riparian forest potential is based on the Priority Species and Habitat Guidance from WA Dept. of Fish & Wildlife (Quinn et al, 2020; Windrope et al, 2020). For the purposes of this guidance:

- In western Washington (WWA), the minimum default width of the RMZ is 215ft.
- In eastern Washington (EWA), the minimum default width of the RMZ is 150ft.

These RMZ widths are based on the average stream length-weighted third quartile of 200-year SPTH of counties in western and eastern Washington (see appendix xx). See also site potential tree height definition further below. WDFW has developed an interactive mapping application[3] that can be used to provide site specific estimates for site potential tree height at 200 years.

RMZs that are not fully forested or composed of wetlands are composed of 3 subdivisions, which are also referred to as "zones" in this guidance. The three subdivisions are the core zone, inner zone, and the outer zone. The purpose and functions of these subdivisions are discussed in the Functions/Purpose Section later in the document. None of these RMZ subdivisions, by themselves, can fulfill all of the riparian and aquatic habitat functions provided by the full RMZ.

On a case-by-case basis, site specific estimates based on WDFW SPTH maps may be substituted for the default total RMZ widths; in these cases, the applicable core zone width and filter strip widths should remain unmodified in order to provide adequate water quality protection.

RMZ Core Zone: the portion of the RMZ which is closest to the streambank.

RMZ Inner Zone: the portion of the RMZ located between the core zone and the outer zone.

RMZ Outer Zone: the portion of the RMZ located between the inner zone and agricultural lands outside of the RMZ.

Site Potential (SP) Plant Community: The native plant community that would occur in an minimally managed condition on a site, e.g. a Douglas fir forest community, Black cottonwood forest community, Sandbar willow community, etc.

Site Potential Tree Height (SPTH): The average maximum height of the tallest dominant trees for a given site class; the index tree age is 200 years, except where shorter-lived trees (such as cottonwoods) are the tallest dominant trees.

Silvopasture: A form of agroforestry that integrates trees, forage, and the grazing of domesticated animals in a mutually beneficial way. (See Silvopasture (usda.gov[4]) for further information)

Soil Hydrologic Group: Soil hydrologic groups describe the surface runoff potential for a soil. According to the NRCS (2007):

Most of the groupings are based on the premise that soils found within a climatic region that are similar in depth to a restrictive layer or water table, transmission rate of water, texture, structure, and degree of swelling when saturated, will have similar runoff responses. The classes are based on the following factors: intake and transmission of water under the conditions of maximum yearly wetness (thoroughly wet); soil not frozen; bare soil surface; maximum swelling

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[3] https://wdfw.maps.arcgis.com/apps/MapJournal/index.html?appid=35b39e40a2af447b9556ef1314a5622d

[4] https://www.fs.usda.gov/nac/practices/silvopasture.php

of expansive clays The slope of the soil surface is not considered when assigning hydrologic soil groups.

The following is a brief summary of the four soil hydrologic groups from the NRCS; for more details about these groupings, refer to the associated chapter of the NRCS National Engineering Handbook (NRCS, 2007).

Group A—Soils in this group have low runoff potential when thoroughly wet.

Group B—Soils in this group have moderately low runoff potential when thoroughly wet.

Group C—Soils in this group have moderately high runoff potential when thoroughly wet.

Group D—Soils in this group have high runoff potential when thoroughly wet.

The NRCS maintains an interactive soil mapping web application[5] that can be used to help determine the soil hydrologic group(s) for soils occurring a particular parcel. It is recommended that soils be field verified since the map accuracy of soil boundaries is variable.

System Potential Shading: the total potential amount of vegetative shading that could occur at a stream site during a specific index period (e.g., season, day, time). The estimate of potential shading potential assumes the presence of a minimally managed, mature native plant community having a species mixture, canopy height and plant density within the natural range of variability for the site.

Western Washington: all counties west of the Cascade Mountain Range crest.

Practice Definition

A Riparian Management Zone (RMZ) functions to:

- regulate the flow of surface runoff generated from the uplands into the riparian area
- capture, retain and/or transform pollutants in the flow of surface and subsurface water
- inhibit stream bank erosion
- provide stream shading (i.e., to prevent temperature pollution)
- provide a supply of organic materials (e.g., wood and leaf litter) to streams and riparian areas
- provide habitat for fish, mammals, birds, amphibians, reptiles, insects, macroinvertebrates, etc.
- provide riparian microclimate and hyporheic zone protection

[5] https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm

RMZs in which agricultural activities are conducted should generally consist of three distinct zones (core, inner, outer), which operate together to achieve the functions listed above. Within a three-zone RMZ, the individual zones serve differing primary functions. As such, the management and the intensity of agricultural activities differs among the zones (described later in the document).

Where the RMZ is fully forested throughout its entire width, the three-zone buffer design does not apply as the functions listed above can be achieved solely through the forest width.

Recommendations for RMZ Conceptual Design

- For streams with riparian forest potential, Ecology recommends fully forested RMZs. This is consistent with WDFW's Riparian Ecosystems, Volume I: Science Synthesis and Management Implications and Riparian Ecosystems, Volume 2: Management Recommendations (Quinn et al, 2020; Windrope et al, 2020).
    - Ecology recommends restoring forest to one site potential tree height at 200 years in width in all other locations where there is existing agriculture in the RMZ.
    - Ecology recommends retaining all forest in places where an existing riparian area consists of forest that is at least one site potential tree height at 200 years in width.
- In western Washington (WWA), Ecology recommends a 215ft default total width of the RMZ in locations having riparian forest potential.
- In eastern Washington (EWA), Ecology recommends a 150ft default total width of the RMZ in locations having riparian forest potential.
- These default RMZ widths do not apply to streams without riparian forest potential; RMZ widths for these streams are primarily based on water quality protection.
- WDFW has developed an interactive mapping application[6] that can be used to provide site specific estimates for site potential tree height. On a case-by-case basis, these site-specific estimates may be substituted for the default total RMZ widths.

Three-Zone RMZ Design for Agricultural use within an RMZ

Where it is not feasible[7] to restore full riparian habitat functions (i.e., not practicable to have a fully forested RMZ due to natural or anthropogenic factors), Ecology recommends that landowners select an alternative RMZ configuration that allows for either:

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[6] https://wdfw.maps.arcgis.com/apps/MapJournal/index.html?appid=35b39e40a2af447b9556ef1314a5622d

[7] Farmers and implementers are expected to follow a stepwise process when determining feasibility. Fully consider whether the preferred option can be implemented at the site. Consider grant programs and other incentives that

1) light intensity agricultural use of the inner zone, or
2) agricultural use of the outer zone that implements a suite of additional BMPs that will effectively control the generation and transport of pollutants

These alternative options will be protective of water quality but may not achieve full protection of riparian ecosystem functions (Quinn et al, 2020).

Ecology also recommends a three-zone RMZ configuration for sites which streams do not have riparian forest potential, and this condition is not due to stream adjacent wetlands.

When implementing an alternative RMZ configuration along streams with riparian forest potential, Ecology recommends that the default total RMZ width remain 215ft in western Washington and 150ft in eastern Washington.

- When using a site specific SPTH estimate to determine the width of these alternative RMZ configurations, the core zone width and filter strip widths should remain unmodified from the widths associated with the applicable default RMZ configuration (see RMZ tables in the Recommendations for RMZ Configuration and Management sections).

Effectiveness of Three-Zone RMZs

Multiple authors have recommended the use of three-zone buffers on agricultural lands (Welsch, 1991; Johnson and Buffler, 2008; Schultz et al, 2004; Palone et al, 1997; Sheldon et al, 2005).

Lowrance et al, 2005 found that three zone buffers were moderately effective at removing nitrate, total N, total P, and dissolved P. Lowrance et al, 2000 found that three zone buffers were effective at removing nitrate from groundwater in SE coastal Plain, likely through denitrification. They also found evidence that harvest of trees in zone 2 did not affect nitrate removal. Newbold et al. (2010) found that three zone buffers in Pennsylvania resulted in moderately low nitrate load reductions, moderate sediment reductions, and no net reduction in P. Sheridan et al, 1999. Georgia found high sediment load reductions from three zone buffers, yet slightly lower reductions when tree harvest occurred in zone 2. A lack of nutrient reductions may be a product more so of environmental conditions than a reflection of three zone buffer effectiveness.

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could help cover implementation costs and offset losses in potential income. If the entire RMZ cannot be fully restored, determine the maximum extent of the RMZ that can feasibly be restored. It is not acceptable to default straight to the minimum core widths found in the other options. We would expect to see documentation of how the maximum feasible option was selected if it is not the preferred option. Examples of situations where it may not be feasible to implement Ecology's preferred recommendation to restore the RMZ to a fully forested state include but are not limited to the presence of structures and infrastructure (e.g., roads, railways, pipelines, powerlines and other utilities), property lines, topography constraints, economic hardship, and small parcels. This is a non-exhaustive list.

The combined literature review conducted for this RMZ effectiveness evaluation indicates that a three-zone buffer is likely to:

- Disperse surface runoff to achieve non-concentrated flows to promote infiltration and sediment trapping;
- Provide sufficient area for runoff infiltration beyond the outer zone, thereby inhibiting transport of pollutants such as pesticides, nutrients, sediment, and pathogens (i.e. meet instream water quality standards for conventional and toxic parameters)
- Provide shading sufficient to inhibit stream warming (e.g., meet instream water temperature standards)
- Provide an adequate large wood supply where appropriate
- Support a riparian microclimate
- Allow for compatible agricultural uses in a portion of the riparian area

RMZs in which agricultural activities are conducted should consist of a core zone, inner zone, and outer zone. The purpose of each sub-zone is described below.

RMZ Core Zone:

The portion of the RMZ which is closest to the streambank, and in which agricultural uses do not occur. This zone consists of self-sustaining, native, perennial vegetation communities.

The purpose of this zone is to provide an area in which pollutants are not generated and in which contributions to aquatic habitat functions remain undiminished. For example, this is necessary for providing an amount of stream shading that will prevent thermal pollution. The core zone also provides protection from stream bank erosion and flooding.

This zone receives surface and subsurface flow that has been "pre-filtered" by the outer and inner zones of the RMZ, which are intended for runoff control and pollutant treatment. Unless this zone is very wide, it is unlikely to adequately protect water quality on its own. Any land management activities in this zone should maintain or improve the ability of this zone to protect water quality, inhibit bank erosion, provide shade, leaf litter and wood to the stream, and provide wildlife habitat.

RMZ Inner Zone:

The portion of the RMZ located between the core zone and the outer zone. The general purpose of this zone is to maximize infiltration of surface runoff into soils. This zone is intended to capture, retain, and/or transformation the vast majority of pollutants before surface and subsurface flow enters the core zone. This zone also supports perennial vegetation communities but has more management flexibility than the core zone. Along streams with riparian forest potential, the inner zone may support carefully managed, low intensity agroforestry and silvopasture uses as described later in this document. The proper implementation of these types of agriculture seeks to promote soil and vegetation community health and avoids the use of synthetic fertilizers and pesticides. When properly implemented, agroforestry and silvopasture have a low potential for pollutant generation and transport. Additionally, the native trees integrated into this type of agriculture can provide a supplementary source of stream shading and organic material inputs to streams.

Where the outer zone is used for agricultural activities, the inner zone should consist of a narrow strip of dense perennial vegetation (i.e., a filter strip) in locations where there is a reasonable likelihood for concentrated flows to traverse from the uplands into the inner zone. The filter strip should be predominantly herbaceous on an area basis but may also contain shrubs or trees. The primary function of the filter strip is to disperse surface runoff, initiate infiltration of runoff into soils, and trap larger sediment particles. Dispersing runoff at the outer edge of the RMZ is of critical importance to its functioning because an RMZ is likely to be ineffective at removing pollutants from flows of concentrated runoff. Agricultural activities conducted in the filter strip should be limited to those that support its runoff dispersal and pollutant capturing functions. For example, compatible agricultural activities may include mowing or haying on an annual basis and short duration rotational grazing; such activities can also help to remove accumulated nutrients and promote vegetation growth.

RMZ Outer Zone:

This portion of the RMZ is located between the inner zone and agricultural lands outside of the RMZ. The purpose of the outer zone is to control the generation and transport of pollutants within close proximity of streams.

Where the inner zone of the RMZ has light intensity agricultural use, the outer zone should consist of a narrow strip of dense perennial vegetation (i.e., a filter strip) adjacent to the inner zone in locations where there is a reasonable likelihood for concentrated flows to traverse from the uplands into the inner zone. The filter strip should be predominantly herbaceous on an area basis but may also contain shrubs or trees. The primary function of the filter strip is to disperse surface runoff, initiate infiltration of runoff into soils, and trap larger sediment particles. Dispersing runoff at the outer edge of the RMZ is of critical importance to its functioning because an RMZ is likely to be ineffective at removing pollutants from flows of concentrated runoff. Agricultural activities conducted in the filter strip should be limited to those that support its runoff dispersal and pollutant capturing functions. For example, compatible agricultural activities may include mowing or haying on an annual basis and short duration rotational grazing; such activities can also help to remove accumulated nutrients and promote vegetation growth.

Where agricultural activities the outer zone of the RMZ, they should implement all applicable agricultural BMPs in accordance with Ecology’s *Voluntary Clean Water Guidance for Agriculture* in order to minimize the risk of pollutant generation and transport.

Recommendations for RMZ Configuration and Management

- RMZ configurations should adequately protect water quality, provide sufficient shading for thermal protection, protect streambanks from accelerated erosion; provide an ongoing source of large wood to streams (i.e., where applicable) and provide maintenance of at least the strongest portion of stream/riparian microclimate gradient.
- Where the 100yr floodplain width and/or channel migration zone (CMZ) are wider than the applicable RMZ width, landowners are encouraged to extend the RMZ width to the full 100yr floodplain width or CMZ width where feasible. It is recommended that at minimum, no new permanent infrastructure (i.e., roads, buildings, etc.) be constructed within the RMZ; wherever feasible, landowners are encouraged to refrain from installing new permanent infrastructure within 100yr floodplains and CMZs.
    - Where extending the RMZ to the full width of a CMZ is not feasible, Ecology recommends that RMZs design, implementation, and management account for anticipated channel migration. For example, landowners can shift an RMZ accordingly as a channel migrates in order to preserve the original width of the RMZ.
- RMZ configuration should vary according to:
    - Climate region (eastern WA vs. western WA)
    - Potential natural riparian vegetation community (e.g., forested vs. non-forested riparian potential)
    - Channel size
    - Soil hydrologic group
    - Topography
    - Land use
- RMZs that are fully forested should be composed of a "minimally-managed" "site potential plant community". RMZs that implement a three-zone design should have a core zone composed of a "minimally-managed" "site potential plant community". Details about minimally managed site potential plant communities are provided below; see also the definitions section.
    - A site potential (SP) plant community is composed of native vegetation species and has a plant density that would occur in a minimally managed condition on a site, e.g. a Douglas fir forest community, Black cottonwood forest community, Sandbar willow community, etc.
    - "Minimally-managed" riparian vegetation (see definitions section earlier in the document) should be established and maintained with the intent of achieving a native species mixture and plant densities that are within the range of natural variability for the site's native vegetation community potential. "Minimally managed" includes activities such as:

        - Establishment or supplemental planting of native vegetation
        - Minimal thinning that is only intended to increase growth of remaining plants (e.g., where growth of the desired dominant native tree species is suppressed in a densely crowded stand). Thin from below and remove only the smaller trees.
        - Minimal harvest of mature trees for personal use. Do not harvest the largest/tallest trees.
        - Control of invasive/noxious plant species, preferably through non-chemical means. Chemical weed/pest management should be limited to prescriptions identified within a RMZ management plan as being necessary to support ecological functions; use of pesticides included in the National List of substances allowed under the National Organic Program (7 CFR 205) is highly encouraged.
        - It does not include harvesting of trees, removal of fallen trees, growing crops, or livestock grazing.
    - The width of the core zone should vary based on stream hydrology and potential natural riparian community (e.g., forested, non-forested, wetland)
        - The core zone should be composed of native species, with species mixtures and plant densities that are consistent with native riparian forest communities in the region.
            - Use current Level IV EPA ecoregions, NRCS Land Resource Area designations, and/or other resources to help determine appropriate native plant communities.
            - The vegetation community potential should be based current NRCS ecological site descriptions and/or an equivalent assessment of the potential natural vegetation community.
    - For agroforestry/silvopasture within an inner zone, compatible activities include:
        - Organic agroforestry/silvopasture that establishes and retains native tree species
        - Establishment of perennial forage, i.e., sod-forming grasses and/or perennial legumes.
        - Soil disturbance that is restricted to that required to establish perennial plants.
        - Periodic mowing of herbaceous vegetation to remove nutrients and promote vigor.
        - Light intensity rotational grazing (e.g., rest-rotation) by livestock, excluding horses; note that trees need be protected from damage.
        - Fruit/nut/fungus/ornamental/medicinal plant production.

        - Precision applications of low-solubility organic fertilizers.
        - Spot application of pesticides following all applicable BMPs; use of pesticides included in the National List of substances allowed under the National Organic Program (7 CFR 205) is highly encouraged.
    - Streams without riparian forest potential due to adjacent wetlands should follow Ecology's wetland buffer guidance (Granger et al, 2005); other streams without riparian forest potential (eastern WA) should have RMZs similar in design to those with forested potential but with modifications to account for the lack of trees to contribute shade, large wood, etc.
    - It is not feasible to provide detailed species mixtures and plant density recommendations for all of the potential native riparian vegetation communities throughout the state. Suggestions on resources to consult for determining the appropriate native species mixtures and plant densities for a given site are provided in Ecology's RMZ Implementation guidance.
    - Infrastructure (crossings, bridges, structures) etc. should occupy no more than 5% of the recommended buffer area within a parcel. This does not apply to fencing.
    - No portion of the core zone or inner zone widths should be less than what is indicated in the applicable RMZ table, except where property boundaries or infrastructure (e.g., roads, railways, bridges, pipelines, power lines, buildings, etc.) prohibit the applicable widths.
        - In some cases, the increased risk to water quality due to a buffer width reduction may be mitigated by implementing site-specific BMPs above and beyond the standard suite of BMPs on a parcel; this approach would require careful consideration of site-specific factors including but not limited to climate, soils, surface/subsurface hydrology, vegetation, and land use factors.
        - Where portions of a buffer are reduced in width from the original prescription, the original cumulative buffer area (channel length x default buffer width) for the site should remain the same whenever feasible; to achieve this, additional width should be added to the portions of the buffer with lesser width constraints and/or areas with higher vulnerability to generate and/or transport pollutants (e.g. seeps/springs/wetlands, areas where surface runoff develops or converges, areas adjacent to more intensive land use or infrastructure, sections of stream more vulnerable to solar radiation, etc.)
- Ecology recommends that the following more intensive agricultural infrastructure and activities should not be located in the RMZ. If permanent infrastructure is already located in the RMZ, we recommend moving it outside the RMZ if feasible. If it cannot be moved, additional BMPs may need to be implemented to prevent pollution from being discharged.

    - Roads
    - Animal waste storage
    - Animal confinement areas
    - Winter feeding areas for livestock
    - Off-stream water facilities
    - Barns and other buildings
- Ecology recommends adhering to WDFW's guidance regarding the following activities that may occur in an RMZ, in order to minimize their impacts on riparian ecosystem function (See Vol. 2, section 3.2.1 of WDFW's PHS guidance for riparian ecosystems (Windrope et al, 2020) for more information):
    - On-site Sewage Systems (OSS)
    - Bank hardening
    - Clearing, grading, and placement of fill
    - Removal of noxious weeds
    - Forest practices and conversions
    - Firewise and wildfire hazard reduction
    - Removal of hazard trees
    - Non-compensatory restoration and enhancement
    - Emergency activities
    - Educational or Recreational Areas

Additional information on implementation and maintenance of RMZs is presented in the implementation guidance for RMZs.

Western WA: RMZ Options for perennial and intermittent stream reaches with riparian forest potential

Preferred Option: Fish & Wildlife Habitat Protection RMZ (No agriculture in the RMZ)[1]

All Channel Widths	**Core zone**: ≥215ft minimally managed site potential (SP) forest[2] **Inner zone**: N/A **Outer zone:** N/A **Total RMZ width**: ≥215ft

[2] Where an existing riparian area consists of forest, Ecology's recommendation is to retain all the forest within the RMZ.

Table 1: Alternative Option 1: Water Quality RMZ with inner zone agriculture[1]

Channel Width	RMZ Configurations
All Channel Widths	**Core zone**: ≥80ft minimally managed site potential (SP) forest **Inner zone**: 110-135ft agroforestry/silvopasture within native forest **Outer zone:** 0-25ft filter strip, depending on topography, soils, and upland land use **Total RMZ width**: ≥215ft

Table 2: Alternative Option 2: Water Quality RMZ with outer zone agriculture[1]

Channel Width	RMZ Configurations
<5ft	**Core zone:** ≥65ft minimally managed site potential (SP) forest **Inner zone**: 0-25ft filter strip, depending on topography, soils, land use **Outer zone:** 125-150ft of agriculture implementing all applicable Ag BMPs[3] **Total RMZ width**: ≥215ft
5 to 30ft	**Core zone:** ≥80ft minimally managed SP forest **Inner zone**: 0-25ft filter strip, depending on topography, soils, land use **Outer zone:** 110-135ft of agriculture implementing all applicable Ag BMPs[3] **Total RMZ width**: ≥215ft
30 to 150ft	**Core zone**: ≥100ft minimally managed SP forest **Inner zone**: 0-25ft filter strip, depending on topography and soils **Outer zone**: 90-115ft of agriculture implementing all applicable Ag BMPs[3] **Total RMZ width**: ≥215ft
>150ft	**Core zone**: ≥125ft minimally managed SP forest **Inner zone**: 0-25ft filter strip, depending on topography, soils, land use **Outer zone**: 65-90ft of agriculture implementing all applicable Ag BMPs[3] **Total RMZ width**: ≥215ft

Western WA: RMZ Options for ephemeral stream reaches with riparian forest potential

Table 3: Preferred Option: Fish & Wildlife Habitat Protection RMZ (no agriculture in the RMZ)[1]

Channel Width	RMZ Configuration
All Channel Widths	**Core zone**: ≥215ft minimally managed site potential (SP) forest[2] **Inner zone**: N/A **Outer zone**: N/A **Total RMZ width**: ≥215ft

[2] Where an existing riparian area consists of forest, Ecology's recommendation is to retain all the forest within the RMZ.

Table 4: Alternative Option 1: Water Quality RMZ with inner zone agriculture[1]

Channel Width	RMZ Configuration
All Channel Widths	**Core zone**: ≥35ft minimally managed SP forest **Inner zone**: 155-180ft agroforestry/silvopasture within native forest **Outer zone**: 0-25ft filter strip, depending on topography, soils, land use **Total RMZ width**: ≥215ft

Table 5: Alternative Option 2: Water Quality RMZ with outer zone agriculture[1]

Channel Width	RMZ Configuration
All Channel Widths	**Core zone**: ≥35ft minimally managed SP forest **Inner zone**: 0-25ft filter strip, depending on topography, soils, land use **Outer zone**: 155-180ft of agriculture implementing all applicable Ag BMPs[3] **Total RMZ width**: ≥215ft

[1]See guidelines that follow tables for determining: when to include a filter strip and how to determine its width; when and how to modify zone widths; what vegetation should consist of in a given zone; and what activities should or should not occur in any given zone.

[2] Where an existing riparian area consists of forest, Ecology's recommendation is to retain all the forest within the RMZ.

[3]See instructions that follow tables for applicable BMPs

Western WA: RMZs for perennial, intermittent, and ephemeral stream reaches without riparian forest potential

The most likely scenario for streams on agricultural lands in western Washington that have an absence of riparian forest potential is because there are stream adjacent wetlands whose conditions are not suitable for tree establishment and persistence. Under this circumstance, Ecology recommends landowners follow Ecology's guidance for protecting and managing wetlands. For more information please see: Granger, T., T. Hruby, A. McMillan, D. Peters, J. Rubey, D. Sheldon, S. Stanley, E. Stockdale. April 2005. Wetlands in Washington State - Volume 2: Guidance for Protecting and Managing Wetlands. Washington State Department of Ecology. Publication #05-06-008. Olympia, WA.

Western WA- Additional Buffer Configuration and Modification Recommendations

- All RMZs with forest riparian potential in western Washington should be a minimum of 215ft in width, regardless of the RMZ configuration option selected.
- The RMZ and subzone widths in this guidance should be treated as estimates. The goal should be to implement an effective RMZ based on known site conditions, yet with the knowledge that future modifications may be needed in order to achieve water quality and habitat protection goals.

- Stream hydrology (perennial, intermittent, ephemeral) is based on flow conditions that would occur in the absence of flow modifications by dams, surface water withdrawals, groundwater withdrawals, or other land uses that may influence stream hydrology.
- Channel width is based on the average width of the bankfull channel in straight sections of the stream.
- Filter Strip Guidelines
    - A filter strip is a recommended BMP wherever concentrated flows may enter the RMZ.
    - Filter strip width is partly determined based on the dominant type of soils located within the RMZ
    - In western Washington, the range for filter strips is 0 to 15ft on Hydrologic Group A or B soils and 0 to 25ft on Hydrologic Group C or D soils
    - Soil hydrologic group should be determined only for soils within the RMZ. Soil Hydrologic Group can be determined by consulting the NRCS's Web Soil Survey internet application (https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm). Assistance with this application may be provided by the local conservation district and/or NRCS office. Multiple soil types may be present along a stream reach within a parcel; therefore, RMZ configuration may vary along a stream reach within a parcel.
    - The lower end of the filter strip width range should be implemented where topographic divergence occurs (e.g. a toeslope of ridge where the slope fans out) within 215ft of the stream.
    - The middle of the filter strip width range should be implemented: on linear (e.g., a uniform slope uphill) or concave hillslopes where there is neither slope convergence nor divergence (i.e., uniform across the hill) within 215ft of the stream; or where moderate intensity land uses occur in or adjacent to the RMZ. See examples of moderate intensity land uses presented earlier in this document.
    - The higher end of the filter strip width range should be implemented where: topographic convergence occurs (e.g., swales, low spots, etc. where surface flow is more likely to concentrate; rills or minor gullies tend to form; the hillslope is convex within 215ft of the stream; and/or high intensity land uses occur in or adjacent to the RMZ. See examples of high intensity land uses presented earlier in this document.
    - Where soil slopes >8% occur within 215ft of the stream, increase the filter strip width by an additional 10ft.
    - A level spreader is a recommended BMP for placement at the upslope edge of the filter strip wherever concentrated flows (any surface runoff depth >1.2 inches) are known or suspected to occur.

    - Recommended core zones for the smallest streams my not be sufficient to achieve shade goals in all cases. On a case-by-case basis additional trees may need to be planted in lieu of the filter strip to ensure temperature is protected.
- The recommended buffer widths for smaller streams may not be wide enough to provide large wood. Additionally, when RMZs are being restored it will take decades for trees to grow and fall into streams. Projects to supplement large wood in streams are recommended and may be necessary in either the short or long term to provide sufficient habitat.
- At minimum, all applicable BMPs include: All BMPs identified by Ecology's Clean Water Guidance for Agriculture such as:
    - Pasture and rangeland grazing BMPs
    - Manure storage BMPs
    - Heavy use area BMPs
    - Conservation tillage & residue management BMPs
    - Structural (e.g., sediment control basins) and vegetative (e.g. cover crops, grassed waterways) BMPs for erosion and sediment control
    - Nutrient management BMPs
    - Integrated pest management BMPs
    - Irrigation management BMPs

Eastern WA: RMZ Options for perennial and intermittent stream reaches with riparian forest potential

Preferred Option: Fish & Wildlife Habitat Protection RMZ (no agriculture in the RMZ)[1]

All Channel Widths	**Core zone**: ≥150ft site potential (SP) forest[2] **Inner zone**: N/A **Outer zone**: N/A **Total RMZ width**: 150ft

[2] Where an existing riparian area consists of forest, Ecology's recommendation is to retain all the forest within the RMZ.

Table 6: Alternative Option 1: Water Quality RMZ with inner zone agriculture[1]

Channel Width	RMZ Configurations
All Channel Widths	**Core zone**: ≥60ft minimally managed SP forest **Inner zone**: 70-90ft agroforestry/silvopasture within native forest **Outer zone**: 0-20ft filter strip, depending on topography, soils, land use **Total RMZ width**: ≥150ft

Table 7: Alternative Option 2: Water Quality RMZ with outer zone agriculture[1]

Channel Width	RMZ Configurations
<5ft	**Core zone**: ≥50ft minimally managed site potential (SP) forest **Inner zone**: 0-20ft filter strip, depending on topography, soils, land use **Outer zone**: 80-100ft of agriculture implementing all applicable Ag BMPs[3] **Total RMZ width**: ≥150ft
5 to 30ft	**Core zone**: ≥60ft minimally managed site potential SP forest **Inner zone**: 0-20ft filter strip, depending on topography, soils, land use **Outer zone**: 70-90ft of agriculture implementing all applicable Ag BMPs[3] **Total RMZ width**: ≥150ft
30 to 150ft	**Core zone**: ≥75ft minimally managed SP forest **Inner zone**: 0-20ft filter strip, depending on topography, soils, land use **Outer zone**: 55-75ft of agriculture implementing all applicable Ag BMPs[3] **Total RMZ width**: ≥150ft
>150ft	**Core zone**: ≥100ft minimally managed SP forest **Inner zone**: 0-20ft filter strip, depending on topography, soils, land use **Outer zone**: 30-50ft of agriculture implementing all applicable Ag BMPs[3] **Total RMZ width**: ≥150ft

Eastern WA, RMZ Options for ephemeral stream reaches with riparian forest potential

Table 8: Preferred Option: Fish & Wildlife Habitat Protection RMZ (no agriculture in the RMZ)[1]

Channel Width	RMZ Configuration
All Channel Widths	**Core zone**: ≥150ft minimally managed site potential (SP) forest[2] **Inner zone**: N/A **Outer zone**: N/A **Total RMZ width**: ≥150ft

[2] Where an existing riparian area consists of forest, Ecology's recommendation is to retain all the forest within the RMZ.

Table 9: Alternative Option 1: Water Quality RMZ with inner zone agriculture[1]

Channel Width	RMZ Configuration
All Channel Widths	**Core zone**: ≥35ft minimally managed SP forest **Inner zone**: 95-115ft agroforestry/silvopasture within native forest **Outer zone**: 0-20ft filter strip, depending on topography, soils, land use **Total RMZ width**: ≥150ft

Table 10: Option 2: Water Quality RMZ with outer zone agriculture[1]

Channel Width	RMZ Configuration
All Channel Widths	**Core zone**: ≥35ft minimally managed SP forest **Inner zone**: 0-20ft filter strip, depending on topography, soils, land use **Outer zone**: 95-115ft of agriculture implementing all applicable Ag BMPs[3] **Total RMZ width**: ≥150ft

Eastern WA: RMZs for perennial, intermittent, and ephemeral stream reaches without riparian forest potential due to climate conditions

Table 11: Eastern WA: RMZs for perennial stream reaches without riparian forest potential due to climate conditions[1]

Channel Width	RMZ Configuration
All Channel Widths	**Core zone**: ≥50ft minimally managed site potential (SP) vegetation **Inner zone**: 0-20ft filter strip, depending on topography, soils, land use **Outer zone**: 30-50ft of agriculture implementing all applicable Ag BMPs[3] **Total RMZ width**: ≥100ft

Table 12: Eastern WA: RMZs for intermittent stream reaches without riparian forest potential due to climate conditions[1]

Channel Width	RMZ Configuration
All Channel Widths	**Core zone**: ≥35ft minimally managed SP vegetation **Inner zone**: 0-20ft filter strip, depending on topography, soils, land use **Outer zone**: 45-65ft of agriculture implementing all applicable Ag BMPs[3] **Total RMZ width**: ≥100ft

Table 13: Eastern WA: RMZs for ephemeral stream reaches without riparian forest potential due to climate conditions[1]

Channel Width	RMZ Configuration
All Channel Widths	**Core zone**: ≥25ft minimally managed SP vegetation **Inner zone**: 0-20ft filter strip, depending on topography, soils, land use **Outer zone**: 55-75ft of agriculture implementing all applicable Ag BMPs[3] **Total RMZ width**: ≥100ft

[1]See guidelines that follow tables for determining: when to include a filter strip and how to determine its width; when and how to modify zone widths; what vegetation should consist of in a given zone; and what activities should or should not occur in any given zone.

[2] Where an existing riparian area consists of forest, Ecology's recommendation is to retain all the forest within the RMZ.

[3]See instructions that follow tables for applicable BMPs.

Eastern WA: RMZs for perennial, intermittent, and ephemeral stream reaches without riparian forest potential due to adjacent wetlands

Some agricultural lands in eastern Washington have an absence of riparian forest potential due to stream adjacent wetlands whose conditions are not suitable for tree establishment and persistence. Under this circumstance, it is recommended that landowners follow Ecology's guidance for protecting and managing wetlands. For more information please see: Granger, T., T. Hruby, A. McMillan, D. Peters, J. Rubey, D. Sheldon, S. Stanley, E. Stockdale. April 2005. Wetlands in Washington State - Volume 2: Guidance for Protecting and Managing Wetlands. Washington State Department of Ecology. Publication #05-06-008. Olympia, WA.

Eastern WA- Additional Buffer Configuration and Modification Recommendations

- All RMZs with forest riparian potential in eastern Washington should be a minimum of 150ft in width, regardless of the RMZ configuration option selected.
- The RMZ and subzone widths in this guidance should be treated as estimates. The goal should be to implement an effective RMZ based on known site conditions, yet with the knowledge that future modifications may be needed in order to achieve water quality and habitat protection goals.
- Stream hydrology (perennial, intermittent, ephemeral) is based on flow conditions that would occur in the absence of flow modifications by dams, surface water withdrawals, groundwater withdrawals, or other land uses that may influence stream hydrology.
- Channel width is based on the average width of the bankfull channel in straight sections of the stream.
- Filter Strip Guidelines
    - A filter strip is a recommended BMP wherever concentrated flows may enter the RMZ.
    - Filter strip width is partly determined based on the dominant type of soils located within the RMZ
    - In eastern Washington, the range for filter strips is 0 to 10ft on Hydrologic Group A or B soils and 0 to 20ft on Hydrologic Group C or D soils

- Soil hydrologic group should be determined only for soils within the RMZ. Soil Hydrologic Group can be determined by consulting the NRCS's Web Soil Survey internet application (https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm). Assistance with this application may be provided by the local conservation district and/or NRCS office. Multiple soil types may be present along a stream reach within a parcel; therefore, RMZ configuration may vary along a stream reach within a parcel.
- The lower end of the filter strip width range should be implemented where topographic divergence occurs (e.g., a toeslope of ridge where the slope fans out) within 150ft of the stream.
- The middle of the filter strip width range should be implemented: on linear (e.g., a uniform slope uphill) or concave hillslopes where there is neither slope convergence nor divergence (i.e., uniform across the hill) within 150ft of the stream; or where moderate intensity land uses occur in or adjacent to the RMZ. See examples of moderate intensity land uses presented earlier in this document.
- The higher end of the filter strip width range should be implemented where: topographic convergence occurs (e.g., swales, low spots, etc. where surface flow is more likely to concentrate; rills or minor gullies tend to form; the hillslope is convex within 150ft of the stream; and/or high intensity land uses occur in or adjacent to the RMZ. See examples of high intensity land uses presented earlier in this document.
- Where soil slopes >8% occur within 150ft of the stream, increase the filter strip width by an additional 10ft.
- A level spreader is a recommended BMP for placement at the upslope edge of the filter strip wherever concentrated flows (any surface runoff depth >1.2 inches) are known or suspected to occur.
- Recommended core zones for the smallest streams my not be sufficient to achieve shade goals in all cases. On a case-by-case basis additional trees may need to be planted in the filter strip to ensure temperature is protected.

- The recommended buffer widths for smaller streams may not be wide enough to provide large wood in all cases. Additionally, when RMZs are being restored it will take decades for trees to grow and fall into streams. Projects to supplement large wood in streams are recommended and may be necessary in either the short or long term to provide sufficient habitat.
- At minimum, all applicable BMPs include: All BMPs identified by Ecology's Clean Water Guidance for Agriculture such as:
  - Pasture and rangeland grazing BMPs
  - Manure storage BMPs
  - Heavy use area BMPs

- Conservation tillage & residue management BMPs
- Structural (e.g., sediment control basins) and vegetative (e.g., cover crops, grassed waterways) BMPs for erosion and sediment control
- Nutrient management BMPs
- Integrated pest management BMPs
- Irrigation management BMPs

Related NRCS Practices

- Riparian Forest Buffer (NRCS practice code 391)
- Riparian Herbaceous Cover (NRCS practice code 390)
- Critical Area Planting (NRCS practice code 350)
- Filter Strip (NRCS practice code 393)
- Silvopasture (NRCS practice code 381)
- Tree-shrub Establishment (NRCS practice code 612)
- Tree-shrub Site Preparation (NRCS practice code 490)
- Stream Habitat Improvement and Management (NRCS practice code 395)
- Streambank and Shoreline Protection (NRCS practice code 580)

Commonly Associated Practices:

- Pasture and rangeland grazing BMPs
- Manure storage BMPs
- Heavy use area BMPs
- Conservation tillage & residue management BMPs
- Structural (e.g., sediment control basins) and vegetative (e.g. cover crops, grassed waterways) BMPs for erosion and sediment control
- Nutrient management BMPs
- Integrated pest management BMPs
- Irrigation management BMPs

Adaptive Management

Adaptive management is important for the conservation and protection of natural resources. The goal of adaptive management in RMZ implementation should be to tailor land management actions to site specific circumstances in a way that ensures protection of water quality and habitat. In this regard, the management of an RMZ should be adjusted based on site specific data and information. For example, in some cases, site specific data and information may indicate that a more restrictive RMZ than recommended in this guidance is needed to protect water quality where, for example, there are poorly draining soils, steep slopes, or urban land uses in close proximity. In other cases, site specific data and information may be used to show that water quality and habitat can be adequately protected with lesser restrictions on the use of the inner and outer zones of the RMZ, and a slightly smaller core zone. In any regard, it is imperative that the basis for adjusting RMZ configuration management is driven by the availability of better scientific data and information about what is needed to achieve adequate water quality protection and not simply landowner or technical assistance provider preference. Such data and information is typically obtained by working with professionals having expertise in the specific issue(s) at hand (e.g. soil scientists/conservationists, hydrologists, biologists, agronomists, etc.).

Chapter 12 Appendix Part A: Effectiveness Synthesis (Riparian Areas & Surface Water Protection)

The following presents the main findings and recommendations of the effectiveness evaluation, with further detail provided throughout the rest of the document.

Function/Purpose

- The functions of an RMZ include:
- Regulate the flow of surface runoff generated from the uplands into the riparian area
- Capture, retain and/or transform pollutants in the flow of surface and subsurface water
- Inhibit stream bank erosion
- Reduce flood damage
- Provide natural levels of stream shading (i.e., to prevent thermal pollution)
- Supply organic materials (e.g., wood and leaf litter) to streams and riparian areas
- Provide habitat for fish, mammals, birds, amphibians, reptiles, insects, etc.
- Support a riparian microclimate
- Support the stability and resilience of aquatic and riparian ecosystems as the climate changes

Applicability

- This guidance is applicable to riparian areas along all perennial, intermittent, and ephemeral streams located adjacent to agricultural lands within Washington State. This includes streams that have been modified (e.g., channelized/ditched/straightened) for agricultural purposes. Agricultural lands include parcels upon which livestock are kept and/or crops are grown for commercial production or personal consumption.

RMZs Conceptual Design

- For streams with riparian forest potential, Ecology recommends fully forested RMZs. This is consistent with WDFW's Riparian Ecosystems, Volume I: Science Synthesis and Management Implications and Riparian Ecosystems, Volume 2: Management Recommendations (Quinn et al, 2020; Windrope et al, 2020).
    - Ecology recommends restoring forest to one site potential tree height at 200 years in width in all other locations where there is existing agriculture in the RMZ.
    - Ecology recommends retaining all forest in places where an existing riparian area consists of forest that is at least one site potential tree height at 200 years in width

- For areas where a fully forested RMZ is not already present, and either 1) is not feasible to restore; or 2) the RMZ does not have forest potential, Ecology recommends that RMZs consist of a modified version of the USDA three-zone buffers (Welsch, 1991). A diagram of a three-zone buffer design is depicted later in the document.

Recommendations for RMZ Configuration and Management

- The recommended RMZ configurations are intended to adequately protect water quality, provide sufficient shading to address temperature, provide an ongoing source of large wood to streams (i.e., for RMZs with riparian forest potential), and provide maintenance of stream/riparian microclimate.
- The primary factors influencing RMZ configuration are: climate (i.e. eastern vs. western WA); stream size; soil hydrology; potential natural riparian vegetation community; topography; land use.
- Ecology recommends that RMZ design be based on: climate region (eastern WA vs. western WA); forested vs. non-forested riparian potential, channel size; and soil hydrologic group.
- Ecology recommends that the RMZ be configured to achieve a fully functioning riparian ecosystem, to include water quality protection and the provision of aquatic and riparian habitat. In areas with riparian forest potential, this requires a fully forested RMZ with a width equivalent to at least one site-potential tree height at 200 years (Quinn et al, 2020; see also WDFW interactive site potential tree height mapping application, with internet link located on the WDFW website at: https://wdfw.wa.gov/species-habitats/at-risk/phs/recommendations).
- In western Washington (WWA), Ecology recommends a 215ft default total width of the RMZ for streams with riparian forest potential.
- In eastern Washington (EWA), Ecology recommends a 150ft default total width of the RMZ for streams with riparian forest potential.
- These default RMZ widths do not apply to streams without riparian forest potential; RMZ widths for these streams are primarily based on water quality protection.
- WDFW has developed an interactive mapping application[8] that can be used to provide site specific estimates for site potential tree height. On a case-by-case basis, these site-specific estimates may be substituted for the default RMZ widths.
- Where it is not feasible to restore full riparian habitat functions (i.e., not feasible to have a fully forested RMZ), Ecology recommends that landowners select an alternative RMZ configuration (presented later in the document) that allows for either: 1) light intensity agricultural use of the inner zone; or 2) agricultural use of the outer zone that implements a suite of additional BMPs that will effectively control the generation and transport of

https://wdfw.maps.arcgis.com/apps/MapJournal/index.html?appid=35b39e40a2af447b9556ef1314a5622d[8] pollutants. Along streams with riparian forest potential, these alternative options will be protective of water quality, but may not achieve full protection of riparian ecosystem functions (Quinn et al, 2020).

    - When using a site specific SPTH estimate for these alternative RMZ configurations, the core zone width and filter strip widths should remain unmodified from the widths associated with the applicable default RMZ.

- More detailed recommendations for RMZ configuration and management are described section titled "Recommendations for RMZ Configuration and Management."
    - Subsections titled "Western WA: RMZ options for perennial and intermittent stream reaches with riparian forest potential", "Western WA: RMZ options for ephemeral stream reaches with riparian forest potential", and "Western WA: RMZs for perennial intermittent, and ephemeral stream reaches without riparian forest potential" have site specific RMZ recommendations for western WA.
    - Subsections titled "Eastern WA: RMZ options for perennial and intermittent stream reaches with riparian forest potential", "Eastern WA: RMZ options for ephemeral stream reaches with riparian forest potential", and "Eastern WA: RMZs for perennial intermittent, and ephemeral stream reaches without riparian forest potential" have site specific RMZ recommendations for eastern WA.
- "Minimally-managed" riparian vegetation should be established and maintained with the intent of achieving a native species mixture and plant densities that are within the range of natural variability for the site's native vegetation community potential. The dominant tree species in sites with riparian forest should be managed in a way that promotes a trend towards a mature or "old growth" condition over the long-term; this is in order to maximize riparian ecosystem functioning (Quinn et al, 2020)
- Ecology recommends cultivating and maintaining plant communities in the RMZ that resemble or mimic plant communities that would occur naturally in that riparian area. However, it is not feasible to provide detailed species mixtures and plant density recommendations for all of the potential native riparian vegetation communities throughout the state in this effectiveness guidance. Please refer to Ecology's RMZ Implementation guidance for more information on determining the appropriate native species mixtures and plant densities for a given site.
- Implementation and maintenance of RMZs is address in the RMZ implementation guidance.

Function/ Purpose

WDFW provides a comprehensive overview of riparian ecosystem functions and the need to conserve them in Riparian Ecosystems, Volume 1: Science Synthesis and Management Implications[9] (Quinn et al, 2020). Please refer to the WDFW publication for a comprehensive discussion of the functions and purpose of RMZs.

Below is a summary of functions and purposes of three-zone RMZs specific to agricultural lands.

Effective RMZs can:

- Regulate the flow of upland surface runoff into the riparian area
- Capture, retain and/or transform pollutants in the flow of surface and subsurface water
- Inhibit stream bank erosion
- Reduce flood damage
- Provide natural levels of stream shading, preventing temperature pollution
- Supply organic materials (e.g., wood and leaf litter) to streams and riparian areas
- Provide habitat for fish, mammals, birds, amphibians, reptiles, and insects
- Support a riparian microclimate
- Support the stability and resilience of aquatic and riparian ecosystems against climate change

The purpose of an RMZ is to intercept and retain, and/or transform pollutants generated from low to moderate intensity agricultural land uses that are close to a stream (within 300ft) and being moving through the buffer in a non-channelized flow, in aerial drift or by solar radiation. An RMZ is not intended to treat any and all pollutants generated upgradient of the RMZ. Suites of agricultural BMPs are needed in addition to a buffer to minimize the generation and transport of pollutants and protect water quality.

Examples of low intensity land uses include:

- Agroforestry
- Silvopasture

Examples of moderate intensity land uses include:

- Grazing under a mgmt. plan designed to maintain or improve soil, forage, and livestock health
- Cropping systems that employ cover crops and/or conservation tillage or no-till planting

[9] https://wdfw.wa.gov/publications/01987

- Irrigation according to BMPs
- Soil fertility mgmt. based on a nutrient management plan
- Cropland, orchards, and vineyards using integrated pest management

The RMZ is not a substitute for implementing other applicable agricultural BMPs. BMPs in the uplands that inhibit runoff and pollutant generation, and transport are necessary for the RMZ to function effectively. Controlling pollutants generated from high intensity land uses or transported from farther away may require structural and vegetative BMPs above and beyond the typical agricultural BMPs, such as sediment control basins, filter strips, terraces, and grassed waterways.

Examples of high intensity land uses include:

- Feedlots and winter-feeding areas
- Manure storage areas
- Cropping systems that do not employ cover crops and conservation tillage or no-till planting
- Irrigation that doesn't employ BMPs
- Grazing without a mgmt. plan designed to maintain or improve soil, forage, and livestock health
- Cropland, orchards, and vineyards not using integrated pest management
- Soil fertility mgmt. not based on a nutrient management plan

Purposes of the three RMZ sub-zones

As noted previously, a three-zone buffer should be implemented where it is not feasible to have a fully forested RMZ that is one SPTH at 200 years in width. Under this scenario, the three zones have differing purposes as described below.

RMZ Outer Zone:

This portion of the RMZ is located between the inner zone and agricultural lands outside of the RMZ. The purpose of the outer zone is to control the generation and transport of pollutants within close proximity of streams.

Where the inner zone of the RMZ has light intensity agricultural use, the outer zone should consist of a narrow strip of dense perennial vegetation (i.e., a filter strip) adjacent to the inner zone in locations where there is a reasonable likelihood for concentrated flows to traverse from the uplands into the inner zone. The filter strip should be predominantly herbaceous on an area basis but may also contain shrubs or trees. The primary function of the filter strip is to disperse surface runoff, initiate infiltration of runoff into soils, and trap larger sediment particles. Dispersing runoff at the outer edge of the RMZ is of critical importance to its functioning because an RMZ is likely to be ineffective at removing pollutants from flows of concentrated runoff. Agricultural activities conducted in the filter strip should be limited to those that support its runoff dispersal and pollutant capturing functions. For example, compatible agricultural activities may include mowing or haying on an annual basis and short duration rotational grazing; such activities can also help to remove accumulated nutrients and promote vegetation growth.

Where agricultural activities the outer zone of the RMZ, they should implement all applicable agricultural BMPs in accordance with Ecology's *Voluntary Clean Water Guidance for Agriculture*.

RMZ Inner Zone:

The portion of the RMZ located between the core zone and the outer zone. The general purpose of this zone is to maximize infiltration of surface runoff into soils. This zone is intended to capture, retain, and/or transformation the vast majority of pollutants before surface and subsurface flow enters the core zone. This zone also supports perennial vegetation communities but has more management flexibility than the core zone. Along streams with riparian forest potential, the inner zone may support carefully managed, low intensity agroforestry and silvopasture uses as described later in this document. The proper implementation of these types of agriculture seeks to promote soil and vegetation community health and avoids the use of synthetic fertilizers and pesticides. When properly implemented, agroforestry and silvopasture have a low potential for pollutant generation and transport. Additionally, the native trees integrated into this type of agriculture can provide a supplementary source of stream shading and organic material inputs to streams.

Where the outer zone is used for agricultural activities, the inner zone should consist of a narrow strip of dense perennial vegetation (i.e., a filter strip) in locations where there is a reasonable likelihood for concentrated flows to traverse from the uplands into the inner zone. The filter strip should be predominantly herbaceous on an area basis but may also contain shrubs or trees. The primary function of the filter strip is to disperse surface runoff, initiate infiltration of runoff into soils, and trap larger sediment particles. Dispersing runoff at the outer edge of the RMZ is of critical importance to its functioning because an RMZ is likely to be ineffective at removing pollutants from flows of concentrated runoff. Agricultural activities conducted in the filter strip should be limited to those that support its runoff dispersal and pollutant capturing functions.

For example, compatible agricultural activities may include mowing or haying on an annual basis and short duration rotational grazing; such activities can also help to remove accumulated nutrients and promote vegetation growth.

RMZ Core Zone:

The portion of the RMZ which is closest to the streambank, and in which agricultural uses do not occur. This zone consists of self-sustaining, native, perennial vegetation communities. The purpose of this zone is to provide an area in which pollutants are not generated and the area's contributions to aquatic habitat functions remain undiminished. For example, this is necessary for providing an amount of stream shading that will prevent thermal pollution. This zone receives surface and subsurface flow that has been “pre-filtered” by the outer and inner zones of the RMZ, which are intended for runoff control and pollutant treatment. Unless this zone is very wide, it is unlikely to adequately protect water quality on its own. Any land management activities in this zone should maintain or improve the ability of this zone to protect water quality, inhibit bank erosion, provide shade, leaf litter and wood to the stream, and provide wildlife habitat.

Parameters Addressed

- Nitrogen
- Pathogens (e.g., harmful bacteria, viruses, parasites, protozoans, etc.)
- Pesticides (insecticides, herbicides, fungicides, etc.)
- Phosphorus
- Sediment
- Water temperature
- Large wood supply to streams
- Stream/riparian microclimate

Applicability

- This RMZ guidance is applicable to riparian areas along all perennial, intermittent, and ephemeral streams located adjacent to agricultural lands within Washington State. This includes streams that have been modified (e.g., channelized/ditched/straightened) for agricultural purposes. Agricultural lands include parcels upon which either commercial or hobby operations keep livestock and/or grow crops.
- The RMZ guidance does not apply to wetlands (or drainage channels excavated within wetlands), or shorelines of ponds, lakes, reservoirs, and marine waters. It also does not apply to ditches or canals excavated for irrigation or drainage, nor management induced channels such as rills and gullies.

Effectiveness

Several hundred literature sources related to the effectiveness of riparian buffers at pollutant removal were reviewed for this evaluation. Although the findings presented in this evaluation reflect the literature review, this evaluation does not attempt to summarize the vast and diverse amount of information represented by these sources. Instead, these sources are individually summarized in the accompanying annotated bibliography.

Numerous factors influence the effectiveness of riparian buffers at controlling specific pollutants including:

- Climate and weather

- Geology
- Geomorphology and topography
- Soil characteristics
- Buffer vegetation type, height, and density
- Land use and land use intensity and practices
- Runoff volumes, rates, and flow types
- Buffer size, and the area of land comprising a buffer relative to the area of land contributing surface and subsurface flow to the buffer (i.e., buffer area ratio).

Accordingly, the removal of a specific pollutant will typically vary as combinations of these factors vary across field, parcel, and watershed, and landscape scales. Furthermore, a given combination of these factors may affect the removal of different pollutants in different ways. For example, site characteristics that lead to an enhanced removal rate of one pollutant may not affect the removal of another pollutant, or in some cases, may even result in a decreased removal rate. A summary of research addressing ability of riparian buffers to attenuate different pollutant types is provided later in this section. Additionally, Ecology has completed an annotated bibliography for the literature that was reviewed in development of this effectiveness evaluation.

Table 14: below summarizes the general estimated effectiveness of riparian buffers at removing pollutants from *non-concentrated flows*. Note that these estimates are by and large based on research conducted in humid climates with annual precipitation amounts exceeding 20 inches. For this reason, it is generally expected that narrower buffer widths than those presented in the table would be required to achieve an equivalent level of pollutant removal in arid and semi-arid regions.

Tables 15 & 16: provide effectiveness estimates for stream shading. Tables 17 and 18 provide effectiveness estimates for large wood supply and microclimate protection, respectively.

Table 14 Estimated Buffer Pollutant Removal Effectiveness on for Agricultural Riparian Buffers: Sediment, Nutrients, Pathogens/Bacteria, and Pesticides[1]

Pollutant (applicable land use)	**Effective Vegetated Buffer Widths[2] Soil Hydrologic Group A**	**Effective Vegetated Buffer Widths[2] Soil Hydrologic Group B**	**Effective Vegetated Buffer Widths[2] Soil Hydrologic Group C**	**Effective Vegetated Buffer Widths[2] Soil Hydrologic Group D**	**Effectiveness Estimate**
Sediment (cropland, orchards, pasture, range)	≥35ft	35 to 50ft	50 to 75ft	75ft to 100ft	≥95% removal from surface runoff, based on analysis of data for Group B/C/D soils.
Pathogens/Bacteria (pasture, range and cropland/orchards with manure applications)	≥50ft	50 to 75ft	75 to 100ft	≥100ft	≥95% infiltration into soil- based on analysis of data for Group B/C soils and estimated distance required to infiltrate ≥95% of sheetflow/shallow overland flow, per sediment studies. Infiltration into soil does not necessarily equate to immobilization.
Nitrogen, dissolved (cropland, orchards, pasture, range)	≥50ft	50 to 75ft	75 to 100ft	≥100ft	≥95% infiltration into soil; based on results of bacteria and pesticides analyses and distance required to infiltrate ≥95% of sheetflow/shallow overland flow in sediment removal studies. Infiltration does not equate to immobilization. Removal varies widely based on site-specific subsurface biogeochemical factors.
Nitrogen, sediment adsorbed/particulate	≥35ft	35 to 50ft	50 to 75ft	75 to 100ft	≥95% removal from surface runoff; based on estimated distance required to infiltrate

Pollutant (applicable land use)	**Effective Vegetated Buffer Widths[2] Soil Hydrologic Group A**	**Effective Vegetated Buffer Widths[2] Soil Hydrologic Group B**	**Effective Vegetated Buffer Widths[2] Soil Hydrologic Group C**	**Effective Vegetated Buffer Widths[2] Soil Hydrologic Group D**	**Effectiveness Estimate**
(cropland, orchards, pasture, range)					≥95% of sheetflow/shallow overland flow, per sediment studies.
Phosphorus, dissolved (cropland, orchards, pasture, range)	≥50ft	50 to 75ft	75 to 100ft	≥100ft	≥95% infiltration into soil; based on results of bacteria and pesticides analyses and distance required to infiltrate >95% of sheetflow/shallow overland flow in sediment removal studies. Infiltration does not equate to immobilization. Removal varies widely based on site- specific subsurface biogeochemical factors.
Phosphorus, sediment adsorbed/particulate (cropland, orchards, pasture, range)	≥35ft	35 to 50ft	50 to 75ft	75 to 100ft	≥95% removal from surface runoff; based on estimated distance required to infiltrate ≥95% of sheetflow/shallow overland flow, per sediment studies.
Low to Moderately Soluble Pesticides in surface runoff[3] (cropland, orchards, pasture, and range where these pesticides were applied)	≥35ft	35 to 50ft	50 to 75ft	75 to 100ft	≥95% removal from surface runoff; based on pesticide removal analysis and estimated distance required to infiltrate ≥95% of sheetflow/ shallow overland flow, per sediment studies. Note that infiltration does not equate to immobilization, which will vary based on site specific biogeochemical factors.

Pollutant (applicable land use)	**Effective Vegetated Buffer Widths[2] Soil Hydrologic Group A**	**Effective Vegetated Buffer Widths[2] Soil Hydrologic Group B**	**Effective Vegetated Buffer Widths[2] Soil Hydrologic Group C**	**Effective Vegetated Buffer Widths[2] Soil Hydrologic Group D**	**Effectiveness Estimate**
Moderate to Highly Soluble Pesticides in surface runoff[3] (cropland, orchards, pasture, and range where pesticides are applied)	≥50ft	50 to 75ft	75 to 100ft	≥100ft	≥95% removal from surface runoff; based on pesticide removal analysis and estimated distance required to infiltrate >95% of sheetflow/shallow overland flow, per sediment studies. Note infiltration does not equate to immobilization, which will vary based on site specific biogeochemical factors.
All Pesticides, aerial application drift (cropland, orchards, pasture, and range where pesticides were applied)	≥50ft	≥50ft	≥50ft	≥50ft	≥95% interception for buffers vegetated with trees and shrubs

[1]Estimates based mostly upon research in humid climates with abundant rainfall. Effectiveness estimates specific to arid areas are not available, but will generally require narrower vegetated buffer widths.

[2]For the identified buffer width ranges, greater width may be needed to achieve the identified effectiveness level on sites with attributes such as: steeper slopes (e.g. >8%) within 300ft of streams; convex riparian slopes; modified infiltration rates; soils with a shallow restrictive layer; sparser vegetation; high rainfall amounts and intensities; high buffer area ratios; more intensive upland land uses (e.g. non-rotational grazing, manure applications above agronomic rates, routine chemical fertilizer/pesticide applications, periods during which upland soils are non-vegetated).

[3]Based on Pesticide Movement Ratings designated by the National Pesticide Information Center. See Section Titled Pesticide Properties for table of Pesticide Movement Ratings.

Estimated buffer widths on agricultural lands needed to provide stream temperature protection[1]

Table 15: Eastern WA Stream with forested buffer potential

Bankfull Channel Width (ft)	Effective Vegetated Buffer Width (ft)	Effectiveness Estimate
<5	50	≥95% system potential shade
5 to 30	60	
30 - 150	75	
>150	100	

Table 16: Western WA Stream with forested buffer potential.

Bankfull Channel Width (ft)	Effective Vegetated Buffer Width (ft)	Effectiveness Estimate
<5	60	≥95% system potential shade
5 to 30	80	
30 - 150	100	
>150	125	

[1]Based on vegetation shading only.

Table 17: Estimated widths needed to provide large wood to streams in areas with forested buffer potential in Eastern and Western WA[1]

Channel Width	Forested Buffer Width	Effectiveness Estimate
All Channel Widths	≥64ft (≥19.5m)	≥90% of the number of large wood pieces recruited from bank erosion and windthrow relative to a fully forested riparian area[2]

[1]An estimate specific to eastern WA is not available due to a lack of applicable studies, but may be assumed to be roughly equal to the forested buffer width needed in western WA.

[2]This objective is based on large wood recruitment estimates for streams in forestlands from windthrow, bank erosion, and soil mass movements on hillsides. It does not and cannot account for recruitment on larger streams associated with channel avulsion within a channel migration zone.

Note, however, that as a channel migrates across a floodplain over long time spans, the forested buffer width would need to be maintained.

Table 18: Estimated forested buffer width needed to support the stream and riparian microclimate in areas with forested buffer potential in Eastern and Western WA

Channel Width	Forested Buffer Width	Effectiveness Estimate
<30ft	≥50ft	Maintenance of the core natural microclimate gradient (e.g. air and soil temperature/moisture) adjacent to streams[1]
>30ft	No estimate	

[1]The "core" refers to the portion of the gradient along which changes in air and soil temperature and moisture levels are likely to be greatest per unit of distance from the stream.

Pollutant Specific Effectiveness Evaluation

Nitrogen (N)

The effectiveness of riparian buffers at inhibiting the delivery of excess nitrogen from surface and subsurface flow originating agricultural runoff is highly variable. Environmental factors influencing buffer effectiveness include:

- climate/weather
- geology/geomorphology/topography
- hydrology
- soils
- vegetation
- subsurface biogeochemical processes.

Anthropogenic factors influencing buffer effectiveness include:

- buffer width
- buffer area ratio
- buffer vegetation
- upland and riparian land use, and associated nitrogen loads. The form of nitrogen (e.g. organic nitrogen, ammonia, nitrate, etc.) is also important, and is influenced by the initial form applied or produced by agricultural production as well as chemical transformations that occur in the environment.

Climate/weather

Climate and weather drive the potential transport of agricultural sources of Nitrogen. Nitrogen mobilization increases as the amount and intensity of precipitation increases (Borin and Bigon, 2002; Lee, 1999; Daniels and Gilliam, 1996; Bingham et al., 1980; Younos et al., 1980). Warmer air, soil, and water temperatures generally increase the rate of biogeochemical processes associated with the N cycle (e.g., nitrification, denitrification, assimilation), resulting in greater denitrification rates. Climate and weather combine with topographic soil, vegetation, and land use characteristics to influence hydrology, which in turn controls N transport.

Soils

Soil characteristics strongly influence nitrogen removal:

- Soil slope, slope length, and the size of contributing area influence the generation and accumulation of surface runoff (Borin et al., 2005; Lee, 1999, Snyder et al., 1998; Mander et al., 1997; Daniels and Gilliam, 1996; Bingham et al., 1980; Young et al., 1980).
- The infiltration rate for precipitation and surface runoff highly influences the transport of soluble N, clay-bound N, as well as sediment-bound and particulate N (Gilley et al., 2016; Dosskey et al., 2007; Borin et al., 2005; Burns and Nguyen, 2002; Lee, 1999; Schmitt et al., 1999; Mander et al., 1997; Chaubey et al., 1995; Dillaha et al., 1988; Dickey and Vanderholm, 1981; Bingham et al., 1980).
- The infiltration rate is influenced by factors such as soil texture, structure, and roughness chemical soil properties, vegetative soil cover, soil slope, and the level of soil saturation prior to precipitation events (Dosskey et al., 2007; Borin et al., 2005; Mayer et al., 2005; Lee, 1999; Correll et al., 1997; Mander et al., 1997; Gilley et al, 1996; Bingham et al., 1980).

Vegetation

Many studies have explored how vegetation influences N capture/removal. Vegetation influences nitrogen removal, although its effects are not always consistent. Vegetation can physically trap N associated with sediment/organic particles and/or adsorbs some dissolved N (Chaubey et al., 1995; Dillaha et al., 1988). The amount of organic litter can also be important (Lee, 1999). Buffer vegetation absorbs nitrate from interflow and shallow groundwater (Spruill, 2004; Borin and Bigon, 2002; Clausen et al, 2000; Dillaha et al., 1988). Nitrogen uptake varies with soil aeration, plant species, disturbances, harvesting rates, and time of yr. Estimates for N uptake are 20 to 70 kg/ha/yr for riparian meadows and 30 to 170 kg/ha/yr for riparian forests (Valkama et al., 2018).

However, Clausen et al. (2000) found that plant uptake accounted for a relatively minor proportion of N removal. Higher vegetation density can increase physical trapping of N bound to sediment particles and can result in greater cumulative N uptake by plants (Borin et al., 2005).

The literature shows mixed results on how vegetation type influences N capture. Tree species influence organic matter accumulation and N content and can therefore influence N dynamics in a buffer (Addy et al., 1999). However, Borin and Bigon (2002) found no effect of tree size on nitrate removal. Grass increases surface roughness which decreases runoff velocity and facilitates infiltration, thereby promoting deposition of sediment/particulate bound N (Borin et al., 2005). The following summarizes some of the specific findings of studies that have examined the influence of vegetation on nitrogen removal.

- Addy et al. (1999) did not find evidence of differing denitrification rates below forested versus herbaceous buffers, but tree roots in the herbaceous site and litter and from nearby trees may have influenced results.
    - Correll et al. (1997) found roughly equivalent nitrate concentration reductions in forested and grassed buffers, but because groundwater flow rate may have been greater in the forested buffer, the mass reduction may have been greater.
- Daniels and Gilliam (1996) did not observe a significant difference in N reductions between narrower grass buffers and grass strip + riparian tree strip having sparse groundcover - but both were frequently overwhelmed by runoff volumes.
- Haycock and Pinay (1993) found that during the winter, buffers with alder had higher nitrate removal than buffers with grass, likely due to higher denitrification rates associated with higher organic carbon availability.
- Jordan et al. (1993) found a large reduction in nitrate concentrations in shallow groundwater as water flowed from a crop field through a forested riparian buffer; the greatest reductions occurred at the edge of the floodplain.
- Kuusemets et al (2001) found that wet meadows and alder buffers assimilated more N from shallow groundwater than cultivated grasslands, and also had greater N content in their soils.
    - However, there was evidence of N exports from wet meadows and alder buffers when incoming concentrations of groundwater N was low (i.e., <1mg/L).
    - Periodic vegetation removal from buffers is suggested in order to remove nutrients (Kuusemets et al., 2001).
- Lee (1999) found that warm-season grass/woody buffers were much more effective at removing total N and nitrate than warm-season grass alone, run-off volume reductions were also much greater in the mixed vegetation buffer; warm-season grass (stiffer stems, more litter, more uniform growth pattern) was more effective than cool-season grass at removing total N and nitrate from surface runoff, although % runoff infiltrated were very similar (note that neither had a high level of N removal effectiveness) (Lee, 1999). (also note that infiltration of nitrate was considered to be “removal” in this study, whereas denitrification was considered removal in other studies).
- Lowrance et al. (2005) found that a three-zone buffer (inner strip of minimally managed forest, middle strip of managed forest, outer strip of managed grasses) reduced nitrate, ammonium, TKN, and total N loads in surface runoff, however, none of the load reductions were particularly high.

- Lowrance et al. (2001) found that adding either pines or grass to buffers with hardwoods resulted in a lower per hectare uptake of N from shallow groundwater.
- Vegetation uptake is highly variable, but can be substantial (e.g., 30 -300 kg/ha/yr in riparian meadows) (Mander et al., 1997). Shrubs, young forest, and wet grassland have relatively high N uptake rates; young alders' uptake more N than older alders, however, older stands return more N to the soil as litter; also, fixation of atmospheric nitrogen in alder stands increases the pool of N (Mander et al., 1997).
- A meta-analysis by Mayer et al. (2007) suggested that there was no relationship between N removal and buffer width for forested, forested/wetland, and wetland buffers, but that removal did increase with width for herbaceous and herbaceous/forested buffers.
- Neilen et al. (2017) found that during high rainfall periods, less N was exported from grassed riparian zones than forested ones; during low rainfall periods, N exports were influenced by soil type, soil carbon pools, and N pools- rather than vegetation.
- Schmitt et al. (1999) concluded that young trees and shrubs did not improve performance of a buffer when planted on the lower half of a plot with grass on the upper half.
- A meta-analysis by Valkama et al. (2018) concluded that tree buffer zones did not remove more N than grassed buffer zones and found that tree buffer zones did not effectively result in removal of N from surface runoff.
- A meta-analysis by Zhang et al. (2010) found that N removal was greater for tree only buffers than mixed grass and tree/grass buffers.

Hydrology

The literature discusses a variety of ways in which hydrology influences N transport. There is clear agreement among studies that buffers are ineffective at N removal when concentrated/channelized flow occurs (Gilley et al., 2016; Borin et al., 2005; Dillaha et al., 1988; Nunez-Delgado et al., 1997; Daniels and Gilliam, 1996). For surface runoff, vegetative uptake can be important, but varies seasonally (Valkama et al, 2018). Nitrate can also be removed from surface runoff by physical retention, microbial immobilization, and denitrification under saturated conditions (Valkama et al, 2018). However, Removal of N from surface runoff is relatively ineffective (especially when considering that infiltration is often falsely equated to removal) (Valkama et al, 2018).

Buffer effectiveness may decrease as the frequency of runoff events increases (Magette et al., 1989). N removal may vary seasonally and can be highly variable among runoff events (Spruill, 2004; Schoonover and Williard, 2003; Snyder et al., 1998; Correll et al., 1997; Magette et al., 1989). Under some circumstances, N captured by a buffer during a runoff event may be remobilized during a subsequent event (Parsons et al., 1994). For example, the frequency, duration, and magnitude of floodplain flooding can influence N inputs from buffers into streams (Parsons et al., 1994). Mayer et al., (2005) asserted that high N loading and high subsurface flow rates diminish N removal. Anbumozhi et al. (2005) suggested that riparian buffers on headwater streams may be more effective at controlling nitrate levels, as most of the water in higher order streams originates in headwaters streams. However, they observed the highest nitrate reductions in riparian buffers along higher order streams with low gradients; they found a linear inverse relationship between riparian forest area and nitrate concentrations in streams (Anbumozhi et al., 2005).

Land use

Studies have found that land use practices influence the effectiveness of riparian buffers by affecting the amount of runoff and N delivered to buffers as well as the capacity of the buffers to remove nitrogen. For example, riparian deforestation can reduce the supply of organic carbon available to fuel denitrification (Parsons et al., 1994), which is the main process that prevents nitrate delivery to streams. When N loading from land use is high, it is more likely to overwhelm the ability of the buffer system to effectively remove the N, especially where shallow subsurface flow is relatively rapid (Newbold et al., 2010; Mayer et al., 2005; Correll et al., 1997). Crop field fertilization rates affect amount of N in runoff (Borin and Bigon, 2002; Mander et al., 1997). Eghball et al. (2000) found that more N was lost from fertilizer plots than manure plots. Manure type, application rates, and time between application and subsequent precip influence N loading to surface runoff (Bingham et al., 1980). Manure applications to cropland during winter increase pollution risk due to decreased infiltration of runoff (Doyle et al., 1975). Prior land use and associated N loading can influence N dynamics in newly established buffers (Addy et al., 1999). Valkama et al. (2018) concluded that buffer zones for N removal are more important for cropland and feedlots than for areas with permanent vegetation (e.g. pasture and rangeland) since N loads from the latter are typically low.

According to Mayer et al. (2005), effective control of N loading requires buffers on all streams, including headwaters. However, buffers should not be relied upon as the primary means of reducing loads of total N in surface runoff (Magette et al., 1989). For nitrate in particular, BMPs are needed to minimize surface runoff since its removal from surface runoff is largely ineffective (Burns and Nguyen, 2002). The amount of soil cover influences runoff amounts and N exports (Borin et al., 2005; Eghball et al., 2000).

An absence of cover can result in soil surface sealing and reduced infiltration (Gilley et al., 2016Soil compaction, loss of vegetation, drain tiles, and stream incision in buffers reduces effectiveness (Mayer et al., 2007, 2005). Livestock treading on wet soils (e.g., wetland and variable runoff source areas) causes compaction, which reduces soil macroporosity and infiltration rates, thereby facilitating overland flow and higher nitrate levels in runoff (Burns and Nguyen, 2002). McKergow et al. (2001) found that livestock exclusion fencing along streams modestly reduced in-stream total N concentrations since retired riparian pastures exported much less N. However, Kozlowski et al. (2016) did not find a decrease in total N concentrations in a semi-arid watershed following improved rangeland grazing management.

The age of riparian buffers has also been found to affect nitrogen removal. Dosskey et al. (2007) found that buffer effectiveness at total N removal increased over a period of several years (starting from initial installation) as vegetation became established and infiltration rates increased, although nitrate plus nitrite removal did not change significantly over time. According to Borin et al. (2005)

buffer effectiveness initially increases with age, but will decrease if sediment deposition promotes channelized flow or nutrients in the buffer are later remobilized. A meta-analysis by Valkama et al. (2018) concluded that N removal for surface, but not groundwater, was higher for younger buffers. Periodic vegetation biomass removal in a buffer has been suggested as a means to promote plant growth and maintain N removal effectiveness (Borin et al., 2005; Mander et al., 1997).

Buffer size

Buffer width is essentially a surrogate for a variety of interrelated factors that influence buffer effectiveness over time and space (Mayer et al., 2007; Mayer et al., 2005). Multiple studies have concluded that Total N, ammonia, TKN, and (sometimes) nitrate removal tends to increase with increasing buffer width (and distance within a buffer) (Borin et al., 2005; Lowrance et al., 2001; Schmitt et al., 1999; Lim et al., 1998; Srivastava et al., 1996; Chaubey et al., 1995; Chaubey et al., 1994; Uusi-Kamppa et al., 1992; Dickey and Vanderholm, 1981; Young et al., 1980). However, buffer width is not a good predictor of N removal in all situations. In fact, statistically rigorous meta-regressions performed by Valkama et al (2018) indicated that buffer width had no effect upon N removal in ground or surface water. The following summarizes some of the literature findings on the effects of buffer width on N removal.

- Dilution and water infiltration may decrease N concentrations as buffer width increases, so it is important to look at the mass removed when evaluating effectiveness (Borin and Bigon, 2002; Schmitt et al., 1999; Chaubey et al., 1994); Rosa et al. (2017) found reductions in TN concentrations but not mass for overland flow using a 10m willow buffer.
- N removal rates are not constant across a buffer, so ascribing a given removal level with a specific buffer width can misrepresent effectiveness. Vidon and Hill (2004) found that at 3 of 8 sites, >90% of denitrification occurred in the first 15m of the buffer. Hence, the distances at which 90% removal occurred were often significantly different than the full buffer widths. This may be one reason why many studies have found the relationship between buffer width and N removal to be so variable.
- Lowrance et al. (2001) found an increasing removal of nitrate with buffer width; for narrower buffers, nitrate in water seeping out of the subsurface was most of the N output from the buffer; for wider buffers, nitrate and ammonium were more equal in the total surface + subsurface outputs, but very little ammonium was in subsurface flow.
    - A meta-analysis by Valkama et al. (2018) concluded that N removal was not related to buffer width for surface or groundwater runoff (however, nitrate and total N were treated interchangeably).
    - A meta-analysis by Zhang et al. (2010) found that N removal increased with increasing buffer width (all forms of N were pooled, and it appears that surface and subsurface results were pooled).; the estimated theoretical maximum removal level (asymptote). for buffers was 92%; buffer width and vegetation explained about 50% of the variability in removal efficacy, with tree-only buffers showing greater removal than mixed grass or tree/grass buffers.

    - The relationship between N removal from surface runoff and buffer width appears to have an asymptote; that is, after a certain distance, further reductions are insignificant (Chaubey et al., 1995; Chaubey et al., 1994; Dickey and Vanderholm, 1981), unless of course no runoff leaves the buffer (Borin et al., 2005; Dickey and Vanderholm, 1981).
    - A meta-analysis of buffers and N removal concluded that buffer width was not a determining factor for subsurface N removal; wider buffers generally remove more N from surface runoff, but the relationship is not strong; there is little scientific evidence that very narrow buffers are effective; subsurface removal was more effective than surface removal (Mayer et al., 2007, Mayer et al., 2005). Factors associated with buffer width that may influence N removal include vegetation and rooting depth, as well as hydrology that promotes microbial denitrification (anaerobic conditions, carbon supply, floodplain connectivity). Nitrate mass removed per unit buffers did not vary by buffer width, flow path, or vegetation type; soil type, subsurface hydrology, and subsurface biogeochemistry are likely to better explain variability in nitrogen removal than buffer width alone.
- Loads of N in and out of a mature, minimally managed buffer are thought to reach an equilibrium; in other words, buffers cannot remove infinite amounts of N (Mander et al., 1997).
- Clausen et al. (2000) found that most of the denitrification within a riparian buffer occurred within a narrow wetland area adjacent to the stream.
- Lowrance et al. (2001) estimated that denitrification rates peaked in moderate width buffers (10.7 to 16.8m in their study). Since wider buffers were likely limited by nitrate availability and narrower buffers did not have enough storage volume/distance to retain water long enough for denitrification rates to be high.
- As ratio of source area to buffer area increases, pollutant reductions tend to decrease (Webber et al., 2010; Lee, 1999; Magette et al., 1989; Bingham et al., 1980).

Chemical form of N

The mobility of N is strongly affected by its chemical form (Borin et al., 2005; Daniels and Gilliam, 1996; Chaubey et al., 1995; Chaubey et al., 1994). For example, Gilley et al. (2016) found that ammonia concentrations from manure were reduced by a 12.2m buffer, but nitrate and total N were not effectively reduced. According to Lee (1999), most N in surface runoff from crop fields is associated with suspended solids, unless a runoff event occurs soon after application of inorganic fertilizer. Total N or sediment-bound N mass removal rates for surface runoff tend to be greater than removal rates for the soluble fractions of N (Borin et al., 2005; Lee, 1999; Schmitt et al., 1999; Dillaha et al., 1988). Total N removal is better correlated with sediment removal, while nitrate removal was correlated with infiltration (Lee, 1999). This is because nitrate is highly soluble and tends to leach through soils (Neilen et al., 2017), whereas a large fraction of the total N tends to be of lower solubility (e.g. adsorbed to sediment or incorporated into organic particles such as vegetative material). For this reason, buffers are relatively ineffective at removing nitrate from surface runoff (Burns and Nguyen, 2002; Schmitt et al., 1999; Chaubey et al., 1995; Chaubey et al., 1994; Dillaha et al., 1988; Young et al., 1980). In fact, multiple studies have found that soluble N can increase in surface flow through buffers when runoff volume exceeds infiltration capacity (e.g., Lee, 1999; Parsons et al., 1994; Dillaha et al., 1988; Young et al., 1980), or when a buffer contains nitrogen fixing plants, such as alder (Mander et al., 1997).

Nitrate can be removed from shallow groundwater through denitrification, microbial immobilization, and plant uptake (Valkama et al., 2018; Schoonover and Williard, 2003; Burns and Nguyen, 2002; Weller et al., 1994). Plant uptake rates of N is highly variable because it depends upon a number of site-specific factors. Microbial immobilization is no doubt important but has not been well studied. Most of the literature regarding riparian buffers and nitrate removal focuses on denitrification.

Soil drainage and groundwater flow characteristics have a strong influence on denitrification. Poorly drained soils tend to have more organic matter in the saturated zone and higher denitrification rates than moderately well drained soils (Spruill, 2004; Addy et al., 1999). However, all else being equal, poorly drained soils will have relatively higher surface runoff N loads than soils with greater drainage (Lee, 1999). Wetlands facilitate denitrification (Burns and Nguyen, 2002); the vast majority of nitrate reduction occurs in the wetland subsurface rather than in surface waters (Mayer et al., 2005). Groundwater characteristics that influence denitrification include: the depth to the water table (Snyder et al., 1998); water table fluctuations (Addy et al., 1999); groundwater slope and velocity, i.e., slower velocity of shallower groundwater facilitates higher denitrification rates (Burns and Nguyen, 2002; Snyder et al., 1998; Correll et al., 1997). It is important to note that farmland drainage can reduce subsurface denitrification capacity (Parsons et al., 1994).

Analysis of N removal by buffers

Denitrification rates also vary relative to nitrate and organic carbon supply, oxygen levels, temperature, pH, and populations of denitrifying microorganisms (Snyder et al., 1998; Pinay and Décamps, 1988). These factors typically vary over the course of the year and can vary considerably even over the span of meters on a given site (Clausen et al., 2000; Addy et al. 1999). As such, denitrification rates are highly variable (e.g., ranging from <1 - 1600 kg/ha/yr per Mander et al., 1997). Under favorable conditions some sites display nearly complete denitrification over the span of a few meters while other sites show little denitrification over the span of hundreds of meters (Mayer et al, 2005). It is important to recognize that denitrification may occur beneath the surface of riparian buffers as well as beneath lands used for agricultural production. Similarly, significant denitrification can occur as groundwater is discharged through a streambed, even at sites without riparian buffers (Spruill, 2004).

Without knowledge of site-specific subsurface biogeochemical processes, it is generally infeasible to estimate denitrification rates. Predicting denitrification rates on a given site would require substantial field work, lab analysis, data evaluation, and potentially computer modelling, which are rarely performed outside of multi-year scientific studies. This is why predictions of nitrate removal according to buffer width are unreliable- the rigor of the body of nitrate removal literature is insufficient to accurately characterize the high spatial and temporal variability in nitrate removal. For example, assume that a given study reported a 90% nitrate mass removal rate for a 100ft buffer. Unless nitrate removal measurements are made along a transect spanning the width of the buffer, it is not appropriate to attribute the overall removal rate to the total buffer width. It may be that no nitrate removal occurred in the first 80ft of the buffer and 90% of the nitrate removal occurred remaining 20ft of the buffer.

Furthermore, some studies have equated nitrate removal with nitrate infiltration into soils, stopping short of investigating what happened to the nitrate once it was transported into the subsurface environment.

Therefore, while the factors influencing buffer effectiveness at nitrate removal are fairly well-known, it is not currently feasible, based on the available science, to quantify the general effectiveness of riparian buffers at nitrogen removal in a way that would be meaningful for any particular site. The removal estimates for dissolved and particulate N on page 47b are based on the width of a buffer needed to infiltrate surface runoff; as noted, infiltration of runoff containing N does not necessarily equate to the immobilization of N and prevention from it reaching surface waters. By no means does this mean that riparian buffers are ineffective at nitrogen removal- they can be highly effective under site conditions favorable to denitrification. Instead, it means that preventing agricultural sources of nitrate delivery to streams should focus on enhanced source control (as described in other Agricultural BMP chapters) and promoting conditions that facilitate nitrogen capture and removal. In general, landowners should implement practices that:

- Promote soil health (e.g. physical, chemical, biological functions and processes)
- Are based on a nutrient mgmt. plan that considers site specific surface and subsurface hydrology, topography, soils, etc.
- Facilitate hydrological functioning in uplands and riparian areas (e.g., those that inhibit concentrated flow generation and promote precipitation infiltration)
- Improve conservation of soils having a naturally higher denitrification potential (e.g., areas where soils are seasonally or perennially saturated and/or where shallow groundwater is known to occur)
- Allow for wider buffers where agricultural sources of nitrogen are relatively greater
- Manage vegetation communities in a way that maximizes their potential to uptake nitrogen and supply carbon to the soil for denitrification

Pathogens

Factors that influence the effectiveness of riparian buffers at removing pathogens (bacteria, protozoans, viruses, parasites) from surface runoff

Buffer effectiveness at removing pathogens from surface runoff is a product of interrelationships among climate and weather, hydrology, soils, vegetation, land use, and buffer size.

Climate/weather

Climate and weather are key drivers of pathogen removal by riparian buffers. As with other pollutants of surface runoff, higher rainfall amounts and intensities tend to result in hydrological conditions that reduce buffer effectiveness (Sullivan et al., 2006; Tate et al., 2006; Tate et al., 2004; Atwill et al., 2002; Chaubey et al., 1994; Coyne et al. 1995; Moore et al., 1982). On the other hand, if the pathogen source is relatively finite, then greater amounts of precipitation can dilute the concentration of pathogens in surface runoff (Coyne et al. 1995; Fajardo et al., 2001). This is important given that water quality standards for pathogens in surface water bodies and in groundwater tend to be expressed as concentrations. In addition to precipitation, air temperatures and amount of sunlight can influence the loading of bacteria to riparian buffers and therefore their effectiveness. Fecal bacteria is killed by sunlight (ultraviolet radiation) (Tyrrel et al., 2003; Moore et al., 1982) as well as drying coupled with high heat (e.g. >28^{o}C) (Tyrrel et al., 2003; Doyle et al., 1975; Entry, 2000b; Moore et al., 1982).

Hydrology

There are a variable way in which hydrology influences the ability of buffers to remove pathogens from surface flow. Greater volumes, rates, and velocities of overland flow and lower runoff detention time decrease the effectiveness of pathogen removal processes within a buffer (Sullivan et al., 2006; Tate et al., 2006; Tyrrel et al., 2003; Atwill et al., 2002; Stoddard et al., 1998; Coyne et al. 1995; Fajardo et al., 2001; Schellinger and Clausen, 1992; Moore et al., 1982). Buffers are ineffective at removing pathogens from concentrated flows of runoff (Coyne et al. 1995; Schellinger and Clausen, 1992). Established preferential flow paths such as soil macropores, animal burrows, rills, gullies can lead to accelerate delivery of pathogens to surface waters (Sullivan et al., 2006; Trask et al. 2004; Atwill et al., 2002). Depth to groundwater can be important since shallower groundwater tends to receive higher pathogen loading rates (Moore et al., 1982). The turbidity and suspended sediment concentration in runoff can also influence pathogen removal rates in buffer; bacteria attached to sediment may have different removal rate than non-attached bacteria (Abraham et al. 2016; Trask et al., 2004).

Soils

The primary way that pathogens are removed from surface runoff is through entrapment within the soil matrix through physical and chemical adsorption in soil (Entry et al., 2000b; Moore et al., 1982). It is for this reason that the soil infiltration rate/capacity for runoff and soil hydraulic conductivity are key factors influencing buffer effectiveness (Sullivan et al., 2006; Tate et al., 2006; Atwill et al., 2002; Chaubey et al., 1994; Coyne et al. 1995; Moore et al., 1982). Basically, where surface runoff containing pathogens enters a buffer, any amount of surface runoff that subsequently exits the buffer and discharges to surface waterbodies will contain pathogens. Fecal bacteria levels in unmitigated agricultural surface runoff are often so high (e.g. tens of thousands of bacteria per liter of runoff) that even a very high removal rate by a buffer (e.g. 95% removal) may not be sufficient to keep the bacteria loading rate to surface water bodies below a level at which water quality standards can be achieved.

Infiltration rates and hydraulic conductivity are influenced by a variety of soil characteristics including soil texture, structure, porosity, and bulk density (Sullivan et al., 2006; Atwill et al., 2002; entry et al., 2000b; Stoddard et al., 1998; Moore et al., 1982). The retention of bacteria in soil increases as particle size distribution decreases (Moore et al., 1982). For this reason, a soil with a higher clay content will capture more bacteria than a similar soil with a lower clay content. Similarly, soils with a higher organic matter content tend to capture more bacteria (Sullivan et al., 2006; Tate et al., 2006; Moore et al., 1982). Adsorption of bacteria to soil particles and aggregates is influenced by soil pH and cation exchange capacity (Atwill et al., 2002 Moore et al., 1982). Under saturated conditions, a higher pH inhibits attachment of negatively charged bacteria to the soil whereas a lower pH increases bacteria die-off. A higher cation exchange capacity is associated with increased adsorption of bacteria to soil particles.

Although the soil infiltration rate/capacity is critical for buffer effectiveness, a high potential infiltration rate, by itself, does not guarantee a high pathogen removal rate. Infiltration rates are not constant at a given location. Bacteria removal/immobilization is greater under unsaturated conditions, which means that buffer effectiveness can be substantially reduced during wetter conditions even for a soil with a relatively high porosity and infiltration capacity (Moore et al., 1982). As a soil becomes more saturated, bacteria previously entrained in the soil matrix can be remobilized, i.e., in saturation excess overland flow (Stoddard et al., 1998). Likewise, decreased infiltration occurs with frozen soil (Moore et al., 1982). Coyne et al. (1995) noted that high sediment levels in runoff may seal pores and inhibit infiltration, thus, reducing bacteria removal. It's also important to recognize that greater infiltration rates lead to increased numbers of bacteria load entering the soil, but retention in the soil matrix decreases as soil particle size increases (Moore et al., 1982). Stoddard et al., 1998 found that fecal coliform contamination of shallow groundwater beneath crop fields increased whenever there was enough rainfall to cause water to percolate through the soil profile. Therefore, high infiltration rates can result in bacteria loading to shallow subsurface water and/or groundwater (Entry, 2000b; Moore et al., 1982), which may discharge to surface waters.

Infiltration rates are partially influenced by topography and soil slope (Atwill et al., 2002; Coyne et al. 1995). Experimental evidence indicates that at lower slopes, substantial transport of pathogens occurs in subsurface flow, while at higher slopes, almost all transport is via overland flow (Tate et al., 2004). Atwill et al., 2002 found that C. *parvum* (a protozoan) oocyst removal was generally greater for higher sloped soils, particularly for lower bulk density soils. Trask et al. (2004) found a similar occurrence at low rainfall intensity but not at high rainfall intensity (with bare ground showing a more pronounced pattern than vegetated soil). They noted that this may not be a direct product of the increase in slope as runoff and suspended sediment also increased with slope which may have affected the oocyst measurements, i.e., reduced counts (Trask et al., 2004). In near-surface flow, removal of oocysts was less for vegetated than for bare ground and less removal for lower slopes occurred, which may be due to greater infiltration at lower slopes (Trask et al. 2004). At higher rainfall intensity, greater slopes had less removal (Trask et al. 2004).

Overall, vegetated soil had more total removal than bare soil. (Trask et al. 2004). Trask et al. (2004) concluded that slope was the most significant factor in removal in their experiment and that vegetated filter strips with low slopes are more effective at *C. parvum* removal from runoff.

Soil, soil water, and ground water temperature and moisture are also known to influence bacteria removal (Entry et al., 2000a, 2000b; Moore et al., 1982). Entry et al., 2000a found fecal coliform numbers to be positively correlated with soil water and groundwater temperature and soil moisture. The effect of soil temperature and moisture upon bacteria survival appears to be interdependent. Entry (2000b) found that survival decreased as soil increasing soil temperature and decreasing soil moisture. In other words, although warmer conditions appear to increase bacteria survival, drier conditions tend to counteract the influence of warmer temperatures.

Vegetation

The literature indicates that vegetation has mixed effects upon pathogen removal. Higher levels of vegetation cover and density are associated with higher pathogen removal rates (likely by providing resistance to runoff and facilitating runoff infiltration into soils); however, there is insufficient evidence that vegetation type affects pathogen removal (Atwill et al., 2002; Entry et al., 2000a, b; Lim et al., 1998; Chaubey et al., 1994; Moore et al., 1982). In contrast, the survival times of bacteria on the soil surface will be greater in areas where vegetation results in higher levels of soil shading, thereby protecting bacteria from lethal solar UV radiation. (Moore et al., 1982). Similarly, greater levels of residual organic matter on soil surfaces inhibits pathogen die-off (Tate et al., 2006). Vegetation with high evapotranspiration rates that can reduce soil moisture may facilitate reduced survival of bacteria as well as reduced amounts if surface runoff (Entry et al., 2000b).

Land Use

Land use and upland BMPs influence pathogen removal by riparian buffers in a variety of ways. Most of these ways are related to how livestock and livestock wastes are managed. Animal densities, manure/waste application rates, and the initial amount of pathogens in animal waste determine the magnitude of the pathogen reservoir from anthropogenic sources (Tate et al., 2004; Tyrrel et al., 2003; Atwill et al., 2002; Moore et al., 1982). As mentioned earlier, since even high removal rates by buffers can result in bacteria concentrations in runoff that remain a threat to water quality in surface waterbodies, the magnitude of the bacteria source is of high importance. The form of waste is also important. Liquid waste applied to fields has better soil contact than solid waste and therefore may lead to decreased mobilization of bacteria following rainfall (Moore et al., 1982). The age of manure, temperature and moisture content of manure, and the distance of manure from waterways can affect pathogen loading to surface runoff and therefore the level of removal that may occur in a buffer (Tate et al., 2006; Lim et al., 1998; Coyne et al. 1995; Doyle et al., 1975). Soil compaction associated with agricultural activities leads to decreased infiltration rates which can strongly affect buffer effectiveness.

In terms of tillage, no-till and conservation tillage practices with manure applications were found to not have different levels of groundwater contamination (Stoddard et al., 1998); under the conditions in which the study occurred, both resulted in groundwater contamination. Additionally, irrigation can "short—circuit" buffer effectiveness where excess water concentrates and follows preferential flow paths though a buffer (Entry et al., 2000a).

Waste storage and mgmt. practices and the timing of such practices can have a significant effect upon the amount of pathogen loading to runoff, and therefore the ability of a buffer to capture pathogens. Pathogens can generally survive in upper soil layers for 4 to 160 days (Entry et al. 2000b). Therefore, if runoff occurs soon after waste is deposited on soil, then risk of surface and groundwater pollution is greater, even if BMPs are in place (Coyne et al. 1995). Waste collection, composting, spreading, chaining, and soil incorporation can reduce the potential for (Sullivan et al., 2006; Tyrrel et al., 2003; Coyne et al. 1995; Moore et al., 1982). Again, though, the timing of mgmt. activities are key. For example, Stoddard et al., 1998 found that spring manure application resulted in greater bacteria levels in soil leachate for both no-till and conservation tillage. Applying manure or wastewater when soils will be dry for long periods of time (e.g., 2 to 4wks) is expected to decrease bacteria survival and therefore decrease the water pollution risk (Entry, 2000b).

Buffer Size

Lastly, as with other pollutants, buffer width tends to serve as a surrogate for the variety of factors that facilitate pathogen removal by buffers (Tate et al., 2004; Atwill et al., 2002; Chaubey et al., 1994; Young et al., 1980; Doyle et al., 1975). Multiple studies have found that wider buffers generally result in greater pathogen removal than narrower buffers (Sullivan et al., 2006; Tate et al., 2004; Atwill et al., 2002; Young et al., 1980). Where soil infiltration rates are high, buffer width has been found to be relatively unimportant in affecting bacteria numbers in surface runoff (Sullivan et al., 2006; Lim et al., 1998).

However, this didn't necessarily equate to buffer effectiveness, it just meant that after a certain distance, no further reductions in pathogens were observed (Lim et al., 1998; Coyne et al. 1995; Moore et al., 1982). Therefore, it appears that the link between buffer width and effectiveness is primarily about the soil properties and how much soil surface is needed to achieve full runoff infiltration, if possible. In other words, wide buffers aren't more effective if water does not infiltrate, and narrow buffers can be highly effective if the soil has a high infiltration rate. Nevertheless, as noted previously, even complete infiltration of runoff doesn't necessarily mean that high bacteria loads won't reach surface waters since some sites can have a high rate of pathogen transport in subsurface flow.

Analysis of pathogen removal by buffers

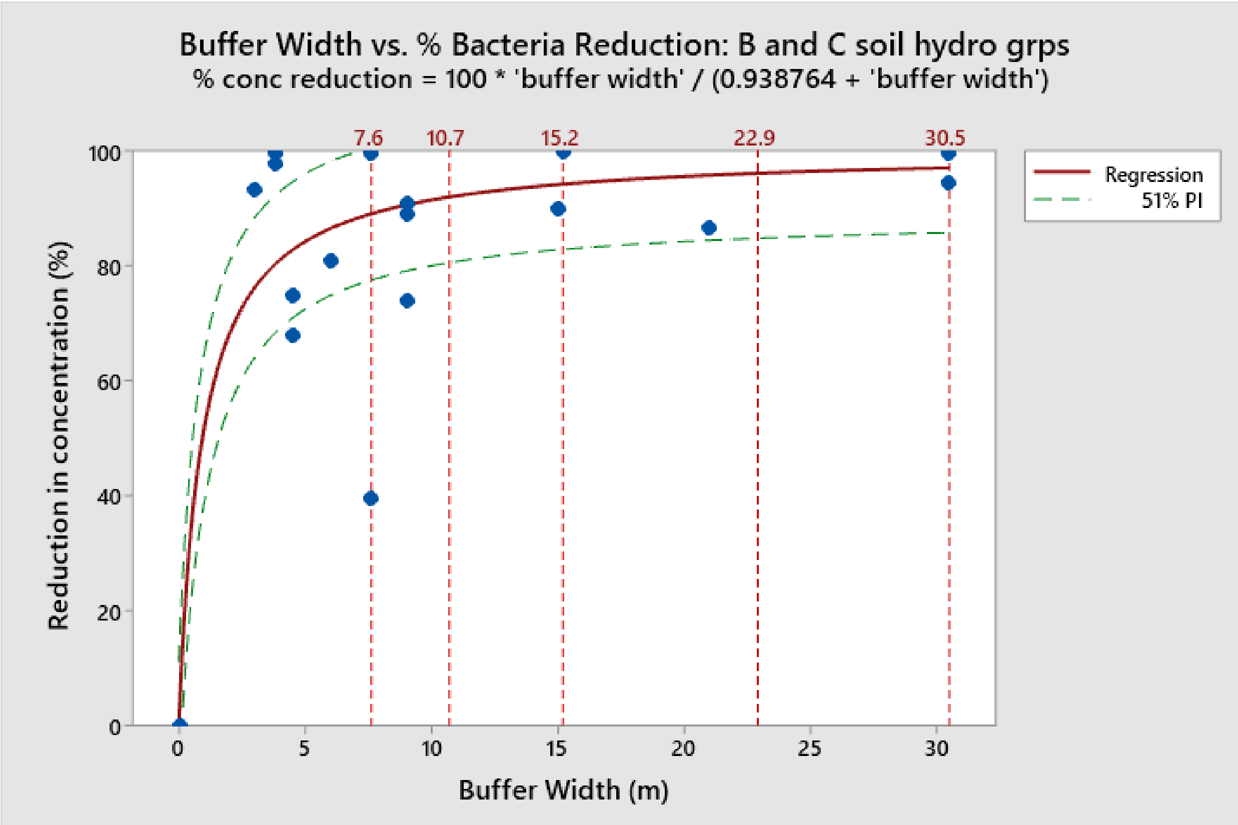
A quantitative analysis of pathogen removal within buffers was performed using data from published literature. Extractable data was identified for only ten studies listed in the annotated bibliography. It was determined that data from seven of these studies was not viable for inclusion in the analysis. The reasons are noted below:

- The Atwill et al. (2002) study data wasn't not directly comparable to data from actual field conditions because it was derived from trials using constructed soil boxes.
- The Coyne et al. (1995) study results were not directly comparable due to channelized flow; also, plots were covered with tarps in hot weather which may have biased subsequent bacteria mortality results.
- Fajardo et al. (2001) data was not directly comparable because it simulated extreme conditions (i.e., a 100yr 24hr event) which could bias estimates of buffer effectiveness for storms of more moderate frequency and intensity (i.e. (10yr, 24hr event).
- Results from Lim et al. 1998 were excluded because of suspected inaccuracy; runoff at various plot distances contained all other constituents analyzed, except fecal coliform (FC) was 0cfu at every filter strip distance except the 0m distance where it was pretty high at 1.8×10^6; infiltration would not selectively remove FC but not N, P, TSS.
- The results from Mankin et al. 2006 are not comparable because they were derived from an engineered feedlot runoff collection and distribution system.
- The results of Sullivan et al. (2006) were incomparable because runoff was a mixture of overland and shallow subsurface flow- unlike other studies; also, soils were intentionally "loosened" prior to experimentation which may have biased the results by artificially inflating infiltration rates.
- The results of Young et al. (1980) are incomparable because the study examined runoff from compacted soils in feedlots with high bacteria levels.

Minitab statistical software was used to perform a nonlinear regression of buffer width versus bacteria removal data from Chaubey et al, 1994, Coyne et al, 1998, Doyle et al, 1975. These three studies were performed on soils of either Hydrologic Group B or C in humid climates. The studies used simulated or natural rainfall; the simulated rainfall studies used relatively high precipitation volumes. A fictitious point {0,0} was added to the datasets to assist with the fitting the equation for buffer width vs. bacteria reductions since there were no data for low reductions in bacteria (e.g., <40%), i.e. for a 0m buffer width, a 0% reduction can be expected. High variability in the data is likely due to unexplained factors influencing site-specific bacteria removal, such as infiltration rates, for which data was not available for all results. Variability in the bacteria removal rates were described using a prediction interval.

Whereas, a confidence interval is used to estimate the variability of observed results, a prediction interval is used to estimate results for a *new* observation (i.e., what could we expect the bacteria removal to be if a new trial were performed). This is what we are interested in- a reasonable estimate for the bacteria removal rate if new observations were made under similar study conditions. The confidence level of the prediction interval was set at 51% due to the high variability in the data. The 51% level of probability is analogous to a preponderance of evidence approach; in other words, it simulates a scenario in which it is “more likely than not” that a new observation would fall within the estimated range. A graph of the regression is depicted below. Table XXX. Provides estimated bacteria removal rates for select buffer widths having soils in Hydrologic Groups B and C (i.e., soils with moderately low to moderately high runoff potential when thoroughly wet).

Figure 1: Fecal bacteria removal rates in buffers in humid climates having Hydrologic Group B & C soils.



Reference lines at buffer widths of {7.6, 10.7, 15.2, 22.9, 30.5} meters correspond to distances of {25, 35, 50, 75, 100} feet, respectively.

Table 19. Estimated buffer effectiveness for fecal bacteria removal from shallow overland flow on Hydrologic Group B/C soils in humid climates.

Buffer Width (ft)	25	35	50	75	100
Estimated Pathogen Removal, Average (%)	89.0	91.7	94.2	96.1	97.0
Estimated Pathogen Removal, Range (%)	78 to 100	81 to 100	83 to 100	85 to 100	86 to 100

Pesticides

Pesticides are chemicals used to control the occurrence of undesirable insects and other animals, fungus, disease, and plants on agricultural lands. The general factors that influence the effectiveness of riparian buffers at removing pesticides from surface runoff, subsurface flow, or aerial drift include pesticide characteristics, climate/weather, soil characteristics, vegetation, hydrology, land use, and buffer size.

Pesticide Characteristics

Differing water solubility among pesticides affects their potential for transport (Rice et al. 2016; Paterson et al., 1992). Pesticides with weak to moderate adsorption to mineral and organic soil particles are primarily transported in solution (Delphine et al, 2001). For example, atrazine (low/moderate soil adsorption properties) sorption is influenced by organic carbon, clay amount and type, and pH in soil (Reungsang et al., 2001). For chemicals with low to moderate sorption properties, infiltration has been identified as the most significant factor affecting their capture by buffers; for highly soil-adsorbing chemicals, the most significant factor tends to be the ratio of mass in dissolved vs. sediment adsorbed form, followed by sediment reduction (Sabbagh et al. 2009). The potential for transport is described by a specific pesticide's soil adsorption potential identified by the Kd (soil/water partitioning coefficient) and Koc (or organic carbon sorption coefficient)) (higher sorption coefficients = greater adsorption to soil particles) (Arora et al., 2003; Boyd et al., 2003; Arora et al., 1996; Misra et al., 1996). Sabbagh et al. (2009) considered chemicals with Koc ≤147 as having a low adsorption potential (i.e. tend to be transported in dissolved form) and chemicals with Koc ≥ 9930 as having a high adsorption potential (i.e. tend to be transported with sediment).

Climate/Weather

The rainfall intensity and amount that an area receives has a primary influence over the potential for pesticides to be transported in runoff and leached through soils (Arora et al., 2003; Boyd et al., 2003; Arora et al., 1996). Naturally, areas of low intensity rainfall have lower risk of pesticide mobilization via surface runoff or leaching (Vianello et al., 2005). In addition to influencing the mass of toxins that are transported by surface and subsurface flow, rainfall amount influences the concentration of pesticides (Vianello et al., 2005; Boyd et al., 2003). Pesticide concentrations in runoff are typically the highest during the first few runoff events following pesticide application (Boyd et al., 2003). However, removal effectiveness has been found to be greatest during earlier part of a storm when soils are drier (Misra et al, 1996). Misra et al. (1996) found that dilution of inflow concentrations by rainfall on buffers to be important; this is why estimates of effectiveness for pesticides should be based on the mass of a toxin removed from runoff rather than reductions in its concentration within runoff. The time between application of pesticide and subsequent precipitation event is also important (Delphine et al, 2001). The amount of pesticide transported by runoff tends to decrease as the amount of time increases between pesticide application and subsequent precipitation events. Seasonal changes in weather also affect toxin mobility.

For example, Delphine et al. (2001) found that the risk of pesticide leaching is increased as the amount of precipitation occurring during time of year when vegetation is dormant increases. Lastly, as wind speed increases, pesticide drift (i.e., aerial transport from the location of pesticide application) has been shown to increase (De Snoo et al., 1998).

Soils

There are several types of soil characteristics that are of high importance to the capacity of buffers to protect surface waters from toxins. Soil texture is the one key attribute. Adsorption to soil is a primary means of removal for pesticides (Mickelson et al., 2003; Wu et al., 2003; Popov et al., 2006; Arora et al., 1996; Asmussen et al., 1977) and metals (Wu et al., 2003), particularly under saturated conditions (Krutz et al. 2003). Certain pesticides are thought to preferentially adsorb to the smallest particle size fractions (Syverson and Bechmann, 2004). Therefore, the percent clay in a soil can be an important factor. For pesticides that tend to adsorb to soil particles, Sabbagh et al. (2009) found that the sediment removal rate for a buffer was a significant predictor of how much pesticide was removed. In contrast, the authors found that the neither the sediment removal rate by buffers nor the clay content in soils helped predict a buffer's ability to remove pesticides from runoff which have a greater tendency to dissolve in water than adsorb to soil particles; for these pesticides, runoff infiltration into soils was the only significant predictor of pesticide removal.

Rates of runoff infiltration are a second, and perhaps the most important soil attribute influencing buffer effectiveness (Popov et al., 2006; Mickelson et al., 2003; Wu et al., 2003; Arora et al., 2003; Boyd et al., 2003; Reungsang et al., 2001; Misra et al., 1996; Asmussen et al., 1977). A high degree of runoff infiltration is essential for removing pesticides with moderate to non-adsorption to sediments in runoff (Arora et al., 1996). Yet it is nearly as important for removing pesticides that tend to adsorb to sediment since infiltration rates strongly affect how much sediment is retained in a buffer. Spatial and temporal variation in soil infiltration rates occur due to a variety of factors. Infiltration rates tend to be higher on lower slope soils (Arora et al. 2010). Soil density and porosity affect infiltration (Boyd et al., 2003). Although infiltration is crucial for preventing pesticide delivery to surface waters through surface runoff, it must be recognized that infiltration of pesticides does not necessarily mean that they immobilized and will not reach surface or groundwater (Boyd et al., 2003). For example, soil macroporosity is particularly important for infiltrating water where soils have a high clay content (Seybold et al., 2001). However, the same attribute that enhances infiltration will promote preferential flow that can increase subsurface pesticide transport (Reungsang et al., 2001). If buffer soils become saturated, then removal efficiency will significantly decrease (Rice et al. 2016; Boyd et al., 2003; Misra et al., 1996); under this condition, runoff movement into the soil becomes controlled by saturated hydraulic conductivity rates within the soil profile, which are going to be lower than the rate of infiltration under unsaturated conditions.

Reungsang et al. (2001) asserted that where runoff is from saturation excess overland flow, buffer soils need to drain more quickly than the adjacent ag land in order to infiltrate the incoming runoff.

Antecedent soil moisture (the amount of water in the soil prior to a runoff event) is important not only because it affects infiltration, but also because it affects the amount of pesticides that are originally mobilized in runoff (Boyd et al., 2003; Delphine et al., 2001; Asmussen et al., 1977).

For example, Asmussen et al. (1977) found that a greater amount of pesticide was in runoff following wet antecedent conditions relative to dry antecedent conditions.

One area of developing research is the role of degradation processes in preventing pesticide delivery to surface water and groundwater. Reungsang et al. (2001) found larger populations of atrazine degrading microbes in cropland than in buffer soils, which was associated with a much higher atrazine degradation rate. Ironically, this suggests that on lands where pesticides are used, a more infrequent delivery of pesticides to a buffer may constrain the rate at which microbial breakdown occurs within the buffer. Along these same lines, Krutz et al. (2006) found that mineralization (i.e., breakdown) of atrazine and most of its metabolites were greater in cultivated soil than in vegetated filter strip soil. They suggested that "the potential for subsequent transport of atrazine and many of its metabolites may be greater in VFS [vegetated filter strip] soil than in cultivated soil if reduced mineralisation is not offset by increased sorption in the VFS". This again points to the importance of runoff infiltration and soil characteristics that facilitate adsorption of pesticides to soil particles.

Hydrology

Surface water runoff flow rates/volumes influence the effectiveness of buffers at capturing pesticides (Mersie et al., 2003; Boyd et al., 2003; Arora, 1996; Misra et al., 1996). As noted previously, higher amounts of runoff from agricultural lands are likely to decrease buffer effectiveness. Higher suspended sediment levels in runoff are often associated with higher loads of pesticides that adsorb to sediment (Arora et al., 2003; Arora et al., 1996; Misra et al., 1996). Buffers having conditions that make them that effective at removing sediment from runoff tend to be effective for removing pesticides that strongly adsorb to sediment (Zhang et al., 2010; Sabbagh et al., 2009; Arora et al., 2003; Boyd et al., 2003; Schmitt et al., 1999; Arora, 1996). Groundwater hydrology is also relevant. Pesticides may be removed from shallow groundwater as it flows beneath a buffer (Boyd et al., 2003). However, transport of pesticide metabolites to surface water via groundwater has been observed (Rice et al. 2016). Additionally, chemicals can be temporarily trapped in a buffer and released in subsequent precipitation events, often as a metabolite (Vianello et al., 2005).

Vegetation

Vegetation influences buffer effectiveness in several important ways. Adsorption of pesticides to vegetation and organic matter is an important removal process (Vianello et al., 2005; Krutz et al. 2003Wu et al., 2003; Arora et al., 1996; Misra et al., 1996; Asmussen et al., 1977). More dense buffer vegetation provides greater hydraulic resistance and can lead to lower runoff volume leaving the buffer as surface flow (Vianello et al., 2005). The state (e.g., growth vs. seasonal dormancy) of the buffer vegetation during the first few runoff events after pesticide application can be important (Boyd et al., 2003). Evapotranspiration by vegetation can decrease leaching of pesticides into the soil (Delphine et al, 2001). Uptake of pesticides by plants in the buffer has been found to be a significant removal process (Misra et al., 1996; Paterson et al., 1992). For example, Franks et al. (2018) found a rapid and substantial uptake of pharmaceuticals and a pesticide (atrazine) by willows, but it was noted that sequestration in plant tissue or transpiration out of the leaves and return to the aquatic environment is chemical specific.

Aerial drift of pesticides from adjacent fields (via volatilization and particle sorption) is deposited on riparian vegetation and can be washed off by subsequent rainfall. In this manner, pesticides in wash-off may enter streams even if the rain event does not generate any surface runoff (Rice et al., 2016).

Land use

Land use practices have a key influence upon the effectiveness of buffers at preventing pesticide delivery to surface waters; the summary here is by no means exhaustive. Land use can alter soil characteristics (e.g., soil structure, chemistry, erodibility, etc.) vegetation (plant composition, density, soil cover, etc.), hydrology (frequency, volume, rate of runoff, etc.), which in turn influences the magnitude, frequency, and timing of pesticide delivery to riparian buffers. The amount of pesticide applied, how it is applied, and the timing of the application strongly influences the potential loading to buffers. Even the type of device used to spray pesticides influences how much pesticide transport may occur (e.g., in aerial drift) (De Snoo et al., 1998). Pesticides applied to soil tend to be retained in the soil surface, although those with moderate to weak adsorption properties become dissolved in runoff (Misra et al., 1996). Therefore, whether pesticides are applied to bare or vegetated soil can influence pesticide mobility since less precipitation is generally required to produce runoff on bare soils (Misra et al., 1996).

The type of tillage system in place can indirectly affect buffer effectiveness. No-till fields will have more rapid infiltration due to macro-porosity (Reungsang et al., 2001). As described earlier, the fate of infiltrated pesticides (e.g. immobilization or transport to subsurface flow or groundwater) will depend on pesticide and soil characteristics. Lastly, as with other pollutants, drainage tiles can result in direct transport of pesticides to surface waters, thereby negating the purpose of a buffer (Boyd et al., 2003). Lastly, it needs to be acknowledged that in many locations residual pesticides exist in riparian areas as a result of historic land use practices. Many of these pesticides take a long time to degrade and their removal from riparian areas is impractical to achieve. Riparian management that seeks to avoid soil erosion and promotes riparian vegetation community health will facilitate conditions that will help degrade legacy pesticides over time.

Buffer Size

Buffer width influences pesticide removal effectiveness (Wu et al., 2003; Boyd et al., 2003; Vellidis et al., 2002; Schmitt et al., 1999; De Snoo et al., 1998; Nichols et al., 1998; Patty et al., 1997; Payne et al., 1988). Many studies show greater removal with greater width (Zhang et al., 2010; Wu et al., 2003; Boyd et al., 2003; Vellidis et al., 2002; De Snoo et al., 1998; Nichols et al., 1998; Patty et al., 1997; Payne et al., 1988). As cited by Sabbagh et al. (2009), the Soil and Water Assessment Tool (SWAT) estimates removal efficiencies for sediment, nutrients, and pesticides using the following equation: $\Delta C = 0.367(W_B)^{0.2967}$, where ΔC is removal efficiency and W_B is buffer width in meters. However, Sabbagh et al. (2009) found that filter strip width was not a significant predictor of removal, but rather is partially related to two variables associated with width: the amount of sediment removed from runoff and amount of water infiltrated into soils. Both of these variables do not necessarily require increases in width beyond some baseline width in order to achieve high levels. Sabbagh et al., (2009) suggested that width may provide a general estimate of pesticide reductions, but they asserted that "pesticide trapping cannot be predicted solely from the physical dimensions of the VFS or by considering the chemical properties of the pesticide, but rather from the combined effect of the hydrologic response to the runoff event, which is an implicit function of VFS width, and the distribution of pesticide between the sorbed and dissolved phases". A few studies have examined pesticide reductions in relation to buffer area ratios (i.e., the ratio of contributing area to buffer area). Boyd et al. (2003) found that sediment reduction was greater when the ratio of drainage area to buffer area was lower, resulting in greater pesticide retention. Studies in Iowa at the same site showed that a 15:1 ratio was found to have no difference in pesticide removal from 30:1 ratio (Arora et al., 2003; Arora, 1996; Misra et al., 1996), whereas a difference was found between 15:1 and 45:1 ratio, suggesting that the maximum ratio without sacrificing effectiveness could be between 30:1 and 45:1 in that area (Boyd et al., 2003).

Analysis of pesticide removal by buffers

A quantitative analysis of pesticide removal within buffers was performed using data from published literature. Extractable data was identified for 19 studies listed in the annotated bibliography. Minitab statistical software was used to perform a nonlinear regression of buffer width versus pesticide mass removal. Separate analysis were performed for higher mobility chemicals (organic carbon partitioning coefficient (Koc) ≤ 100) and low to moderate mobility chemicals (organic carbon partitioning coefficient (Koc) greater than 100). Studies which evaluated pesticide concentration reductions rather than mass reductions were eliminated from the analysis. This is because a change in concentrations can be caused either by removal of pesticides from runoff or by dilution, thereby confounding interpretation of the results. Initial results of analyzing pesticide mass reductions by buffer width showed considerable scatter, which appeared to be associated with data from studies using simulated rainfall or simulated runoff. These types of studies tend to set the water application rate at an amount that intentionally exceeds infiltration rates in order to force runoff to reach the end of the study plots.

The average % runoff infiltration and % pesticide removal (see Table 20 below) appears to support the notion that simulated rainfall and runoff may bias the pesticide removal results. In subsequent analyses, only studies using data associated with natural rainfall were evaluated. This narrowed down the data set to only two studies (Patty et al, 1997; Vellidis et al, 2002).

Table 20: Average % runoff infiltration and % pesticide reduction for the three runoff generation methods utilized in studies

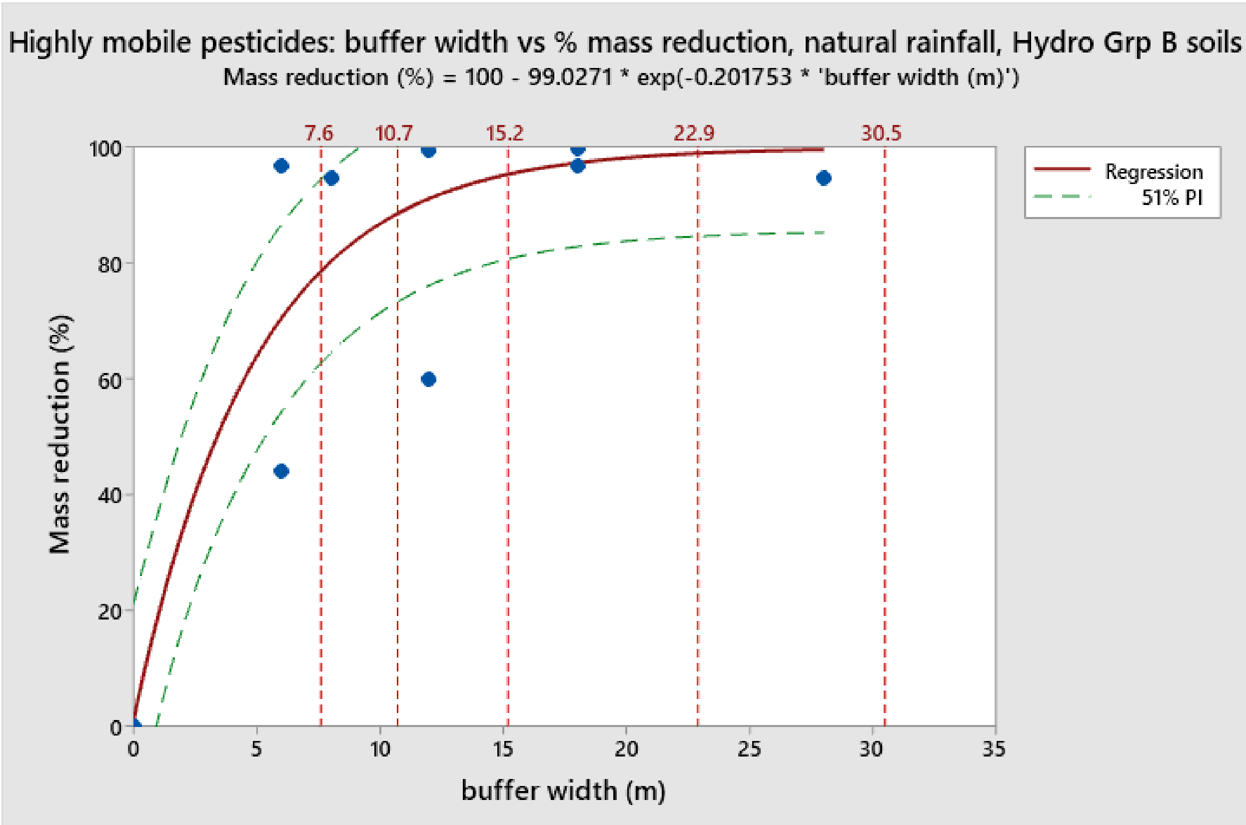
Study Method	Average % Runoff Infiltration	Average % Pesticide Mass Reduction
Natural rainfall	77.9	92.2
Simulated rainfall	63.0	76.7
Simulated runoff	58.6	66.9

The two remaining studies on the data analysis had been performed on soils of Hydrologic Group B (i.e., having a moderate infiltration rate when thoroughly wet) in humid climates. In addition to buffer width and pesticide mass reduction, these two studies also contained data on buffer slope and % runoff infiltrated. Relationships between pesticide mass reductions, runoff infiltration, and buffer slope were explored. For high mobility pesticide data, there was a strong correlation between % runoff infiltrated and pesticide reduction. For low to moderate mobility pesticides there was a moderate correlation between % runoff infiltrated and pesticide reduction. For both pesticide groups, mass reductions did not appear to be related to buffer slope. A fictitious point {0,0} was added to the datasets to assist with the fitting the equation for buffer width vs. pesticide mass reductions since there were no data for narrow buffer widths (e.g., <5m) or low pesticide mas reductions (e.g. <40%), i.e. for a 0m buffer width, a 0% reduction can be expected (See figure 2 and 3 below).

Variability in the results is likely due to unexplained/undescribed factors influencing site-specific pesticide removal, such as those described previously in this chapter (e.g., related to soils, hydrology, vegetation, etc.). Variability in the pesticide removal rates were described using a prediction interval. Whereas, a confidence interval is used to estimate the variability of observed results, a prediction interval is used to estimate results for a *new* observation (i.e., what could we expect the pesticide removal to be if a new trial were performed). The confidence level of the prediction interval was set at 51% due to the high variability in the data. The 51% level of probability is analogous to a preponderance of evidence approach; in other words it simulates a scenario in which it is "more likely than not" that a new observation would fall within the estimated range.

Graph of the regressions representing removal rates for low to moderate mobility pesticides and high mobility pesticides are depicted below. Tables 23 and 24 provide estimated pesticide removal rates for select buffer widths having soils in Hydrologic Group B.

Figure 2: Mass reductions for highly mobile pesticide (Koc ≤100) vs. buffer width

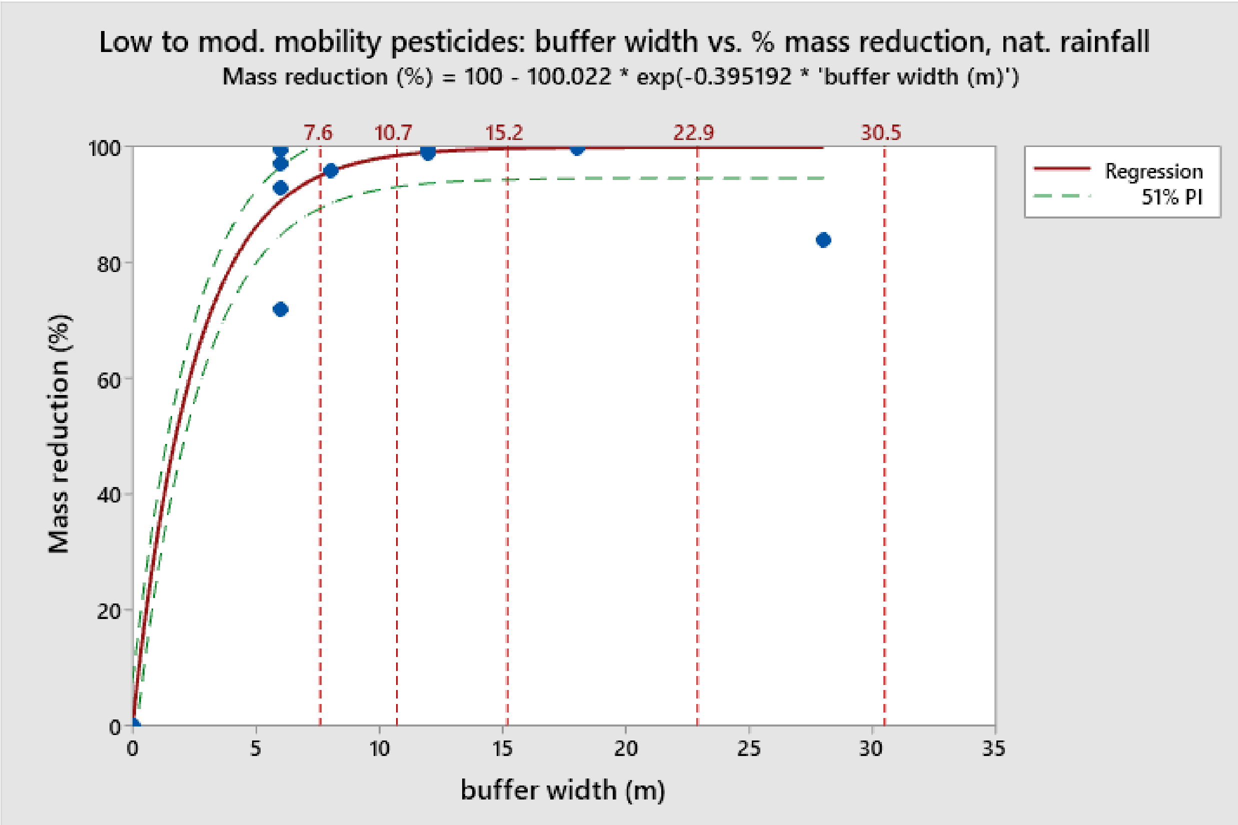


Reference lines at buffer widths of {7.6, 10.7, 15.2, 22.9, 30.5} meters correspond to distances of {25, 35, 50, 75, 100} feet, respectively. Based on data from: Patty et al., 1997; Vellidis et al., 2002.

Table 21 Estimated Buffer Effectiveness for Removal of Highly Mobile Pesticides from Shallow Overland Flow on Hydrologic Group B Soils

Buffer Width (ft)	25	35	50	75	100
Estimated pesticide removal, average (%)	78.6	88.6	95.4	99.0	99.8
Estimated pesticide removal, range (%)	63 to 94	73 to 100	81 to 100	85 to 100	86 to 100

Figure 3: Mass reductions for low to moderate mobility pesticides (Koc of 100 to 10,000) vs. buffer width



Reference lines at buffer widths of {7.6, 10.7, 15.2, 22.9, 30.5} meters correspond to distances of {25, 35, 50, 75, 100} feet, respectively. Based on data from: Patty et al., 1997; Vellidis et al., 2002.

Table 22: Estimated Buffer Effectiveness for (Koc 100 to 10,000) Removal of Low to Moderate Mobility Pesticides from Shallow Overland Flow on Hydrologic Group B Soils

Buffer Width (ft)	25	35	50	75
Estimated pesticide removal, average (%)	95.0	98.5	99.8	100
Estimated pesticide removal, range (%)	90 to 100	93 to 100	95 to 100	95 to 100

Phosphorus (P)

Phosphorus is an essential plant nutrient that is commonly applied to cropland to fertilize the soil. Even a small increase in phosphorus loading rates to surface waters can result in cascading effects upon aquatic ecosystems. Phosphorus can stimulate an increase in aquatic plant and algae biomass, and the increased photosynthesis and biomass decay can significantly alter the pH and dissolved oxygen levels and surface waters. The resultant physical and chemical changes in an aquatic habitat can lead to drastic changes to aquatic food webs and biological diversity.

The general factors that influence the effectiveness of riparian buffers at removing phosphorus from surface runoff and subsurface flow include the form of phosphorus, climate/weather, soil characteristics, vegetation, hydrology, land use, and buffer size.

Form of phosphorus

P on agricultural landscapes exists either in an insoluble particulate form or a water-soluble form. The particulate form tends to be sediment bound and includes sorbed P, organic P, and mineral P. Soluble P includes orthophosphate, inorganic polyphosphates, and organic P compounds. Particulate P tends to comprise the majority of the load from agricultural lands (Neilen et al., 2017; Abu-Zreig et al., 2003). "Once in surface runoff, phosphorus can deposit along with sediments, adsorb to suspended solids, adsorb to surface soil and vegetation, be assimilated by microorganisms and plants, infiltrate down into soil profile, or move downslope with the runoff." (Abu-Zreig et al., 2003)

According to Daniels and Gilliam (1996), riparian zones are less effective at removing phosphorus from runoff than they are at nitrogen or sediment removal. Removal effectiveness varies with the proportion of particulate vs. soluble P, with effectiveness tends to be much lower for the latter (Clausen et al., 2000; Chaubey et al., 1995; Chaubey et al., 1994; Dillaha et al., 1988). Removal of particulate P primarily occurs by removing sediment from runoff (Borin et al., 2005; Abu-Zreig et al., 2003; Schmitt et al., 1999; Magette et al., 1989; Dillaha et al., 1988). Removal of soluble P primarily occurs through infiltration of runoff (Borin et al., 2005; Chaubey et al., 1994), absorption by vegetation, and soil sorption (Dillaha et al., 1988). A given buffer may be effective for removal of sediment bound P, but not dissolved P (Georgakakos et al., 2018; Borin et al., 2005; Kronvang et al., 2003; Parsons et al., 1994; Dillaha et al., 1988).

Storage of P in riparian buffers varies based on soil adsorption, uptake of dissolved inorganic P by plants, microbial uptake, and storage of organic P in peatland (Mander et al., 1997). These processes are influenced by factors such as soil moisture, P saturation level, buffer width, vegetation type, and riparian management factors (Georgakakos et al., 2018). Estimations for soil adsorption (in soil and sediment) rates for P in freshwater wetland/riparian areas ranges from 1.7 to 38kg/ha/year (Mander et al., 1997). Estimated P storage through sedimentation for constructed riparian wetlands ranges from 5.9 to 130g/m^2/year (Mander et al., 1997). Wetland soils and buffers may release previously captured soluble phosphorus (Mander et al., 1997; Dillaha et al., 1988). Nitrates can influence the redox potential of sediments, thereby altering P release. Estimated P inactivation rates for riparian/wetlands due to nitrate release range from 26 -42 kg/ha/yr. in a riparian fen to 7.3 -1044 kg/ha/yr. in a riparian forested wetland (Mander et al., 1997).

Climate and weather

The intensity and amount of rainfall an area receives is a primary control on the potential for P to be transported in surface runoff (Kelly et al., 2007; Borin et al., 2005; Lee et al., 2003; Gburek and Sharpley, 1998; Younos et al., 1998; Bingham et al., 1980). For example, Bingham et al. (1980) state that P loads are lower for small precip/runoff events than for large events. In relation to riparian buffers, Daniels and Gilliam (1996) assert that high-energy storms that occur while agricultural fields in a watershed have their lowest protective cover can create runoff that overwhelms the filtering capacity of buffers.

Hydrology

Site hydrology is critically important to the effectiveness of a buffer to capture and retain P. The rate, velocity, and volume of overland flow typically drives P transport to a buffer as well as within it (Gilley et al., 2016; Lowrance et al., 2005; Abu-Zreig et al., 2003; Younos et al., 1998; Mander et al., 1997). For example, Borin et al., (2005) found that soluble P loading to buffers is positively correlated with runoff volume. Lower runoff velocity and greater water retention time in a buffer increase result in more contact time with soil and vegetation and less transport capacity for fine particles to which P can be adsorbed (Abu-Zreig et al., 2003). As expected, multiple researchers have determined that buffers are ineffective at removal of P from concentrated flows (Gilley et al., 2016; Schmitt et al., 1999; Daniels and Gilliam, 1996; Dillaha et al., 1988). Concentrated runoff flows from agricultural fields should be dispersed before entering a riparian buffer (Daniels and Gilliam, 1996; Dillaha et al., 1988). Similarly, tile drains that cause runoff to bypass a buffer will reduce P removal effectiveness (Georgakakos et al., 2018).

Buffer retention is most efficient when the P loading events are infrequent and of short duration (Schmitt et al., 1999; Mander et al., 1997; Magette et al., 1989). According to Weld et al. (2001), "most of the P exported from agricultural watersheds generally comes from only a small part of the landscape during a few relatively large storms." This highlights the importance of implementing general BMPs that minimize runoff from smaller, more frequent storm events as well as BMPs targeted to address areas that are more likely to produce runoff during larger, more infrequent storms.

Buffers P generally retain more P from surface flow than from subsurface flow (Mander et al., 1997). Soluble P can leach into and be transported by groundwater or shallow subsurface water flow (McKergow et al., 2001; Clausen et al., 2000). Subsurface flow may be a significant source of dissolved P delivery to surface waters in some settings (Gburek and Sharpley, 1998). However, Newbold et al. (2010) found evidence that P levels in agricultural streams are driven more by inputs of sediment from overland flow than from groundwater inputs.

Topography

Topography influences P loading to a buffer (and therefore buffer effectiveness) at multiple spatial scales. At a broader scale, the general slope of a watershed influences the potential for P to be transported (Daniels and Gilliam, 1996). At the hillslope scale, the size of the contributing area to a buffer, slope lengths, and the steepness of the hillslope and buffer are important factors (Mander et al., 1997; Bingham et al., 1980). For example, Smith et al. (1989) suggested that in steeper areas, soil stability can vary by aspect, which can influence vegetation, runoff characteristics and P loads. Lastly, at the micro-topographic scale, the surface roughness of soils can influence site hydrology and the ability of a buffer to impede and infiltrate surface runoff (Mander et al., 1997).

Soils

Soil characteristics within a buffer have a fundamental influence on the capture and sequestration of P. The rate at which soils can infiltration runoff in the buffer is important for both sediment-bound P and soluble P removal (Dosskey et al., 2007; Borin et al., 2005; Lee et al., 2003; Schmitt et al., 1999; Mander et al., 1997; Chaubey et al., 1995; Dillaha et al., 1988; Bingham et al., 1980). Research has identified a number of ways in which infiltration rates are influenced by soil physical and chemical attributes, vegetative and plant residue cover, and soil slope. For example, a high degree of residue cover protects the soil from pores from sealing during rain events, thereby preventing a reduction in infiltration rate (Gilley at al., 2016; Lee et al., 2003). Nevertheless, Dillaha et al. (1988) caution that buffers should not be designed based on infiltration rates alone, because there are other factors that influence pollutant removal.

Various research findings on how soils can influence buffer effectiveness include:

- The importance of soil chemistry: P retention is influenced by amount of precipitation with Fe, Al, and Ca. (Mander et al., 1997); soils can become saturated with P more readily when elements to form precipitates are in low supply (McKergow et al., 2001).
- The role of soil texture, structure, and erodibility (Borin et al., 2005; Younos et al., 1998; Mander et al., 1997).
    - P has a tendency to sorb to smaller soil particles (Dillaha et al., 1988).
    - The P trapping efficiency is likely to vary if soil particle size among runoff events varies, since finer soil particles tend to have higher P content, and coarser particles are more readily retained in a buffer (Borin et al., 2005; Schmitt et al., 1999).
    - Sandy soils generally have low P retention (McKergow et al., 2001).
- The role of antecedent moisture.
    - Higher antecedent soil moisture is associated with lower P removal (Dosskey et al., 2007; Bingham et al., 1980).
    - Buffer effectiveness can vary considerably among years due to differences in antecedent soil moisture (Dosskey et al., 2007).

- The role of soil surface roughness.
    - Higher soil roughness impedes surface runoff and promotes infiltration (Borin et al., 2005; Bingham et al., 1980).
- The role of areas prone to saturation.
    - Areas where saturation excess overland flow (and infiltration excess overland flow to a lesser extent) occurs are important in runoff generation and P transport (Walter et al., 2009; Lowrance et al., 2005; Gburek and Sharpley, 1998).
- The role of critical source areas for P.
    - Critical sources areas are those where high soil P occurs in areas where surface runoff tends to occur, but areas with coarser soils or preferential flow paths that promote subsurface flow are also important (Weld et al., 2001).

Vegetation

Vegetation facilitates runoff infiltration and can sequester P through from soils and shallow groundwater. As vegetation density and litter increases, resistance to overland flow increases, resulting in greater more physical trapping of sediment and greater runoff infiltration; research has shown that P removal is higher in buffers with more soil roughness, vegetation having higher density, and more surface litter (Gilley et al., 2016; Borin et al., 2005; Lee et al., 2003; Schmitt et al., 1999; Schmitt et al., 1999; Dillaha et al., 1988; Bingham et al., 1980). Buffer vegetation also increases organic matter in the soil, which facilitates soil aggregation and roots increases the porosity, leading to increased infiltration (Lee et al., 2003).

P retention in buffers appears to depend on vegetation composition (Zhang et al., 2010). In general, trees appear to be more effective than shrubs and grass at sequestering P delivered to buffers, although there have been some contradictory findings among research studies. The following summarizes various research findings regarding the role of vegetation composition.

- Mander et al. (1997) observed greater P retention in a buffer with grass, wet meadow, and alder strips than in buffers composed of a single one of these communities. Buffers with shrubs, young stands of trees, and wet meadows with high microbial activity and high soil adsorption capacity had high P uptake. If P uptake decreases with the age of trees in a buffer, then removal of older trees may increase P uptake in the buffer.
- Neilen et al. (2017) found that wooded riparian zones exported less P than grassed riparian zones, regardless of rainfall amount.
- Addition of a fast-growing woody species to a buffer may enhance P removal (Kelly et al., 2007).
- Lowrance et al. (2001) found that the per hectare removal rate for P was lower for a three-zone buffer consisting of an inner hardwood zone, an inner pine zone, and an outer grass zone than for the hardwood zone alone.
- Kelly et al. (2007) found that cottonwood trees accumulated much more P than two species of grass and alfalfa.

- Kuusemets et al. (2001), found that grasses and alder removed P from shallow groundwater (varied between 10-80cm depth), but that grasses in both a cultivated grassland and a wet meadow assimilated more P than a streamside strip of grey alder. P levels in the soil surface increased along a downslope transect of grassland to wet meadow to alder; leaf litter appeared to account for the peak in soil P in the alder stand.
- Clausen et al., (2000) found that P in groundwater increased as it flowed beneath a buffer and suggested that forested buffers may not be effective at removing dissolved P from overland flow or groundwater.
- Rosa et al. (2017) also found an increase in P in shallow groundwater below a willow buffer (but decrease in P in overland flow).
- Lee et al. (2003) found that a warm-season grass/shrub/tree buffer removed significantly more total P and dissolved P than a grass only buffer.
- Mycorrhizal fungi is believed to increase P uptake in plants (Fillion et al., 2011).
- Browsing by wildlife or livestock can impede tree growth in the buffer and thus impede P capture (Newbold et al., 2010; Kelly et al. 2007).

Land use

Land use has a strong influence on how much runoff and P is transported to buffers, which in turn affects the ability of buffers to capture and retain P**.**

Source areas of P can vary at field and farm scales. According to Gburek and Sharpley (1998), “because storm-generated flows exhibit the highest P concentrations, export most P, and occupy very short time intervals within the total flow regime, controls within their source areas offer the greatest opportunity for limiting or controlling P export”. Therefore, identifying areas of runoff and erosion generation (critical areas) can help target BMPs for P reduction. On croplands, the amount of soil cover during precipitation events affects amounts of runoff and P loss (Lee et al., 2003). On grazed lands, livestock can induce micro-topographic changes that promote saturation excess flow and concentrated flow paths. This observation led Georgakakos et al. (2018) to recommend that buffers should be modified to incorporate new runoff generating areas as they are identified. Reducing soil P levels in the critical areas is more important than controlling P soil levels in areas that do not generate surface runoff, except where substantial subsurface flow occurs such as in areas of coarse textured soils (Gburek and Sharpley, 1998).

Nutrient management plays an important role in buffer effectiveness. The timing of and amount of fertilizer/manure application relative to precipitation event timing and degree of incorporation into soil affects P transport (Kronvang et al., 2003; Mander et al., 1997; Bingham et al., 1980). Eghball et al. (2000) found that buffers trapped less mass of P in runoff from manured crop fields than was trapped for fields with P fertilizer applied, even though ten times more P was lost from the fertilized fields than the manured fields. Although P loads from livestock are generally less than P loads from fertilized fields, P in manure is primarily organic which is more mobile than inorganic P, which tends to be associated with soil particles (Eghball et al., 2000; Dillaha et al., 1988). Where continual nutrient inputs occur on agricultural lands, periodic removal of above ground plant biomass (woody and/or herbaceous) in a buffer may be necessary to ensure that it can maintain its effectiveness at P removal from runoff; otherwise, an equilibrium may be reached in which seasonal uptake of P more or less equals the amount returned to the soil (Kelly et al., 2007).

Some studies have found that buffers did not reduce total P concentrations in runoff (e.g. Newbold et al, 2010; McKergow et al., 2001), or that total P declined but dissolved P was relatively unaffected (e.g. Georgakakos et al., 2018; Borin et al., 2005; Daniels and Gilliam, 1996; Dillaha et al., 1988). For example, Georgakakos et al. (2018) found that livestock exclusion and farm settling pond renovation led to a significant reduction in total P loads but a non-significant reduction in soluble reactive P; post-BMP SRP accounted for a larger proportion of the total P load than pre-BMP levels. Other studies have found increases in dissolved P through a buffer (Clausen et al, 2000; Uusi-Kamppa, 1992); For example, Uusi-Kamppa (1992) found a seasonal increase in soluble P exiting grass buffers. Newbold et al. (2010) found that a reduction in particulate P was balanced by increased dissolved P.

Buffers, in combination with upland BMPs are needed to control P losses from agricultural lands (Mbonimpa et al., 2012; Magette et al., 1989). For example, when soils have low P retention and subsurface flow pathways, additional BMPs should be designed to reduce the amount of dissolved P available for transport (McKergow et al., 2001). Pesticides may also play a role in buffer effectiveness. For example, herbicides may decrease mycorrhizal fungi in soil, which are known to enhance P uptake in plants (Lekberg et al., 2017; Zaller et al., 2014; Druille et al., 2013).

Some research has explored concerns about the long-term effectiveness of buffers at sequestering P. Studies have found that buffer effectiveness at P removal increased over a period of several years (starting from initial installation) as vegetation became established and infiltration rates increased (Dosskey et al., 2007; Schmitt et al., 1999). However, Abu-Zreig et al. (2003) pointed out that the accumulation and P saturation of sediments in a buffer may lead to decreased P removal over time as the trapping ability reaches storage capacity. Mander et al. (1997) agreed with this point when they stated that “buffers can have a very high retention capacity, but this capacity is not unlimited”. If soil P becomes saturated in a buffer, it may remobilize and exported out of the buffer; this can occur abiotically through desorption and dissolution or biotically through microbial mediated processes (Georgakakos et al., 2018; Dodd et al., 2018; Gilley et al., 2016). This is why Mander et al. (1997) suggested that nutrient loading into a riparian area and exports from it can reach an equilibrium, and that periodic vegetation removal may help maintain the effectiveness of a buffer. Dodd et al. (2018) even noted that there are problems with traditional testing of soils to determine how whether P is saturated in field and buffer soil. They asserted that the degree of P saturation is a good predictor of inorganic water extractable P, but not organic water extractable P; their point was that P levels in soil can be underestimated, which confers a risk of not implementing appropriate BMPs to control P exports.

Buffer size

P removal from runoff generally increases as buffer width increases (Zhang et al., 2010; Abu-Zreig et al., 2003; Lowrance et al., 2001; Lim et al., 1998; Mander et al., 1997; Srivastava et al., 1996; Chaubey et al., 1995; Chaubey et al., 1994; Parsons et al., 1994; Magette et al., 1989). Increasing buffer width increases the area of soil surface available for infiltration of runoff (Schmitt et al., 1999). Inflow rate, vegetation type, and vegetation density have been found to have lesser influence on P removal than buffer width (Abu-Zreig et al., 2003). However, P removal is not constant with buffer width because particle size influences the distance at which P-bound sediment is trapped (Borin et al., 2005; Dillaha et al., 1988). Also, for a given buffer width, P removal can be highly variable among runoff events (Newbold et al., 2010; Parsons et al., 1994; Magette et al., 1989). When evaluating effectiveness, it is important to look at the mass of P removed since dilution may decrease P concentrations as buffer width increases (Abu-Zreig et al., 2003).

The general relationship between total P removal and filter width appears to have an asymptote, that is, after a certain distance, further reductions are much smaller (Abu-Zreig et al., 2003; Chaubey et al., 1995; Chaubey et al., 1994), unless of course, no runoff leaves the buffer (Borin et al., 2005). P removal tends to be lower than sediment removal and increases more steadily with buffer width, whereas sediment removal tends to level off sooner (Chaubey et al., 1994; Abu-Zreig et al., 2003). The reason is that more of the P tends to be bound to finer particles, which take longer to settle out of runoff (Abu-Zreig et al., 2003) and also that some of the P is in solution. "The difference between sediment and phosphorus trapping appears to be large for strips and small for longer strips" (short mean narrow width and longer means wider) (Abu-Zreig et al., 2003). Lowrance et al., 2001 found that in three zone buffers, total P removal roughly corresponded to sediment removal rates. Total P appeared to reach a removal asymptote of approximately 80% for buffers of 20m in width. Removal of dissolved P did not significantly increase for buffers wider than 20m, and most of the P leaving the buffer in this study was dissolved P in surface runoff.

Key Takeaways

- Similar to the case for nitrate, retention of dissolved P is widely variable and seems to be unpredictable without studying site specific removal rates. In many circumstances, buffers are not effective at capturing dissolved P from runoff.
- Total P retention rates generally correspond to sediment removal rates, driven by physical trapping of sediment particles and settling of sediment as runoff is infiltrated.
- Buffer effectiveness for sediment capture can therefore provide a reasonable estimate of P capture since it appears that most P is associated with sediment and organic particles.
- Since total P capture is approximated by sediment removal and dissolved P removal is generally unpredictable, a quantitative evaluation of buffer effectiveness for phosphorus was not undertaken for this evaluation.
- Buffer effectiveness can be maximized by:

- Implementing BMPs that promote soil health and inhibit soil erosion
- Implementing upland nutrient management BMPs
- Implementing BMPs that prevent concentrated flows from entering buffers
- Planting trees in at least a portion of a buffers wherever the riparian area can support a riparian forest community
- Periodic removal of sediment deposited in the buffer, and redistribution upon upland fields
- Maintaining a relatively high density of vegetation in the buffer
- Periodic removal of vegetation in the buffer to remove sequestered nutrients

Sediment in Runoff

Factors that influence the effectiveness of riparian buffers at removing sediment from runoff include: climate/weather; geomorphology/topography; hydrology; soils; vegetation; land use; buffer size.

Climate and weather events

Rainfall amount and intensity influences the generation and transport potential for sediment (Dosskey et al. 2011, 2008; Duda et al., 1985). For example, as precipitation intensity increases, the potential runoff volume increases, and larger runoff volumes are generally associated with increased sediment transport (Liu et al, 2008; Renard et al., 1997; Williams and Nicks, 1988). Similarly, Wissmar et al (2004) assert that areas where rain on snow occurs have a greater risk of soil erosion. Wind can also influence the amount of sediment in runoff. For example, windthrow of trees can result in localized areas of soil erosion (Lynch et al., 1990; Broderson, 1973).

Geomorphology and topography

The ability of buffers to capture and retain sediment is affected by the shape the land at watershed, hillslope, and micro-topographic scales. At the watershed scale, valley morphology controls the potential riparian area width and valley side-slope characteristics such as hillslope length and gradient and thus influences vulnerability to sediment generation and transport (Nagel et al. 2014). At the hillslope scale, slope (for the buffer area and the source area) (Lee, 1999; Nigel et al., 2013; Verstraeten et al., 2006; Zhang et al., 2009; Dosskey et al., 2008; Phillips, 1989; Tolzman, 2001; Xiang, 1993).

Sediment retention tends to decrease with increasing buffer slope (Nigel et al., 2013; Dosskey et al. 2006). Linear, concave, and convex slopes have differing erosional characteristics (Roose, 1996; Williams and Nicks, 1988). Buffers on convex slopes tend are likely to retain less sediment than those with linear or concave slopes (Williams and Nicks, 1988). Slopes that converge (e.g., in a swale) are more prone to generate concentrated flow in comparison to those that diverge (e.g., on the nose of a toeslope). Because of this difference, some researchers have asserted that buffers along divergent slopes do not need to be as wide as those along areas with convergent slopes ((Bren, 1998; Dillaha et al. 1989). Surface roughness (typically described by Manning's roughness coefficient) can impede overland flow, thus inhibiting sediment transport (Xiang, 1993; Williams and Nicks, 1988). However, micro-topography can promote concentrated flow which reduces sediment trapping by buffers (Dosskey et al. 2002, Hay et al. 2006, Helmers, 2005, Lakel et al. 2010).

Soils

Soil characteristics influence buffers in a variety of ways. Soils with higher erodibility reduce the effectiveness of buffers (Tomer et al., 2005). Soil erodibility is particularly high where frozen subsoil is overlain by thawed surface soil (Renard et al., 1997). The greater the soil roughness, the more runoff flow is impeded. Sediment particle size distribution has strong influence on the transport of sediment loads in runoff (Gharabaghi et al. 2006, Lee et al. 2003, Lee et al. 2000, Lee, 1999; Muñoz-Carpena et al., 1999; Verstraeten et al., 2006). Larger particles settle out of suspension at a faster rate than smaller particles (Gharabaghi et al. 2006).

Infiltration rates are one of the most important factors affecting sediment trapping in buffers (Dosskey et al., 2007; Lee, 1999; Robinson et al., 1996; Dosskey et al., 2006; Tolzman, 2001). Riparian buffer soils with higher infiltration rates tend to trap more sediment (Dosskey et al., 2007; Lee, 1999; Coyne et al., 1995). Coarser textured soils have higher infiltration rates and produce sediment that has lower transport capacity (Tomer et al., 2005). Infiltration rates are typically affected by antecedent soil moisture (Muñoz-Carpena et al., 1999; Duda et al., 1985). Soils prone to infiltration excess and saturation excess overland flow will produce more runoff and result in decreased buffer effectiveness (Duda et al., 1985). Placing vegetated buffers on soils prone to saturation can help prevent soil erosion and transport by runoff (Tomer et al., 2005). The saturated hydraulic conductivity of soils is also important; soils with higher conductivity tend to drain more readily, allowing for greater amounts of runoff to be infiltrated (Muñoz-Carpena et al., 1999; Phillips, 1989; Tolzman, 2001; Xiang, 1993).

Vegetation

Buffer effectiveness is influenced by the type and density of vegetation, as well as amount of surface litter (Yuan et al., 2009; Dosskey et al., 2007; Gharabaghi et al. 2006; Lee et al. 2003; Lee et al. 2000; Lee, 1999; Muñoz-Carpena et al.; 1999; Verstraeten et al., 2006; Zhang et al., 2009; Tolzman, 2001; Chaubey, 1994). Vegetation (e.g., canopy and litter) protects the soil from rainfall impact and thereby decreases soil particle detachment and potential for subsequent transport. Greater vegetation density and litter accumulation reduces runoff velocities, thereby promoting sediment deposition (Dosskey et al., 2007). Warm-season grasses with stiffer stems have been found to be more effective at trapping sediment than cool-season grasses that have a greater tendency to lay over in runoff flow (Webber et al., 2010; Lee, 1999). Lee (1999) and Lee et al. (2000) found that a grass strip plus a woody vegetation strip had greater sediment removal than grass alone. However, Yuan et al., (2009) concluded in a review that sediment trapping does not vary by vegetation type (e.g., trees vs. grass).

New buffers require a period of years (e.g., up to 10yrs) for vegetation to establish and for infiltration rates to increase (Dosskey et al. 2007). Through time, sediment berms may form at the upslope edge of vegetation in riparian buffers- influencing flow paths and therefore sediment transport (Gilley et al. 2000).

Riparian vegetation helps control streambank erosion rates (Zaimes, 2019; Zaimes, 2004; Schlosser and Karr, 1981). In certain situations, forested riparian areas tend to have wider channels than grassed riparian areas (Sweeney et al., 2004), which can affect the susceptibility to streambank erosion. More detail on buffer effectiveness for streambank erosion is presented later in the document.

Hydrology

The volume, rate, and depth of runoff flow into and through a buffer has a strong influence over buffer sediment trapping effectiveness (Gharabaghi et al. 2006; Hay et al. 2006; Verstraeten et al., 2006; Qui, 2003). Buffers are most effective for removing pollutants from sheet flow (Verstraeten et al., 2006). The deeper the depth of runoff, the less effective a buffer becomes at removing sediment (Verstraeten et al., 2006). Removal of pollutants from concentrated flow is limited (Dosskey et al. 2002, Hay et al. 2006, Helmers, 2005, Lakel et al. 2010, Lee, 1999; Sheridan et al., 1999; Verstraeten et al., 2006; Webber et al., 2010; Dosskey et al., 2006; Daniels et al., 1996).

Some researchers have concluded that buffers have a greater potential to protect water quality on smaller streams than they do for larger order streams because they have a proportionally larger interaction with surface runoff (Tomer et al., 2005; Burkhart et al., 2004). For example, Tomer et al. (2005) asserted that buffers on stream orders one through three have a greater potential for sediment deposition than buffers on larger streams and rivers.

Land use

Land use and associated BMPs are an important factor in determining buffer effectiveness at trapping sediment (Gilley et al. 2000, Lakel et al. 2010; Mbonimpa et al, 2012; Lynch et al. 1990; McKergow et al., 2003). Upland BMPs can reduce the amount of runoff and sediment entering a buffer (Lakel et al. 2010; Gilley et al., 2000; Newbold et al., 2010) and importantly, can be used to minimize concentrated flow into the buffer (Sheridan et al., 1999). Upland BMPs are needed where flow convergence occurs (Verstraeten et al., 2006). A lack of upland BMPs to control erosion and trap sediment can lead to significant sediment loading to waterways regardless of whether or not an effective riparian buffer is in place (Nigel et al., 2013). Gilley et al. (2000) showed that the % sediment reduction for grass buffers was similar between plots with conventional tillage vs. no-till with residue retained; however, the mass of soil lost from the conventionally tilled field was an order of magnitude greater than from the no-till. As the amount of bare soil in the uplands increases the amount of runoff and sediment load increases (Lakel et al. 2010, Gilley et al. 2000). Greater runoff and sediment loads can lead to reduced overall buffer filtration (Gilley et al. 2000). Large runoff volumes can overwhelm the ability of the buffer to trap sediment. Sediment (e.g. infrequent large loads, frequent small loads) can accumulate at the upper edge of a buffer, facilitating the formation of concentrated flow that travels along the berm (Dosskey et al., 2002); eventually these concentrated flows may cut a channel through a buffer, resulting in a “short-circuiting” of its sediment capturing ability. Similarly, runoff can bypass buffers due to dirt roads and associated ditches that facilitate flow concentration and erosion (Wissmar et al., 2004; Lakel et al., 2010) as well as by tile drains that are hydrologically connected to stream channels, e.g., via ditches (Schultz et al., 1991).

Buffer size

Most researchers on buffer effectiveness have concluded that buffer size is an important factor influencing sediment capture (Yuan et al., 2009; Gharabaghi et al. 2006; Lee, 1999; Verstraeten et al., 2006, Zhang et al. 2009; Williams and Nicks, 1988; Xiang, 1993). The effectiveness of a riparian buffer at trapping sediment in runoff depends less upon buffer width than it does upon on the soils, hydrology, and vegetation at a site (Rosa et al., 2017; Dosskey et al., 2007; Verstraeten et al., 2006). However, with increasing buffer width, the overall capacity for the processes (infiltration over a greater area, increased contact with vegetation, etc.) that promote sediment trapping increase (Zhang et al., 2009). Dosskey et al (2002) assert that the buffer area ratio (i.e., the ratio of the upland area contributing runoff to the area of the buffer actually receiving that runoff) is an important indicator of buffer effectiveness. Using modelling (i.e., VFSMOD), Dosskey et al (2002) concluded that buffer area ratios of 0.20 result in maximal sediment trapping; buffers with ratios of 0.10 were estimated to trap approximately 65 to 85% of sediment, while buffers with ratios of 0.20 were estimated to trap 85 to 95% of sediment.

Most sediment trapping in a buffer tends to occur in the first few meters (Lee et al. 2003, Zhang et al., 2009; Gharabaghi et al., 2006; Dosskey et al., 2002). Typically, most of the coarser silt and sand particles are removed from runoff through physical trapping in the first few meters, whereas trapping of fine silts and clay particles is more dependent upon runoff infiltration in the remaining portion of the buffer. Due to this phenomenon, the rate of sediment removal is typically steep for the first few meters, after which the rate gradually levels off. The cumulative sediment removal rate for a buffer ultimately depends upon how much of the runoff is infiltrated into soils. This means that any remaining surface runoff discharging from a buffer into a stream is likely to contain sediment.

Sediment removal effectiveness

Results of published sediment removal meta-analyses

Three meta-analyses of sediment removal by buffers were reviewed for this effectiveness evaluation. Table 23 below displays the results of using the equations derived by each of the meta-analyses to estimate the buffer width needed to achieve differing levels of sediment removal (note that Liu et al. and Yuan et al. have additional buffer width equations that also incorporate buffer slope, and Zhang et al. has additional equations that incorporate buffer slope and vegetation type).

Part of the variability in these results is likely due to the inclusion of TSS data, which leads to under-predictions of sediment removal at wide buffer widths; this issue is discussed further later in this section.

Table 23: Predicted sediment removal rates for buffers based on published meta-analyses.

Sediment Removal Rate	Liu et al. (2008) Buffer Width (m)	Yuan et al. (2009) Buffer Width (m)	Zhang et al. (2010) Buffer Width (m)
50%	0.6	0.08	1.8
75%	3.9	2.8	3.9
85%	8.1	11.3	5.9
90%	11.8	22.6	10.3
95%	17.1	45.6	N/A*

*The Zhang et al. equation has a maximum possible removal rate of 90.9%

Ecology's quantitative analysis of buffer effectiveness for sediment removal

Ecology completed a quantitative analysis of sediment removal within buffers based on data available in published scientific literature. Extractable data was identified for 34 published studies listed in the annotated bibliography. The dataset was the subjected to multiple rounds of refinement.

The first refinement removed studies which reported sediment removal as a percent reduction in sediment concentration in runoff, rather than a percent reduction in sediment mass; this is important because dilution alone (e.g., due to precipitation falling on the buffer) can result in lower sediment concentrations, thereby confounding results. No attempt was made to convert sediment concentration reduction results to sediment mass reductions. A preliminary analysis of the dataset resulting from the first refinement showed no relationship between buffer width and sediment mass removal. This phase of the analysis did reveal, however, that median sediment removal rates were roughly equal for concave and linear slopes (92.5% and 95% sediment removal, respectively), but were considerably lower for convex slopes (59% sediment removal).

The second round of data refinement excluded data: associated with concentrated runoff flows; where the buffer vegetation was a crop; where the buffer vegetation was not well-established; where a disturbance occurred within the buffer (e.g., roads, timber harvest); and where a sediment reduction dataset was only partially reported. Exploratory analysis of the dataset resulting from the second refinement showed little relationship between buffer width and sediment removal.

Further evaluation was completed to explore why individual studies show a relationship between buffer width and sediment reduction at the individual site scale, yet the combined data from the studies showed no such correlation. Per the effectiveness factors summary, sediment removal depends upon factors such as: precipitation amount and intensity; slope; contributing area; runoff volume/rate; soil texture; antecedent soil moisture; soil permeability & infiltration rates; vegetation type; and vegetation density. However, at a broader geographic scale there are complex interactions and variations among the factors influencing buffer effectiveness. Additionally, there are artifacts of individual study designs and methods that result in considerable variability, as discussed below.

The third data refinement removed studies that used total suspended solids analysis methods. The TSS lab analysis method was developed for wastewater, where the primary sediment is not mineral soil particles (Gray et al., 2000). For example, a few of the studies using the TSS method were focused on animal manure solids removal, not soil mineral particle removal, as is the focus of this effectiveness evaluation. The TSS method should not be used for natural waters because it underestimates sediment in samples when sand comprises more than 25% of the solids (Gray et al. 2000).

The final refined dataset consisted of data from 8 studies. Minitab statistical software was used to perform regressions of the data. Preliminary analyses indicated that:

- The amount of runoff infiltrated within a buffer is a better predictor of sediment removal than buffer width; however, % runoff infiltration is strongly correlated with buffer width
- The rate of runoff infiltration per unit of buffer width appears to differ between studies conducted on Hydrologic Group B soils and those conducted on Hydrologic Group C/D soils.

The dataset was divided into two separate groups for further analysis based on hydrologic soil group. The dataset for hydrologic group B soils was derived from Barfield et al., 1998, Coyne et al., 1995, Dosskey et al., 2007, and Gilley et al., 2000. The dataset for hydrologic group C/D soils was derived from Lee et al., 2003; Lee et al., 2000; Lee, 1999; Mihara, 2006. All of these studies employed grass buffers and had complete data for buffer slope, buffer width, % runoff infiltration, and % sediment mass reduction. Other types of data such as buffer area ratio, hillslope length, source area slope, and precipitation intensity were not used due to the data being incomplete and/or incomparable.

Consistent with literature, found evidence that buffer soil texture affects infiltration. The median % of runoff infiltrated was lower for sites with silty clay loam soils (Hydro Group D) than sites with silt-loams (Hydro Group B): 46.4% vs. 86.7%. No clear signal that source area/buffer slope, hillslope length, can reliably predict sediment removal.

Linear regressions were developed between % runoff infiltration and sediment removal for both the more permeable hydrologic group B soils and the less permeable hydrologic group C/D soils (Figures 4 and 5). Non-linear regressions were developed between % runoff infiltration and buffer width refor the two soil groupings (Figures 6 & 7). These two regressions can then be used to estimate sediment removal. First, one can estimate the amount of runoff infiltration that may be expected for a given buffer width on either the more permeable or less permeable soil grouping. Then, one can use the estimated runoff infiltration rate to estimate a corresponding sediment mass removal rate. Based on this method, Figure 4 below provides estimated sediment removal rates for varying buffer widths on different soil hydrologic groupings.

There are study artifacts that should be considered when interpreting these data. For example, most of the data in the final dataset was derived from studies using simulated rainfall at intensities ranging from roughly 1inch/hr. up to 2.72in/hr. These high simulated rainfall intensities forced runoff water to more or less reach the end of the buffers being examined. However, rainfall intensity within this range has a very low likelihood of occurring in any given year in either western or eastern Washington (NOAA, 1973; WA DOT, 2006). This may lead to underestimates of the amount of infiltration and sediment capture that would occur under conditions in Washington State. On the other hand, the studies associated with the final dataset were all conducted at the plot-scale rather than the field scale. Multiple studies cited in the bibliography have addressed the issue of plot vs. field vs watershed scale differences in buffer effectiveness. Field scale runoff entering a buffer may have greater runoff volumes, depths, velocities, and flow durations than runoff from rainfall at the plot scale. With regards to these considerations, the sediment removal estimates in this evaluation are based on the assumption that these plot-scale studies can provide reasonably accurate estimates of buffer effectiveness at capturing sediment from shallow overland flow under field conditions experienced within Washington State.

Figure 4: Hydrologic Grp B Soils % Runoff Infiltration .vs. Sediment Reduction

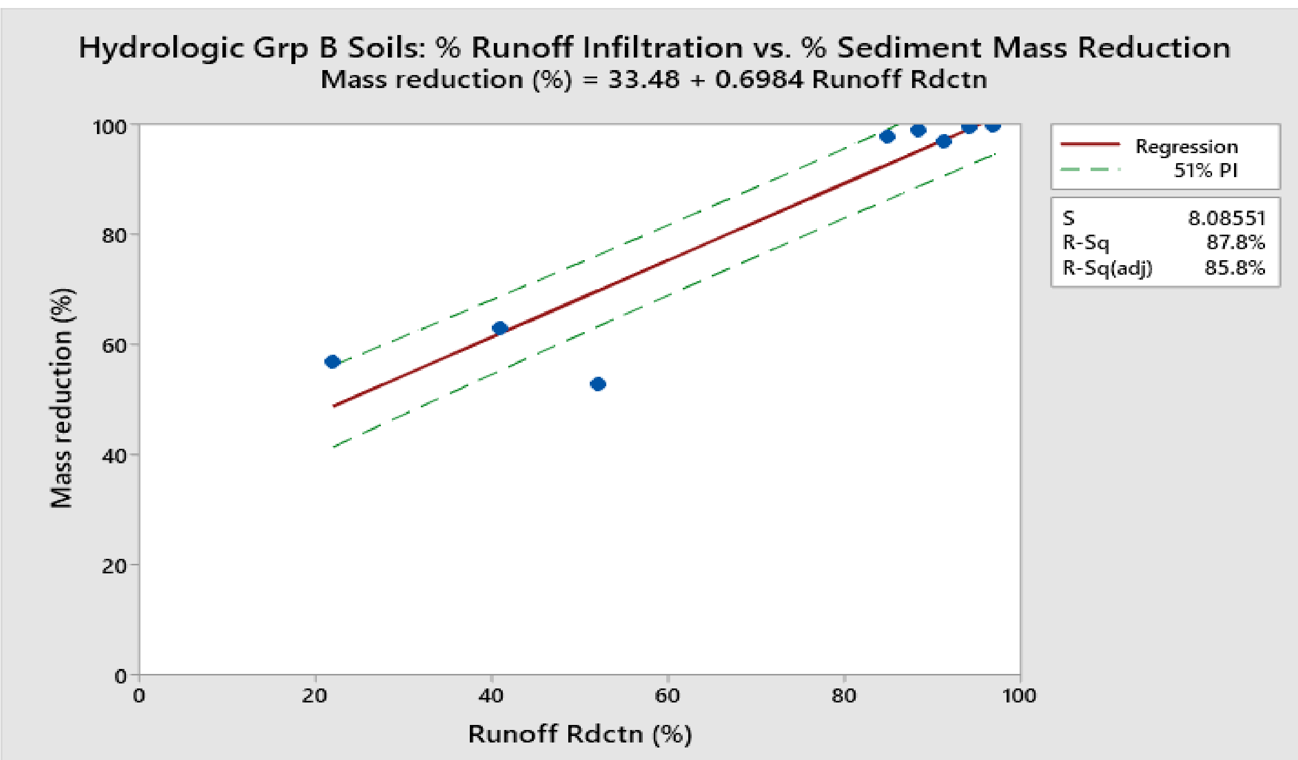
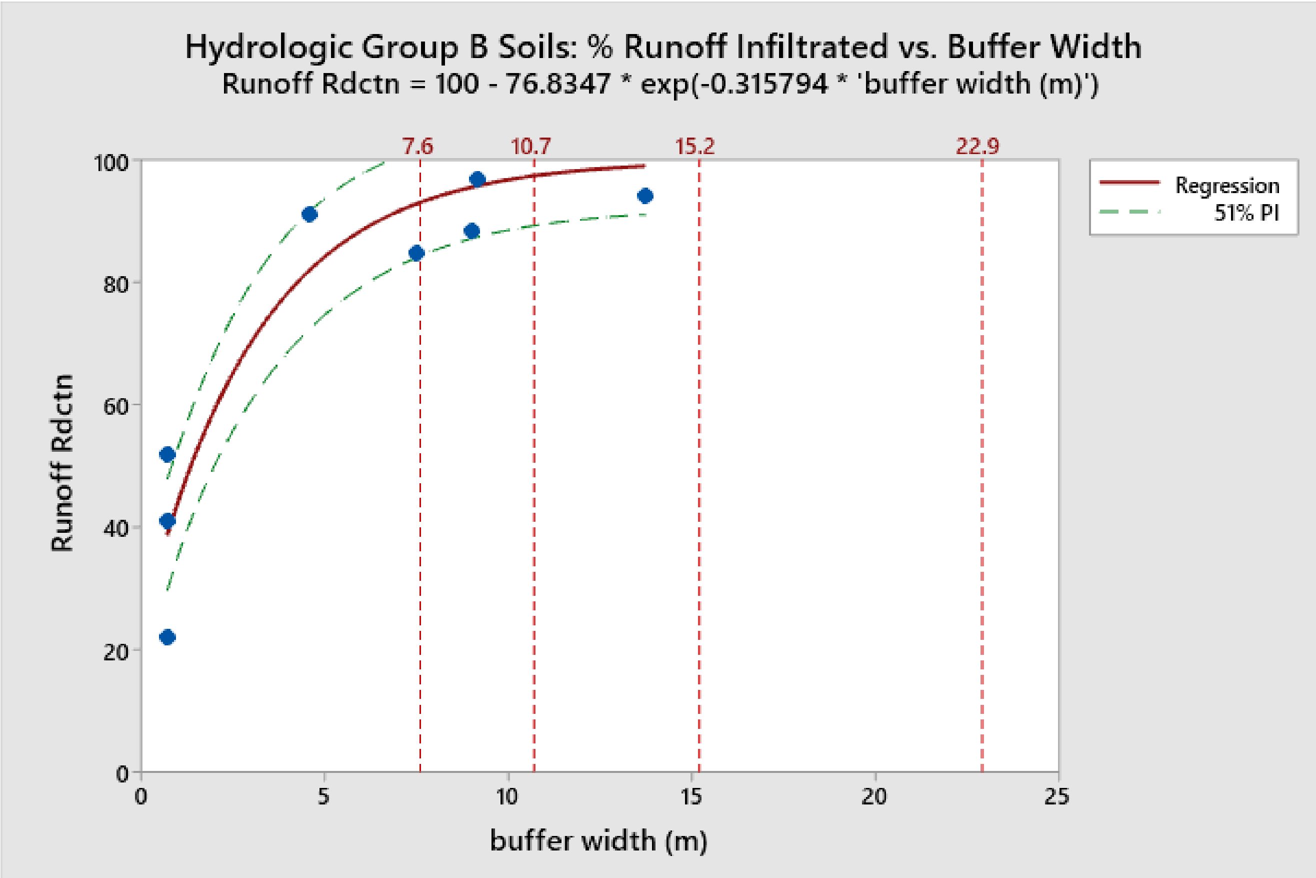


Figure 5: Hydrologic Group B Soils: % Runoff vs Buffer width



References lines at {7.6, 10.7, 15.2, 22.9m} correspond to distances of {25, 35, 50, 75ft}, respectively.

Figure 6: Hydro Grp C\D Solis: % Runoff vs Sediment Reduction

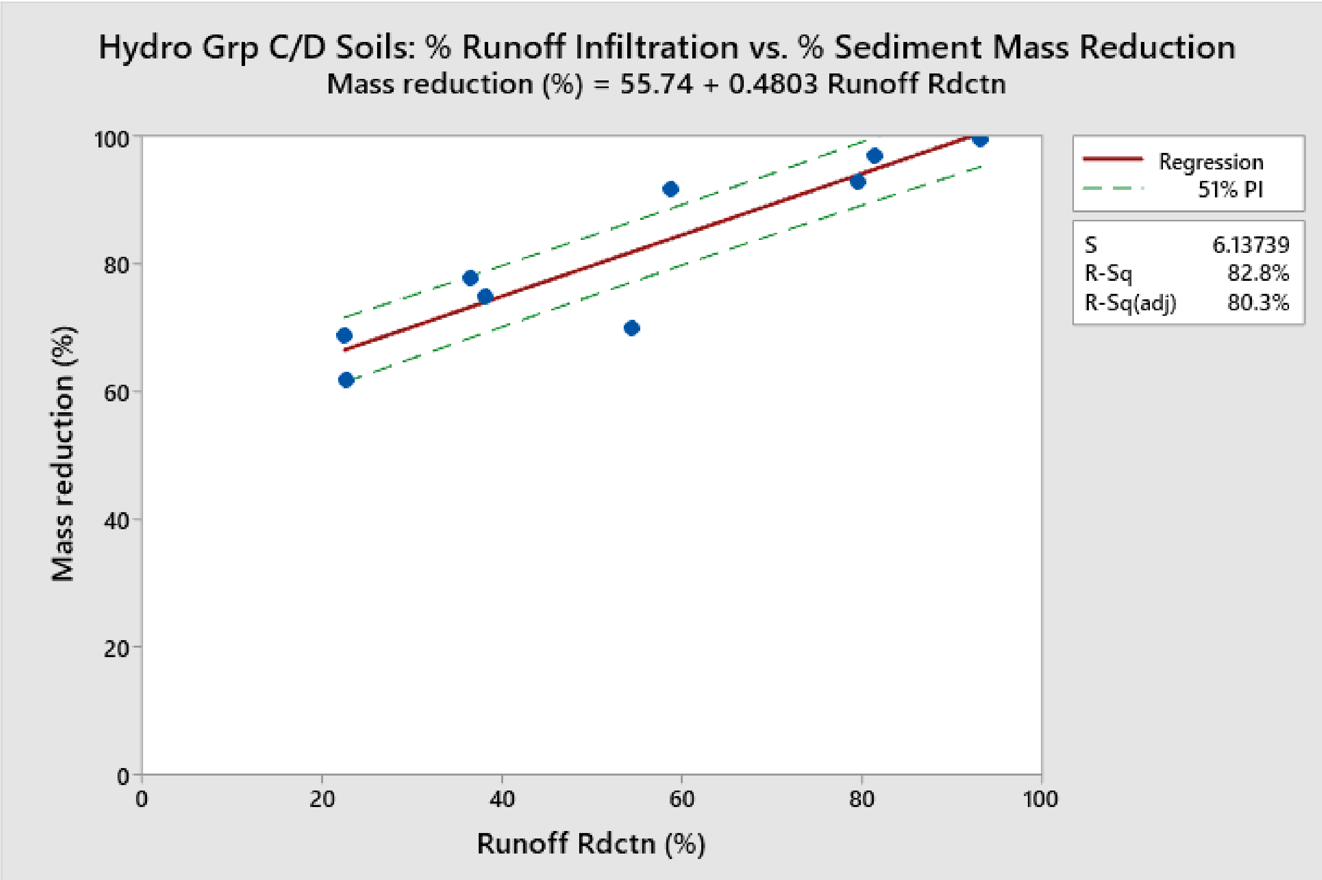
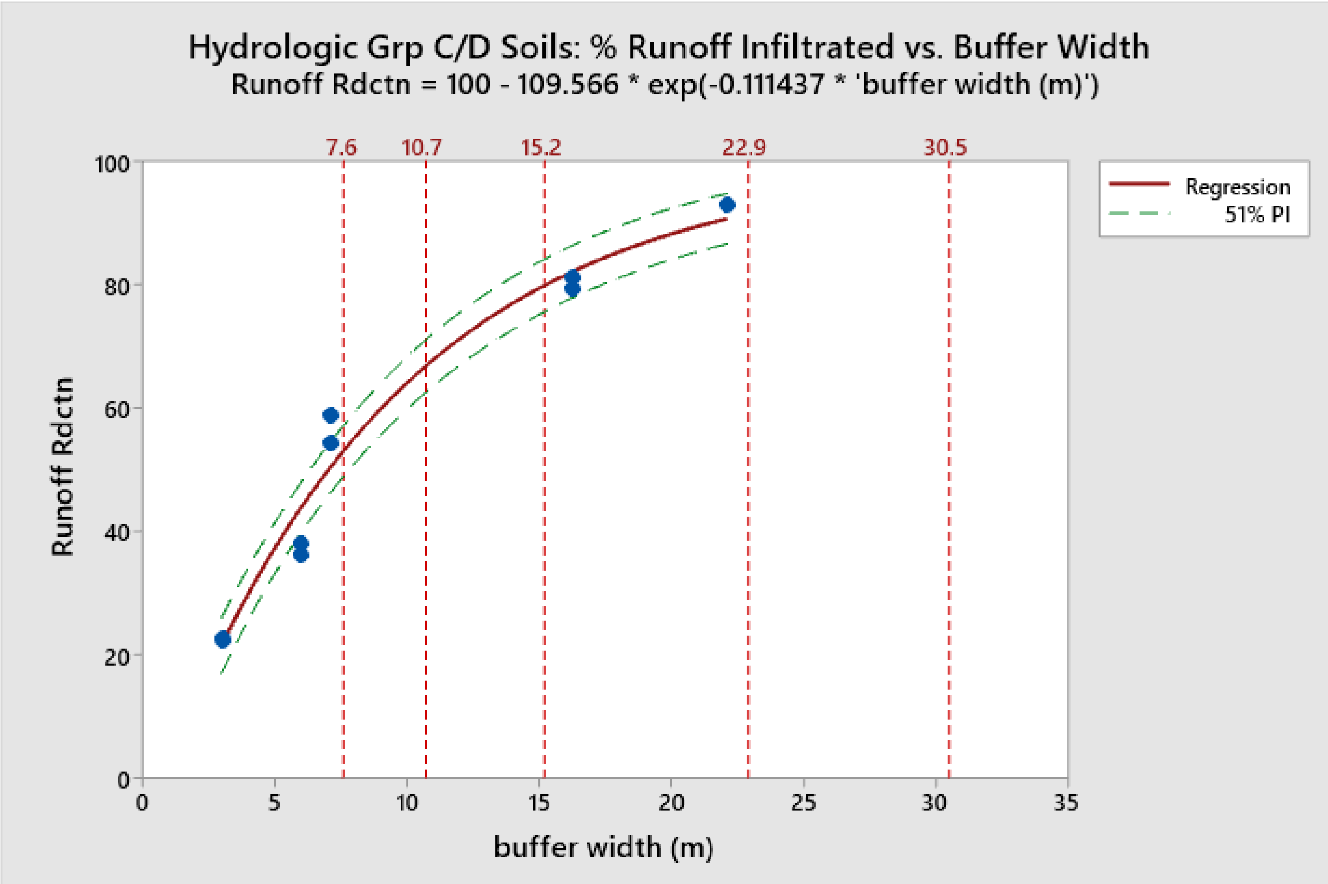


Figure 7: Hydologic Grp C/D Soils: % Runoff Infiltrated vs Buffer Width



References lines at {7.6, 10.7, 15.2, 22.9, 30.5m} correspond to distances of {25, 35, 50, 75, 100ft}, respectively.

Table 24: Predicted infiltration and sediment removal rates for soil B.

Hydro Soil Group B	25ft	35ft	50ft	75ft	100ft
% runoff infiltrated	93.0	97.4	99.4	99.9	100
% sediment mass removed (Range, based on 51% PI)	98.4 (91.9 to 100)	100 (95.0 to 100)	100 (96.2 to 100)	100 (96.7 to 100)	100 (96.8 to 100)

Table 25: Predicted infiltration and sediment removal rates for soils C/D

Hydro Soil Group C/D	25ft	35ft	50ft	75ft	100ft
% runoff infiltrated	53.0	66.8	79.9	91.5	96.3
% sediment mass removed (Range, based on 51% PI)	81.2 (76.5 to 86.0)	87.8 (83 to 92.6)	94.1 (89.2 to 99.1)	99.7 (94.5 to 100)	100 (97.0 to 100)

The estimates provided in Table 24 & 25 assume that soil and water conservation practices are being implemented in the uplands to minimize soil erosion and runoff volumes, and prevent concentrated flows from entering the buffer. This generally involves cropland/orchard/livestock practices that: minimize soil disturbance; prevent soil compaction; provide soil surface cover; increase soil OM content; increase soil aggregation; facilitate water infiltration/percolation; promote the vigor of any perennial plant communities; control erosion/runoff from vehicle access roads, field lanes, etc.

Additionally, the estimates in the table are unlikely to have equal applicability to steep soils, since the soil slope is known to influence processes such as runoff generation, soil erosion, and infiltration. Nigel et al. (2013) found that more often than not, erosion features on slopes greater than 8% were "hydrologically and sedimentologically connected to watercourses." In other words, there is a greater risk that slopes greater than 8% will develop concentrated flow paths that deliver eroded soils to stream channels. This means that all else being equal, wider buffers are likely needed on slopes greater than 8% in order to achieve the same level of effectiveness as indicated by the estimates in Table ABC. In addition to increased buffer width on steeper soils, it is appropriate to implement enhanced soil and water conservation BMPs should be implemented on steep uplands to inhibit concentrated/channelized flows from entering riparian buffers.

Examples of enhanced BMPs include; terraces, field borders, grassed waterways, level spreaders, and water and sediment control basins. Soil disturbance should be avoided on slopes >30% (Nigel et al., 2013).

The sediment removal effectiveness evaluation revealed that the first several meters of a vegetated buffer had the greatest per unit width removal rate. The analysis suggested that about two-thirds of the total sediment load is typically removed in the first six meters and about one-third of the total sediment load is typically removed beyond 6 meters, regardless of total buffer width. Beyond the first several meters, the median overall sediment removal rate did not appear to increase. This finding aligns with two of the primary conclusions from scientific literature on buffer effectiveness for sediment removal. The first is that the rate of sediment removal is not constant across a buffer: most of the sediment mass is trapped by vegetation in the first few meters of a buffer. The second is that the removal rate across the buffer is not equal across sediment particle sizes- larger particles travel less distance than smaller particles. For the studies used in the quantitative analysis, high (e.g., >70%) sediment reductions in thefirst few meters (e.g., 3-5m) appeared to be associated with a relatively high overall sediment capture rate for the buffer level (e.g., >90%) whereas when the removal in the first few meters was low (e.g., <50%) further buffer width tended not to result in a high overall removal rate for the buffer. The studies with high sediment removal rates tended to have high infiltration rates and the studies with low removal rates tended to have low infiltration rates. Since physical trapping and infiltration don't depend on buffer width alone, a shift in what is driving sediment removal would explain why the sediment removal rate per unit of buffer width (e.g., grams per meter) is not constant, but rather the rate of sediment removed is highest at the front of the buffer, then rapidly diminishes and levels out at a very low rate as distance through a buffer increase.

An important artifact of plot-scale studies is that simulated rainfall is set at a high rate to try to force water to reach the end of the experimental buffer strips, in to order to enable to measurements of pollutant masses. This generally means three things: that the runoff volumes in such studies represent larger storm events (e.g., 10yr storm events); 2) that any runoff reaching the other end of the buffer will have some sediment in it; 3) the way to achieve maximum sediment capture is to maximize runoff infiltration.

The amount of sediment trapped for a given buffer width will be strongly influenced by the proportions of sand, silt, & clay in the runoff water. In first several meters sediment mass removal is driven by vegetation "trapping" larger particles (with infiltration also helping reduce runoff volume). Vegetation with a high stem density (e.g., dense grass) is effective for trapping the coarse sediment load. After the first several meters, removal of the fine particle fraction is driven by infiltration. Buffers that include abundant woody species appear to promote greater infiltration, apparently due to a greater occurrence of larger soil pores created when roots decay.

The data suggest that buffers that can infiltrate ≥80% or more of incoming runoff, can achieve sediment reductions greater than 90%. The data suggest that a high level of sediment removal cannot occur if a buffer cannot infiltrate the majority of the runoff.

This is more likely to occur where runoff volume is high, hillslopes are convex, riparian soils are impermeable, and the buffer slope is steep (e.g., >8%). Where a high level of runoff infiltration in a buffer is unlikely, enhanced upland BMPs are needed to reduce runoff volumes and associated sediment loads that enter the buffer.

Sediment from Stream Bank Erosion

Sediment loading from streambank erosion can be a highly significant source of sediment pollution to streams. This guidance does not address natural streambank erosion; it is also not intended to address channel avulsion or migration, which can occur regardless of the width or stability of a buffer.

Planning for a channel migration zone (CMZ) addresses where a stream channel may relocate to rather than how to minimize bank erosion along the channel using a riparian buffer. In many instances, implementing a buffer that fully encompasses a channel migration zone would require a broader land use change than simply installing a buffer adjacent to existing agricultural lands. Whether a channel has a wide or narrow CMZ, a buffer that is appropriately designed, installed, and maintained will inhibit excessive bank erosion.

In general terms, the erosive potential of a channel increases as the size of the channel increases. The susceptibility of banks to erosion is influenced by complex interrelationships among chemical, physical and biological factors. These factors include:

- Climate: Precipitation patterns; temperature patterns.
- Hydrology: channel discharge; water volume/velocity; water pH, water temperature.
- Valley geomorphology: geology; topography; valley slope; valley width
- Channel characteristics: channel dimensions; channel sinuosity; radius of channel curvature; inside vs. outside of meander bend; bank height; bank angle
- Soils characteristics: soil bulk density; particle size distribution; degree of alluvium consolidation; soil pore pressure; matric suction
- Vegetation: vegetation type and density, rooting depth, root size and density
- Buffer width

Forested riparian buffers are generally the most effective for controlling streambank erosion rates on larger channels. Zaimes (2004), found that forested riparian buffers had the lowest bank erosion rate, followed by grass filters, then rotationally grazed pasture, then row-cropped fields. On small, non-incised channels with low stream power, dense stands of deep-rooted grasses can be highly effective at inhibiting bank erosion.

Densely vegetated, wider buffers are more effective at preventing bank erosion than narrower, sparsely vegetated buffers. Bulk density is a fairly good predictor of stream bank erodibility: as it increases, bank erosion rates tend to decrease (Wyn, 2004). Bulk density is influenced by a variety of factors including: soil texture; degree of compaction; root size and density, amount and size distribution of rock, degree of consolidation of one or more layers of streambank material, etc. (Wyn, 2004). These characteristics cannot be accurately determined without extensive field work and therefore cannot be incorporated this into a buffer recommendation.

Reports of bank erosion rates are uncommon in published literature. The following summarizes the literature findings for this evaluation:

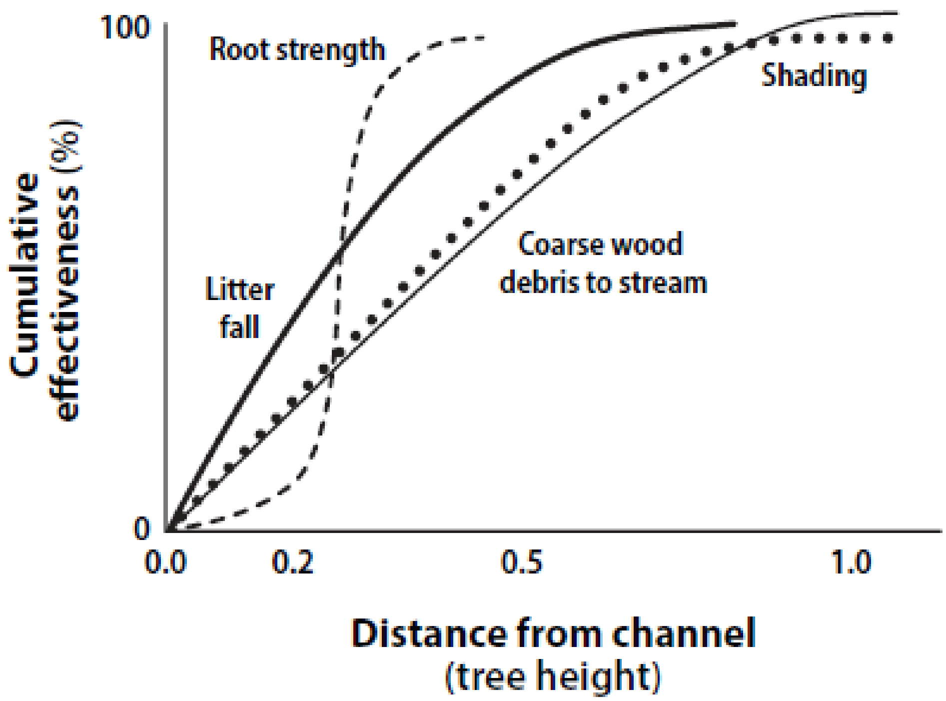
- Zaimes (2019) performed a literature review for streams in Iowa and reported an avg. erosion rate of 8.2cm/yr for forested riparian buffers
- Kuehn (2015) reported erosion rates for channel widths of 28.5 to 70m in Missouri; straight sections and bends had an erosion rate ranging from of 0 to 31cm/yr; the average rate over a 56-year period was 1cm/yr on right bank and 4cm/yr on left bank
- Palmer et al (2014) reported bank erosion rates ranging from 0.6 to 28.2cm/yr (low vs. high flow years with an average of 18.8cm/yr for a 3rd order stream in Iowa whose channel was incised 3m into the valley
- Owen et al. (2011, cited by Kuehn) reported erosion rates in Missouri of 70 to 160cm/yr in unstable reaches and <10cm/yr in stable reaches.
- Martin and Pavlowsky (2011, cited by Kuehn) reported erosion rates in Missouri that averaged 1.0m/yr for outside bend erosion (channel extension) and 2.7m/yr average for up- or downstream shift in a bend (channel translation).
- Zaimes (2004) reported the following bank erosion rates for a second order stream in Iowa: 25 to 52cm/yr for row crops on bank; 18 to 41cm/yr for pasture on bank; 12cm/yr for forested bank.

Overall, bank erosion rates for smaller streams had an average rate ranging from 8.2 to 18.8cm/yr. (Zaimes, 2019, 2004; Palmer et al, 2014). For larger rivers, the rates depended on whether the erosion was occurring along straight sections or meander bends, and whether the reaches were stable or unstable. Erosion on large channels ranged from 70 to 160cm/yr on unstable reaches and <10cm/yr on stable reaches and averaged of 1.0m/yr on outside bends (channel extension) and 2.7m/yr average for up- or downstream shifts in bends (translation) (Kuehn, 2015).

According to Fischer and Fischenich (2000), in some cases bank erosion may be controlled by a buffer spanning only the width of the bank, while wider buffers are needed where active bank erosion is occurring. Their general recommended buffer width for addressing bank erosion is 10 to 20m. The Army Corps of Engineers (1991) suggested that a 5m forested buffer "should" be effective at stabilizing banks over short time spans (e.g., several years). ACOE (1991) cite Whipple et al. (1981) as finding that substantial bank erosion was rare when buffers were ≥15.2m wide, but almost always occurred when buffers were narrower. It was noted that results may not be broadly representative since the streams examined were in highly developed watersheds (with higher erosive potential due to urban runoff) and tended to have narrower buffers. The FEMAT (1999) conceptual curves addressing forested buffer functions suggests that forested riparian buffers equivalent to roughly 1/4 to 1/3 of one site potential tree height is adequate for inhibiting stream bank erosion (see Figure 8 below).

Figure 8: Conceptual models

(FEMAT, 1993) ecosystem functions provided by forested riparian areas vary with distance from a stream channel



Based on this review, Ecology's general recommendation is for the core zone of RMZs along perennial streams with riparian forest potential to be at least 50ft in western Washington and at least 35ft in eastern Washington in order to inhibit sediment loading from bank erosion. This is based on ¼ of site potential tree heights in Washington State as reported by Windrope et al. (2018) and aligns with the FEMAT conceptual curve for root strength. For non-perennial streams or streams without forested potential, a minimum RMZ core zone width of 25 to 35ft) is recommended.

The USDA conservation handbook (2008) recommends that a buffer design width should be the desired width at age of buffer maturity (20yrs is suggested) plus the width of bank erosion estimated to occur until the buffer reaches that age. Ecology agrees with this recommendation and adds that an additional option is to shift the upslope edge of the buffer over time as natural or accelerated bank erosion occurs in order to maintain the buffer width as the channel migrates. Bank stabilization may be needed to allow for the vegetation community to establish (although not a focus of this guidance). The core zone of the RMZ should be vegetated with a native plant community consistent with the ecological site potential, as discussed later in this guidance.

Temperature

Factors that influence the effectiveness of riparian buffers at inhibiting stream temperature increases

Note- This is not intended to be a comprehensive list of the factors that influence temperature in streams, it is focused upon identifying the factors that determine how effective a riparian buffer is at preventing increases in heat loading from direct solar radiation.

The primary factors that influence a buffer's ability to inhibit stream temperature increases include: climate, weather, and solar radiation; geomorphology, topography, and hydrology; vegetation; land use; and buffer size.

Climate, weather, and solar radiation

Climate and weather influence buffer effectiveness in complex interrelated ways. In Washington State, the low amount of summer precipitation means that stream water temperatures are little influenced by precipitation and associated runoff relative to other regions, where warm-season precipitation is more frequent. Air temperatures have a minor effect upon small streams, but the effect increases as stream size increases (Wondzell et al., 2018; Anderson et al., 2007; Sullivan, et al., 1990). Low air humidity promotes evaporation from streams, which increases heat loss, while high air humidity has the opposite effect (Bartholow, 2000). Wind increases evaporation from streams, which increases evaporative cooling; riparian tree removal increases wind speed (Bartholow, 2000). Wind-throw of riparian trees can significantly decrease stream shading (Schuett-Hames et al., 2012; MacDonald et al., 2003; Lynch and Corbett, 1990; Steinblums, 1977; Broderson, 1973). Wetter soils tend to have more wind-throw (Steinblums, 1977). Fire can reduce buffer effectiveness through destruction of vegetation. (Wondzell et al., 2018; Steinblums, 1977). According to Moore et al., 2005, streams are subject to a theoretical equilibrium temperature. At a fixed level of solar radiation, air temperature, humidity, and wind speed there is a water temperature at which no further downstream heating will occur; this theoretical equilibrium temperature is greater under unshaded versus shaded conditions (Moore et al, 2005).

Stream temperatures are strongly influenced by net thermal radiation, and vegetation in riparian buffers affects the amount of net thermal radiation received by a stream (Brown, 1969; Levno, 1967). For example, Moore et al. (2005) stated that peak daytime net radiation for an unshaded reach can be five times greater than under a forest canopy. Direct solar radiation is the largest component of net thermal radiation (Sullivan et al., 1990; Brown and Krygier, 1970). This of course, is why temperature increases are greater on sunny days than on cloudy days as well as why shading from vegetation is a critical mediator of stream temperatures (Hetrick et al., 1998). According to Wondzell et al. (2018), shade appears to influence water temperatures more than air temperature or stream discharge.

The amount of direct solar radiation is affected by the solar angle, which varies by latitude (Dewalle, 2010; DeWalle, 2008). For example, more than 90% of solar radiation is absorbed by water at solar angles greater than 30 degrees, and as the solar angle decreases, the amount of solar radiation reflected off of the stream surface increases (Moore et al., 2005). Other components of net thermal radiation include evaporation, convection, conductions, and longwave radiation. Evaporation and convection appear to play a minor role in net thermal radiation (Brown, 1969). Longwave radiation emitted by terrain can also add heat to streams, but this component is also minor (Moore et al., 2005). Lastly, a minor amount of heat is conducted from channel substrates to the water column and is more important for bedrock channels than for porous gravel bed channels (Brown, 1969).

Geomorphology, hydrology, and topography

Streams at lower elevations tend to be warmer than higher elevation streams, partially due to higher air temperatures and lower relative humidity (Cristea et al., 2007). Topographical shading can be important (either by ridges/hills/mountains, or side slopes when a channel is incised/entrenched into a valley) (Moore, 2007; Moore et al., 2005; Dignan and Bren, 2003). As valley side slopes increase, the distance that shade is cast by trees also increases (Broderson, 1972).

The effectiveness of buffers at inhibiting stream warming is affected by watershed hydrology across multiple different spatial and temporal scales. Buffer effectiveness is influenced by groundwater inflow (Sullivan et al., 1990), whose effects can vary substantially depending upon the position of the stream in the watershed and local influences (Mohseni et al., 1999; Smith, 1972; Hynes, 1970). In the uppermost headwater streams, water temperature is strongly influenced by groundwater temperatures (Mohseni et al., 1999; Smith, 1972; Hynes, 1970). Groundwater temperatures are partially influenced by soil temperatures (Burns et al., 2017; Kurylyk et al., 2015b; Kurylyk et al., 2013; Forster and Smith, 1989), suggesting that shaded soil will transfer less heat to shallow subsurface water than will unshaded soils. Subsurface water beneath dry channels can result in cold-water patches at the confluence with receiving streams (Ebersole et al., 2014). All else being equal, streams with low groundwater input and hyporheic exchange likely need wider buffers to inhibit heating; the effect of subsurface exchange increases as stream discharge decreases (Cristea et al., 2007).

The initial temperature of stream water entering a reach is also important (Li et al., 1994; Pool et al., 2001). For example, if stream water has already warmed above a critical temperature prior to entering a parcel with an adequate buffer, shading may help prevent further warming, but shading itself does not cool water. Cooling the water requires a transfer of heat out of the stream through processes such as conduction, convection, and evaporation, or a transfer of mass into the stream that has a lower heat content (e.g., groundwater inflow that is colder than the stream).

A riparian buffer's thermal effectiveness is influenced by stream discharge, depth, and velocity (Wondzell et al., 2018; Moore et al., 2005; Zwieniecki and Newton, 1999; Sullivan et al., 1990). Small streams have less capacity for heat storage than large rivers (Swift and Messer, 1971; Brown, 1969) and are therefore more sensitive to losses in shade (Moore, 2007; Cristea et al., 2007; Swift and Messer, 1971; Brown and Krygier, 1970). Due to greater flow volumes larger streams have more thermal inertia than smaller streams and therefore require a much larger amount of energy to increase the temperature of the mass of water in a stream reach (Cristea et al., 2007). This is why all else being equal (e.g., not accounting for groundwater inputs), shallower streams heat more quickly than deeper streams (Wondzell et al., 2018; O'Briain et al., 2017; Moore et al., 2005).

At the watershed scale, reductions in vegetation cover tends to result in a more "flashy" hydrograph (Bartholow, 2000), which decreases water storage time in the watershed and makes streams more susceptible to heating. Floods can reduce buffer effectiveness by damaging vegetation and altering channel morphology (Steinblums, 1977). More densely vegetated buffers are more resilient to the damaging forces associated with flood flows. At the reach scale, riparian buffers can contain side channels, alcoves, lateral seeps, and floodplain spring brooks that contribute to cold-water patches in streams (Ebersole et al., 2003). Lastly, beaver ponds can have reach-scale effects upon stream temperatures, e.g. by influencing shading, water surface area, water velocity, etc. (Zwieniecki and Newton, 1999).

Stream geomorphology exerts significant controls on the effectiveness of buffers at preventing thermal pollution. Stream valley morphology (e.g. valley confinement) influences floodplain hydrology (e.g., groundwater storage and movement) and potential riparian vegetation communities, thereby influencing temperature (Nagel et al., 2014). Unconfined valleys tend to develop alluvial aquifers with greater groundwater exchange than confined valleys. Valley and stream gradient can also affect stream heating. Generally, low-gradient streams tend to heat faster than high gradient streams. This is due, in part, to lower flow velocities which results in an increased potential for exposure to shortwave radiation and, importantly, to the relative effect of cold groundwater discharge comprising a greater proportion of the overall flow volume for upper elevation (high gradient) channels in comparison to reaches situated lower in the flow network. However, streams with higher gradients tend to be headwaters streams with shallower mean depths (Cristea et al., 2007) and naturally narrower riparian areas (Moore et al., 2005), which also confers susceptibility to heating.

Channel width and channel orientation together exert a strong influence on potential shading from riparian buffers (Wondzell et al., 2018; DeWalle, 2010; DeWalle, 2008; Cristea et al., 2007; Allen et al., 2001). Stream reaches with increased channel width to depth ratios, a result of elevated catchment erosion rates, will tend to absorb more heat than similar reaches with a lower erosion rates. This is the result of increased exposure to shortwave radiation introduced to a shallower flow depth (Blann and Nerbonne, 2002). Similarly, channel aggradation caused by land-use induced sediment loading can cause channel widening, thereby increasing propensity for warming (Moore et al., 2005). As streams become wider, potential shading and its effectiveness at preventing heating decreases (O'Briain et al., 2017; Cristea and Burges, 2010; Broderson, 1973; Brown and Brazier, 1972). For example, for a north-south or east-west flowing stream at 50^{o}N latitude with 30m tall trees on the bank, blocking 80% or more of direct radiation is limited to channels up to roughly 15m wide (DeWalle, 2008). For wider channels, (and all else being equal), a north-south flowing stream will need a wider buffer than an east-west flowing stream to provide an equivalent level of shading on a given day. For example, for a <u>north-south</u> stream 45m wide with 30m trees on the bank at 50^{o}N latitude, the overall maximum potential shading in a day at the stream centerline is about 50%; for a

25m east-west channel with 30m trees on the bank, the overall maximum potential shading is about 50% at the stream centerline (DeWalle, 2008).

Accordingly, providing shading vegetation along smaller tributary streams is more effective at inhibiting the warming than the same vegetation along a larger receiving stream; this is partly due to wider channels have less potential for shading as well as the greater thermal inertia associated with the mass of water in larger streams (Cristea and Burges, 2010; Swift and Messer, 1971).

Vegetation

Channel shading by vegetation is critical for preventing warm-season temperature increases at the local scale (Shaw, 2018; Moore, 2007; Allen et al., 2001; Bartholow, 2000; Pilgrim et al., 1998; Sullivan et al, 1990). For example, Zwieniecki and Newton (1999) observed a water temperature decrease in a shaded reach downstream of an unshaded reach. Riparian shade typically exerts the primary control over the heating of small to medium sized streams (1st - 3rd order) and is of lesser importance for larger streams (O'Briain et al., 2017).

In order to assess the ability of riparian vegetation to create effective shade over a stream, three characteristics of the "shade" need to be evaluated: (1) **shade quality**; (2) **shade extent**; and (3) **shade duration**. Shade extent is the spatial area over which a shadow is cast over a stream. Shade duration is the length of time during which a portion of stream is shaded. Shade quality is the density of the shade. The removal or modification of trees in riparian areas can affect the spatial extent, duration, and quality of shade on a stream.

The **shade quality** is primarily dependent on two factors: (1) the **path-length** of the sun rays traveling through the riparian stand (i.e., buffer width); and (2) the **canopy density** of trees within the riparian stand the sun passes through (i.e., angular canopy density). In addition, the **height** of the vegetation directly affects these two factors and therefore also affects shade quality.

The **extent and duration of stream shade** associated with riparian vegetation is dependent on: (1) the tree height; and (2) the stream channel width. Ultimately, these attributes determine the time of the day during which riparian vegetation is between the sun and the stream, and thus it determines the time of day which the riparian stand filters the direct beam solar radiation

Shade exerts a stronger effect on temperature *changes* than air temperature or discharge or stream width (Wondzell et al., 2018; Hendrick and Monahan, 2003; Bartholow, 2000). According to Levno (1967), when forest cover over streams is dense, "…changes in water temperature vary primarily with air temperature and convection". Wondzell et al. (2018) asserted that "the effect of restoring shade could result in future stream temperatures that are colder than today, even under a warmer climate with substantially lower late-summer streamflow". Cristea and Burges (2010) also concluded that restoring site potential riparian vegetation along Pacific northwest streams may completely offset projected temperature increases due to climate change. Therefore, the proportion of reach-scale channel length with shading by vegetation is an important consideration in stream thermal protection (Johnson and Wilby, 2015; Cristea et al., 2007; Barton et al, 1985).

Shading can be described in multiple ways. Angular canopy density (ACD) and canopy cover are two common measures of shading (Rex et al., 2012; Dignan and Bren, 2003; Allen et al., 2001; Li et al., 1994; Steinblums et al., 1984; Brazier and Brown, 1973; Brazier and Brown, 1972). ACD describes the density of the vegetation at an angle through the canopy towards the position of the sun in the sky (Brazier and Brown, 1972). The relationship between ACD and buffer width is asymptotic (Brazier and Brown, 1973). Effective shade is another way of describing the amount of shading. Effective shade is one minus the ratio of total below-canopy radiation (direct plus diffuse radiation) to total above-canopy radiation (McIntyre et al., 2018). In other words, it is how much direct plus diffuse solar radiation is intercepted by topographic and vegetation surfaces. Effective shade is significantly and negatively correlated with both riparian vegetation removal and water temperature (McIntyre et al., 2018). McIntyre et al. (2018) found that multiple measures of shade had roughly the same response to vegetation removal treatments (effective shade, canopy closure at 1m above stream, canopy closure at 0m above stream, canopy and topographic density).

The direction a stream is flowing (e.g., east-west vs. north-south) influences the potential amount of shading by vegetation (DeWalle, 2010; DeWalle, 2008; Allen and Dent, 2001; Brown and Brazier, 1972). The Pacific Northwest's mid-latitude proximity (e.g., 30-50ºN), results in buffers on the south side of a stream producing about 70% of the shade, while buffers on the north side produce about 30% (all else being equal) (DeWalle, 2010). For a given vegetation height/density condition, the impact of latitude was shown to be positively correlated stream shade for E-W flowing streams, but this effect largely does not occur for N-S flowing streams (DeWalle, 2008). Cristea et al. (2007) determined that north-south oriented stream channels less than 10m wide receive slightly less shade than streams oriented east-west (e.g., roughly 5%), all else being equal; however, as channel width increases beyond 10m, east-west oriented streams receive progressively less shade than N-S oriented streams (assuming a 120ft buffer, with 80ft red alder and 85% canopy cover).

Vegetation density and height are generally considered to exert a strong influence over stream shading (DeWalle, 2010; DeWalle, 2008; Cristea et al., 2007). Potential shadow length varies with vegetation height (DeWalle, 2010; Dewalle, 2008), and potential vegetation height varies among plant species. Cristea et al. (2007) found that effective shade declines regardless of canopy cover when vegetation height is under 1.4 times bankfull width. Branches that overhang channels cause a significant boost in potential stream shading (Mohamedali, T., 2014). The more that vegetation overhang that occurs along a channel, the less tall the vegetation needs to be to provide an equivalent amount of channel shading (DeWalle, 2010). Allen et al. (2001) found that the cumulative basal area of trees in close proximity to a channel can influence shade. However, timber volume in a buffer is not a good general indicator of shading effectiveness (Brown and Brazier, 1972). However, Groom et al. showed that stream shade was "best predicted by riparian basal area and tree height" (i.e., canopy density (i.e., shade quality) and tree heigh (i.e., shadow length and duration, and indirectly shade quality)) (Groom et al. 2011b). They also showed that stream temperature was most influenced by stream shade.

In addition to the height and density of plants, shading potential varies by vegetation species, due to differences in canopy density (Allen and Dent, 2001; Brazier and Brown, 1973). The relationship between solar radiation blocked by vegetation and buffer width is asymptotic and the rate at which the asymptote is approached depends on vegetation type (Brown and Krygier, 1970). Conifer species tend to have a higher canopy density than deciduous trees species. Shrubs tend to have a denser foliage than trees and therefore a narrower width of shrub canopy can generally provide an equivalent amount of shade as a wider tree canopy (Brown and Brazier, 1972).

Reductions in shade by as little as 6 to 14% have been shown to result in significant increases in maximum daily temperature (e.g., roughly 1.0-2.0^{o}C) in short reaches (e.g. 1000 to 7000ft) of small streams (e.g. <16ft bankfull width) (McIntyre et al., 2018; Guenther et al., 2014; Groom et al., 2011b). Wilkerson et al. (2006) found that a canopy cover reduction of 11% (75-92% canopy closure remaining after partial harvest in 11m buffer) on small streams had a moderate effect (mean longitudinal daily max increase of 1.5^{o}C compared to 0.7^{o}C in control), but was statistically insignificant; however, note that unmeasured groundwater inflow in the reach occurred during this study. In the same study, a canopy cover reduction of roughly 3-4% (82-96% canopy closure remaining after partial harvest of either: a 23m no-cut buffer or 2) no buffer, but selective cutting of riparian trees) on small streams had no observable effect (Wilkerson et al., 2006).

Reductions in shading may not result in a consistent temperature effect throughout a stream network. Moore et al. (2005) asserted that "increased temperatures in one reach due to reduction of riparian shade may reduce the propensity for the stream to warm in downstream reaches, even in the absence of dilution by groundwater or tributary inflow" (i.e., because warming an upstream reach may cause a downstream reach to be closer to its heat equilibrium, as described in the climate and weather section above). Additionally, Zwieniecki and Newton (1999) made the important point that stream temperature will increase in a downstream direction even under fully shaded conditions.

The literature is rife with examples of the complicated ways in which riparian vegetation cover influences stream temperatures. A detailed discussion of this topic is not undertaken in this guidance, although notable examples are listed below:

- Tree cover influences upland, riparian, and instream hydrology across multiple spatial scales (Vadas, 2000; Moore et al., 2005), e.g., through interception of precipitation, evapotranspiration, dampening snowmelt rates, coniferous fog drip, etc.
- Vadas (2000) suggested that unshaded streams may have reduced base flows because of higher evaporation, which exacerbates the vulnerability of streams to heating.
- Riparian vegetation can have a strong influence on the vertical thermal gradient of cold-water patches (Ebersole et al., 2003).
- Evapotranspiration by riparian trees can reduce stream flows (Salemi et al., 2012), and a reduction in stream flow facilitates heating (Wondzell et al., 2018; O'Briain et al., 2017; Moore et al., 2005).

- Evapotranspiration by riparian trees is a source of heat loss to a stream (Zwieniecki and Newton, 1999).
- A reduction in insulating vegetative cover can promote ice formation (anchor and frazil ice) during the wintertime which can have significant negative effects upon aquatic life (Hynes, 1970).
- Vegetation canopies emit longwave radiation that can be absorbed by streams (Moore et al., 2005).
- Riparian vegetation can have a strong influence on channel morphology (e.g., width and depth) (Sweeney et al., 2004). Streams where riparian forest has been removed typically become wider and shallower (Sweeney et al., 2004) via bank erosion. As noted previously, channel widening causes streams to be more susceptible to heating.
- For very small streams (<2.5m width), a dense grass riparian buffer has been determined to result in narrower channels than those situated in forest settings This is likely due to erosive processes that cause channel degradation – narrowing and deepening - with the result being that, for these channels shading may be similar. At widths above 2.5m, tree cover provides more shade, followed by cover from a mixture of grass, shrubs, and forbs (Blann and Nerbonne, 2002).
- The age of vegetation is important since it serves as a surrogate for tree height in Pacific Northwest forests and for this reason is an important determinant in stream shading potential (Kaylor et al., 2017; Teti, 2006).
    - Teti (2006) found that natural shade levels decrease steadily as wetted channel width increases to about 30 m, at which point the seral stage of riparian vegetation may have little effect on average shade on a reach; however, late-seral riparian vegetation tends to ensure consistently high reach average ACD levels on small streams (e.g., bankfull width <7m).
    - Old-growth tree stands often have more canopy gaps between the understory and overstory than do younger forest stands (Cristea et al., 2007).
- Shade from overstory may be more effective at maintaining stream and local air temperatures than shade from understory (Rex et al., 2012). After vegetation removal there may be a substantial lag time (years) in temperature response following vegetation regrowth and shade increases (because the initial shade gains are typically from understory vegetation) (Rex et al., 2012).
- Microclimate in a riparian area is influenced by vegetation density, and the microclimate (air temperature, humidity, air movement/turbulence) can influence heat fluxes particularly for small streams (Klos and Link, 2018; Anderson et al., 2007; Moore et al., 2005; Danehy et al., 2000; Chen et al., 1999; Dong et al, 1998; Brosofske et al., 1997; Brown, 1969).
- Bartholow (2000) asserted that removal of tree cover can cause higher daytime air temperatures and lower nighttime temperatures in the vicinity of the stream. Similarly, Moore et al. (2005) state that under forest canopies, air temperature and wind speed are typically

lower and humidity higher. Changes in air temperatures and humidity have a minor effect upon the heat budget for a stream.

- Riparian trees contribute large wood to streams, whose aggregations influence water temperatures through direct shading, modification of channel morphology and, in some cases, through hydraulic modifications such as increased proximal groundwater retention that discharges during the summer period.

Land Use

Land use influences the effectiveness of riparian buffers at providing thermal protection to streams through its effects upon both upland and riparian vegetation communities. The effects of land use can occur at site, reach, and watershed scales.

It is well established that removal of vegetation from riparian areas at the site scale can lead to substantially increased water temperatures (McIntyre et al., 2018; Guenther et al., 2014; Rex et al., 2012; Groom et al., 2011b; Danehy et al., 2007; Wilkerson et al., 2006; Moore et al., 2005; MacDonald et al., 2003; Young et al, 1999; Holtby et al., 1998; Hetrick et al., 1998; Lynch and Corbett, 1990; Brownlee et al., 1988; Lynch et al., 1985; Brazier and Brown, 1973; Swift and Messer, 1971; Brown and Krygier, 1970). The magnitude of the effect of vegetation removal varies with stream size, because as stream size increases, potential shading decreases (Sullivan et al., 1990).

Grazing and vegetation thinning within riparian areas can significantly reduce stream shading (Teply et al., 2014; MacDonald et al., 2003; Allen et al., 2001), thereby decreasing thermal protection. Blann and Nerbonne (2002) conducted modelling which indicated that grazed buffers would result in higher stream temperatures than successional buffers, and both of these would result in higher temperatures than wooded buffers. During warmer than average years, mean temperature changes (i.e., ^{o}C/km) would double along grazed reaches, whereas successional and wooded buffers would have much lesser change.

Cumulative effects of land use have also been observed at the reach to watershed scale. Vegetation removal can change the microclimate surrounding a stream (Moore et al., 2005). For example, riparian vegetation removal can affect air temperatures and humidity above stream channels (UCD, 1997; Anderson et al., 2007). Vegetation removal can affect channel morphology and stream hydrology (Moore et al., 2005). Bartholow (2000) asserted that BMPs that lead to decreased stream width can have a substantial influence on stream temperatures. Substantial removal of upland vegetation at the sub-watershed scale (e.g., 1-10 km^2 in size) has been associated with significant stream temperature increases (Pollock et al., 2009; Hatten et al., 1995). Multiple studies have found evidence that removal of vegetation from upland areas can result in groundwater temperature increases (Curry, 2002; Kurylyk et al., 2015a; Kurylyk et al., 2015b; Guenther et al., 2014; Steeves, 2004; Alexander et al., 2003; Henriksen et al., 2000; Taniguchi et al., 1998). The effect upon groundwater may differ based on underlying geology (Bladon et al., 2018). The increase in groundwater temperatures after forest removal for agricultural development can be long-term (Taniguchi et al., 1998). Curry (1996) and Kurylyk et al. (2015) assert that where removal of upland vegetation results in increased groundwater temperatures, warmer groundwater can be discharged to streams even if an adequate riparian buffer is in place.

Buffer Width

Buffer width influences buffer effectiveness through its association with stream shading (Sweeney and Newbold, 2014; Groom et al., 2011b; DeWalle, 2010; DeWalle, 2008; Rykken et al., 2007; Cristea et al., 2007; Jones et al., 2006; Wilkerson et al., 2006; Hetrick et al., 1998; Brosofske et al., 1997; Davies and Nelson, 1994; Steinblums et al., 1984; Erman et al., 1977; Steinblums, 1977; Broderson, 1973). Shading increases as buffer width increases (McIntyre et al., 2018; Dignan et al 2003; Broderson, 1973), but approaches an asymptote at a certain distance (DeWalle, 2010; Brown and Brazier, 1972). Light attenuation has been found to be rapid in first 10-30m of a buffer, with gradual declines thereafter (Dignan and Bren, 2003). The effectiveness of a given width buffer depends upon the canopy density, canopy height, stream width, and stream discharge (Brazier and Brown, 1973). Narrow buffers with low canopy are less effective than wider buffers with high canopy (Cristea et al., 2007). DeWalle (2010) concluded that "Increasing buffer width or height tends to cause shifts in the rate of change of stream shading due to complex interactions between stream azimuth and the pathways for direct beam solar radiation through the sides and tops of buffers on both banks". Narrower streams are highly sensitive to buffer width; as stream width increases, the temperature response per unit width of buffer decreases (Cristea et al., 2007).

For small streams, as buffer width increases, solar radiation on a stream decreases exponentially (Brosofske et al., 1997). As buffer width declines, the incremental increases in temperature tend to be greater in smaller streams than in larger streams (Cristea et al., 2007). Buffer width alone is not a good general predictor of effectiveness (Brown and Brazier, 1972).

Quantitative valuation of buffer width effectiveness for thermal protection

A quantitative analysis of temperature response to riparian buffer was performed using data from published literature. Extractable data was identified for 15 studies listed in the annotated bibliography. These data were all associated with forestry studies conducted on streams with channels widths generally less than 5m wide. It was determined that data from six of these studies was not viable for inclusion in the analysis. Some of these studies were excluded because they did not have sufficient rigor (e.g., did not evaluate temperature relative to a control/reference). All except one of the studies in the refined dataset were BACI (before-after-control-impact) studies. The other excluded studies had data that was not comparable; most studies looked at maximum average daily summertime temperature (e.g., excluded data looked at periods longer than just summer or did not have a comparable temperature statistic). The final refined data set was based on: Bisson et al, 2012; Bladon et al, 2016; Bladon et al, 2018; Cupp and Lofgren, 2014; De Groot et al, 2007; Janisch et al, 2012; McIntyre et al, 2018; Wilkerson et al, 2006; Zwieniecki and Newton, 1999. Note that a majority of these studies had some degree of tree thinning within the buffer.

A nonlinear regression was performed on the refined dataset using Minitab® statistical software (Figure 9). The data statistic for this regression was for the **average daily maximum summertime**

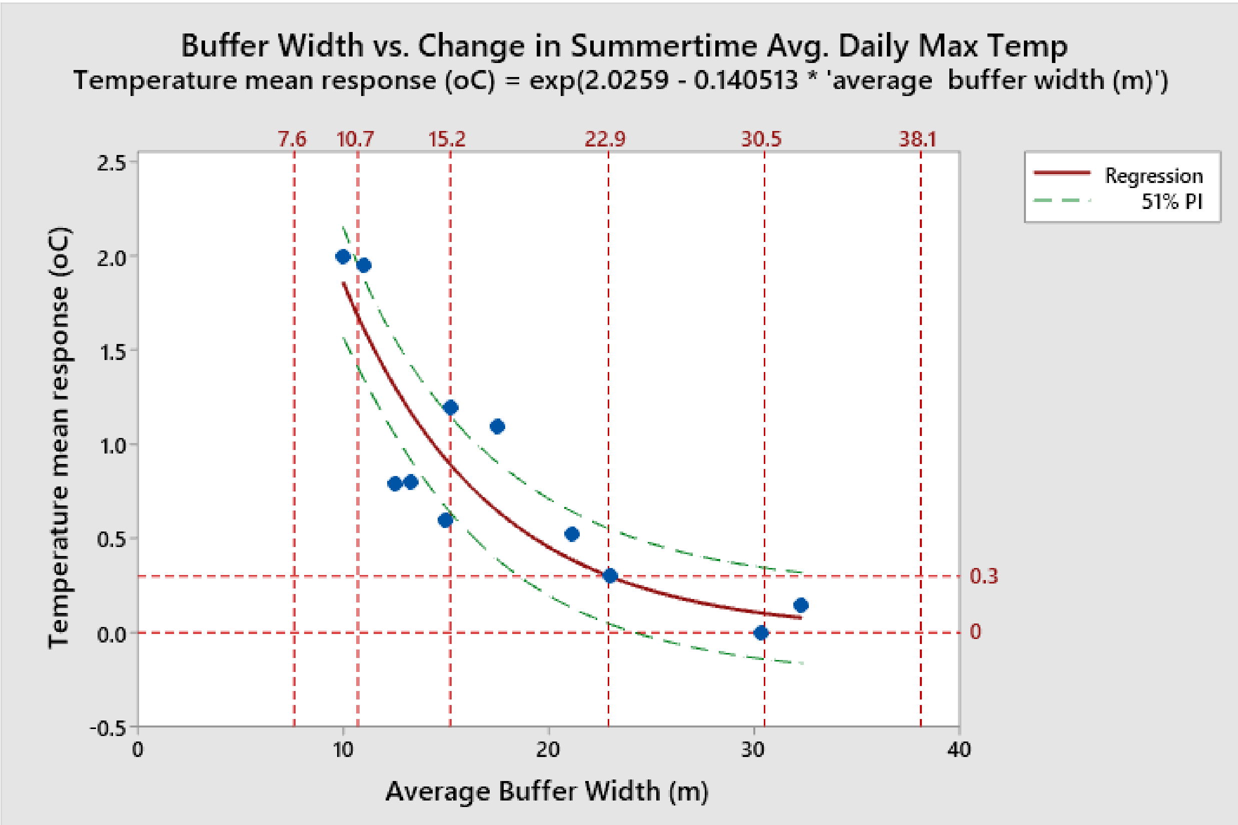
temperature response. In other words, how much of an increase in the daily maximum summertime temperature occurred for varying buffer widths. The regression employed a “generalized linear model with log link” because it was the best fit for the data (as opposed to linear regression - the data follows an exponential function, e.g., as buffer width increases from 0m, there is a rapid initial drop in temperature response, but the response flattens out beyond approx. 23m). Note, for these curvilinear models, the function approaches zero at a buffer width of infinity (i.e., the asymptote is zero, so a T response of zero degrees Celsius is not possible.

Variability in the results is likely due to unexplained/undescribed factors influencing site-specific influences on stream temperature, such as those described previously in this chapter (e.g., related to climate, hydrology, geomorphology, vegetation, etc.). Variability in the temperature response to buffer width were described using a prediction interval. Whereas, a confidence interval is used to estimate the variability of observed results, a prediction interval is used to estimate results for a *new* observation (i.e., what could we expect the temperature response to be if a new trial were performed). The confidence level of the prediction interval was set at 51% due to the high variability in the data. The 51% level of probability is analogous to a preponderance of evidence approach; in other words, it simulates a scenario in which it is “more likely than not” that a new observation would fall within the estimated range. Note that using a higher confidence level for the prediction interval of 95% would expand the lower and upper wider bounds of the estimate (e.g., from 18.6 - 35m at 51% PI to about 14 -90m at 95% PI; 90m would be a very large and questionable extrapolation of the data). A graph of the regression representing the temperature response rates are depicted below.

Two reference lines are included in Figure 9 parallel to the X-axis. One of these is a 0°C response level. The second reference line is set at a temperature response objective of 0.3°C. A temperature response objective of 0.3°C seems more appropriate than a 0.0°C objective because: 1) most of the studies had substantial tree thinning in the buffers, so the observed temperature response may have been less if thinning had not occurred (and it’s not objectively possible to adjust the temperature response to approximate an un-thinned buffer); 2) zero is the asymptote for the best-fit curvilinear regression function (e.g. the function approaches zero at an infinite buffer width) and selecting a different function that would result in negative temperature response beyond some width, which would not make sense; 3) state WQ standards define a measurable temperature change as 0.3°C. Following the graph is a table (Table 28) which provides an average estimated temperature responses and an estimated range in temperature response for select buffer widths.

Figure 9: Estimated temperature increase at differing forested buffer widths on forest lands, following timber harvest.

Based on data from forestry studies on small streams, e.g., <10m wide.



References lines at {7.6, 10.7, 15.2, 22.9, 30.5, 38.1m} correspond to distances of {25, 35, 50, 75, 100, 125ft}, respectively.

Table 26 Estimated temperature response (i.e., change in average daily max temperature during summer) associated with residual forested riparian buffers along streams (<10m in width) during timber harvesting.

Buffer Width (ft)	35	50	75	100	125
Estimated temperature response (°C)	+1.69	+0.90	+0.30	+0.10	+0.04
Estimated range in temperature response (°C)*	+1.42 to +1.96	+0.65 to +1.15	+0.06 to +0.56	-0.13 to +0.35	**

*Based on a 51% prediction interval. **No estimate: buffer width is beyond the range of the prediction interval.

The results suggest that an *un-thinned*, 75ft wide conifer dominated buffer can prevent a measurable increase in summertime average daily maximum stream temperatures on small streams (e.g., <5m wide) within forested watersheds managed primarily for timber harvest. This conclusion is in agreement with the conclusions of Groom et al (2018) and findings of Barnowe-Meyer et al. (2021). Again, note that the majority of the buffers in this analysis included some degree of tree thinning; it is therefore reasonable to expect a smaller temperature response in buffers without tree thinning. However, there are notable differences to consider between riparian buffers on forest lands and buffers on agricultural lands.

Nearly all research examining the effect of buffers on stream shading and temperature comes from forestry studies. Nevertheless, the physics underlying stream shading and thermodynamics of stream temperature are the same on forest lands and agricultural lands. Without studies on agricultural lands, forestry studies provide some of the most relevant information we have in evaluating temperature response to buffers on agricultural lands.

On forest lands buffers are swaths of riparian trees remaining after harvesting adjacent timber, while on many agricultural lands, a buffer often needs to be established by planting young trees. As such, riparian areas in forest lands tend to be dominated by mature trees, while on agricultural lands it often takes decades of growth for trees to reach their height at maturity.

The temperature response to leaving buffers of mature trees on forest lands may differ from what would be observed in response to establishing buffers on agricultural lands. On forest lands, riparian trees have grown with trees adjacent to them resulting in a denser canopy in the upper half of the tree than in the lower half. This can permit greater light penetration through the understory than through the canopy (DeWalle, 2010). In contrast, when establishing a new buffer on agricultural lands, vegetation could potentially have a more uniform density from the ground to the tops of trees. Because there aren't adjacent upland trees casting shade upon the riparian area, the riparian understory on agricultural lands tends to have a higher leaf density.

Other differences between forest and agricultural lands include: forest lands in WA tend to have steeper slopes, more annual precipitation, shallower soils, and cooler air temperatures. Furthermore, for western Washington in particular, the majority of agricultural lands adjacent to buffers were historically forested, yet are now maintained in non-forested vegetation condition, whereas harvested forestlands are revegetated within several years following harvest. This distinction is important because each buffer type results in differences in evapotranspiration processes, infiltration and percolation of precipitation into soils, and soil and shallow groundwater temperatures.

Given the differences between forestland and agricultural buffers, it may not be appropriate to conclude that the temperature response from a given buffer width will be equivalent. In addition to differences described previously, the estimates above do not account for boundary conditions. These conditions would include the stream discharge, temperature, gradient, etc. entering an agricultural parcel.

Additional quantitative evaluation based on system potential shade modelling

The second quantitative approach to addressing buffer width needed to provide thermal protection via stream shading utilized results from Ecology's *Shade.xls* model (See Mohamedali, T, 2014). This model estimates potential effective stream shading but does not address whether the potential shade will actually prevent temperature changes. The primary input variables for the model include channel orientation (e.g., north-south vs. east-west); channel width; height of dominant vegetation; vegetation canopy density; length of branches overhang the channel; width of near shore disturbance zone (e.g., dry gravel and point bars during low flows); day of the year. Based on these input variables, one can estimate how much potential shade is available to be cast on a stream at a given site. The effectiveness objective for this evaluation was set at providing 95% of system potential shade. This objective aligns with the conclusions of Barnowe-Meyer, S. et al. (2021) which found that maintaining stream shade levels of at least 93% of system potential shade is associated with no measurable increase in water temperature.

Tables 29, 30, 31, 32) show the estimated buffer widths needed to provide 95% of system potential shade for streams of varying widths that are oriented east-west or north-south in eastern or western Washington. Following the tables are important notes on the model parameter settings. Overall, the model parameter settings that were applied in this evaluation seem more likely than not to result in a conservative estimate for the width of buffers (dominated by mature conifer trees) needed to provide 95% of system potential shade.

For the smallest headwater streams (e.g., <5ft wide), the buffer widths needed to achieve 95% system potential shade are likely overestimated in the tables below. This is due to the strong effect that overhanging branches have on these streams, a factor which was not accounted for in the estimates below. According to Mohamedali (2014):

> "Overhang increases the amount of shade received by the stream. Narrow streams are more sensitive to the addition of overhang since a larger proportion of the stream surface receives direct shading from overhang. For example, 4.5 m of overhang on each side of a 10 m wide stream will cover most of the stream if there is no NSDZ. On average, including overhang in a typical westside stream increases the effective shade by 27% across all combinations of wetted widths and buffer widths."

Estimated buffer widths needed to provide full system potential effective shade for differing channel widths and channel orientations, based on modelled system potential effective shade

Table 27: Eastern WA Stream with forested buffer potential: East-West Channel Orientation[1].

Bankfull Channel Width (m)	Bankfull Channel Width (ft)	100% system potential shade (%)	95% System Potential Effective Shade (%)	Estimated Buffer Width for 95% System Potential Shade (ft)
<5	<16	74	70	39
5	16	74	70	40
10	33	72	69	40
15	49	71	67	40
20	66	69	65	41
25	82	67	63	51
30	98	64	60	66
40	131	52	50	77
50	164	43	41	77
60	197	37	35	77
70	230	32	31	77
80	262	29	27	77
90	295	26	25	77
100	328	24	22	77

Table 28: Eastern WA Stream with forested buffer potential: North-South Channel Orientation[1].

Bankfull Channel Width (m)	Bankfull Channel Width (ft)	100% system potential shade (%)	95% System Potential shade (%)	Estimated Buffer Width for 95% System Potential Shade (ft)
<5	<16	74	70	62
5	16	73	69	62
10	33	70	66	63
15	49	68	64	63
20	66	65	62	64
25	82	63	60	64
30	98	60	57	67
40	131	56	53	75
50	164	52	49	81
60	197	48	46	90
70	230	45	42	97
80	262	42	39	104
90	295	39	37	109
100	328	36	34	113

[1]Based on Figures in Ecology (2014). Buffer width estimates are rounded to the nearest ft. Assumptions applied in the Ecology Shade Model for Eastside Streams: Simulation Day of August 1st; average height of dominant vegetation is 30m; canopy density of 75%; no branches overhanging channel; no near shore disturbance zone; no topographic shading; riparian area is the same elevation as the stream water surface; no clouds in the sky.

Table 29: Western WA Stream with forested buffer potential: East-West Channel Orientation[2].

Bankfull Channel Width (m)	Bankfull Channel Width (ft)	100% system potential shade (%)	95% system Potential shade (%)	Buffer Width for 95% System Potential Shade (ft)
<5	<16	84	80	54
5	16	84	80	54
10	33	82	78	54
15	49	81	77	54
20	66	80	76	55
25	82	78	74	59
30	98	76	72	73
40	131	70	67	104
50	164	59	56	108
60	197	51	48	108
70	230	44	42	108
80	262	39	37	108
90	295	36	34	108
100	328	32	31	108

Table 30: Western WA Stream with forested buffer potential: North-South Channel Orientation[2].

Bankfull Channel Width (m)	Bankfull Channel Width (ft)	100% system potential shade	95% system Potential shade (%)	Buffer Width for 95% System Potential Shade (ft)
<5	<16	84	79	86
5	16	83	79	87
10	33	80	76	87
15	49	78	74	88
20	66	76	72	89
25	82	74	70	90
30	98	71	68	92
40	131	67	64	98
50	164	63	60	108
60	197	59	56	114
70	230	55	53	119
80	262	52	49	123
90	295	48	46	125
100	328	45	43	127

[2]Based on Figures in Ecology (2014). Buffer width estimates are rounded to the nearest ft. Assumptions applied in the Ecology Shade Model for Eastside Streams: Simulation Day of August 1st; average height of dominant vegetation is 45m; canopy density of 85%; no branches overhanging channel; no near shore disturbance zone; no topographic shading; riparian area is the same elevation as the stream water surface; no clouds in the sky.

Large Wood

Large wood derived from riparian forests is important for maintaining aquatic habitat (Quinn et al, 2020) and can be important for maintaining water quality. Large wood influences pool formation (Shaw, 2018; Hemstrom in Gresswell et al., 1989) and provides localized shade (Poole and Berman, 2001; Steinblums, 1977). Large wood can also influence stream temperature by promoting hyporheic exchange (Cristea et al., 2007). Young et al. (1999) found that riparian forest harvest that included removal of large wood and debris from a stream channel and hillslopes was associated with a much greater water temperature increase than harvest without removal of large wood and logging debris.

The dominant processes for large wood recruitment are stream bank erosion, windthrow, and landslides (Quinn et al, 2020), although recruitment from landslides is probably of minor occurrence on riparian areas located in agricultural lands. The proportion of recruitment from bank erosion likely increases as stream size increase (Quinn et al, 2020). In western WA the prevailing storm (and storm related wind) direction is from the south and southwest. Grizzel et al (2000) found evidence that in WA state, trees in buffers perpendicular to damaging winds (east-west oriented buffers) had greater chance of toppling than trees in buffers oriented north-south. The authors also asserted that windthrow vulnerability varies by tree species. For example, they noted that Big Leaf maple is deep rooted and has low susceptibility to windthrow, whereas Douglas fir has a higher vulnerability to windthrow because it is not deep rooted.

Schuett-Hames, D. and Stewart, G. (2019) evaluated wind-caused tree mortality in 50ft buffers on timber lands. They found substantial levels of windthrow in riparian buffers following timber harvest. Vulnerable trees tended to topple in the first 5 years after clearcutting outside the buffer and wind mortality rates declined substantially by year 10. The difference between timberlands and agricultural lands is that on timberlands there is a sudden removal of outlying trees that leaves standing mature trees more prone to windthrow. This is not commonly the case on agricultural lands when riparian buffers have been established and wind hardened. Therefore, it may be that the trees established in riparian buffers on agricultural lands will have greater wind-firmness than observed in forestry studies of riparian buffers. An implication of this dynamic is that wood grown in riparian areas that are planted today with trees will likely take decades, perhaps centuries, before being recruiting into streams.

Research on the width of riparian buffers needed to provide enough large wood to support aquatic ecosystem functioning is relatively sparse and evolving. The table below shows research findings for the amount of large wood recruited from differing types of forest stands and differing distances from stream channels. Most of the data are from the Coast and Cascade Mountain ranges in CA, OR, and WA. In general, the distance from the channel form which wood is recruited increases as the height of trees increases. Additionally, hardwood stands appear to have much higher level of recruitment from distances closer to the stream channel in comparison to conifer stands.

Given the generally smaller tree heights in eastern WA, it could be expected that the source-distances for wood recruitment would be less than that of western WA, e.g., 90% of wood recruitment would occur from distances from the channel that are significantly less than what occurs in western WA.

Table 31: Results of research on large wood delivery to streams

Percent Recruitment	Distance of wood source m (ft.)	Forest Type	Metric	Other	Location	Author
90%	63 m (206.7 ft.)	Old Growth Conifer	Volume	Alluvial channels	SW OR	May and Gresswell (2003, *published*)
90%	55 m (180.4 ft.)	Old Growth Conifer	Volume	Colluvial channels	SW OR	May and Gresswell (2003, *published*)
90%	30 m (98.4 ft.)	Mixed Ages and Species	Volume	Managed coastal forests with 22% landslide. modeled	NW CA	Benda and Bigelow (2014, *published*)
90%	16.5-38.9 m (54-127.5 ft.)	Mixed Ages and Species	Volume	Meta-analysis - Range converted to 150ft height	Pacific NW	Johnstone et al. (2007, *unpublished B.C. Min.of the Env.*)
90%	15-35 m (49.2-114.8 ft.)	Mixed Ages and Species	Volume	Less managed with 0-18% landslide recruitment. modeled	NW CA	Benda and Bigelow (2014, *published*)
85%	35 m (114.8 ft.).	164 ft. Conifer	Trees	Uniform stand of conifer - Modeled	OR Cascade	VanSickle and Gregory (1990, *published*)
85%	30 m (98.4 ft.)	Old Growth Conifer	Pieces		W. WA & OR	**McDade et al. (1990, published)**

Percent Recruit ment	Distance of wood source m (ft.)	Forest Type	Metric	Other	Location	Author
85%	24.9-28 m (82-91.9 ft.)	150-170 yr. old Conifer	Pieces	RAIS model no-cut buffer	NW OR	Spies et al. (2013, *unpublished USFS and NOAA science report*)
70%	20 m (65.6 ft.)	Old Growth Conifer	Pieces		W. WA & OR	**McDade et al. (1990, published)**
50%	20 m (65.6 ft.),	Mature Conifer	Pieces	Within riparian buffers	NW WA & OR.	**Grizzel et al. (2000, unpublished TFW cooperative mon. report)**
58%	18.3 m (60 ft.)	150-170 yr. old Conifer	Pieces	RAIS Model - 250 ft. Thinned to 55 TPA, 60 ft. no-cut	NW OR	Spies et al. (2013, *unpublished USFS and NOAA science report*)
50%	10 m (32.8 ft.)	Old Growth Conifer	Pieces		OR & W. WA	**McDade et al. (1990, published)**
28%	9.1 m (30 ft.)	150-170 yr. old Conifer	Pieces	RAIS Model - 250 ft. Thinned to 55 TPA, 30 ft. no-cut	NW OR	Spies et al. (2013, *unpublished USFS and NOAA science report*)
50%	3 m (10 ft.)	Mature Conifer	Pieces	All study reaches	NW WA	**McKinely (1997, unpublished senior research paper)**
85%	23 m (75.5 ft.)	Mature Conifer	Pieces		W. WA & OR	**McDade et al. (1990, published)**
*90%	18 m (59 ft.)	Mature and Old Growth	Pieces	*90% of sites, median height	Cent. & S. B.C.	**Johnston et al. (2011, published)**

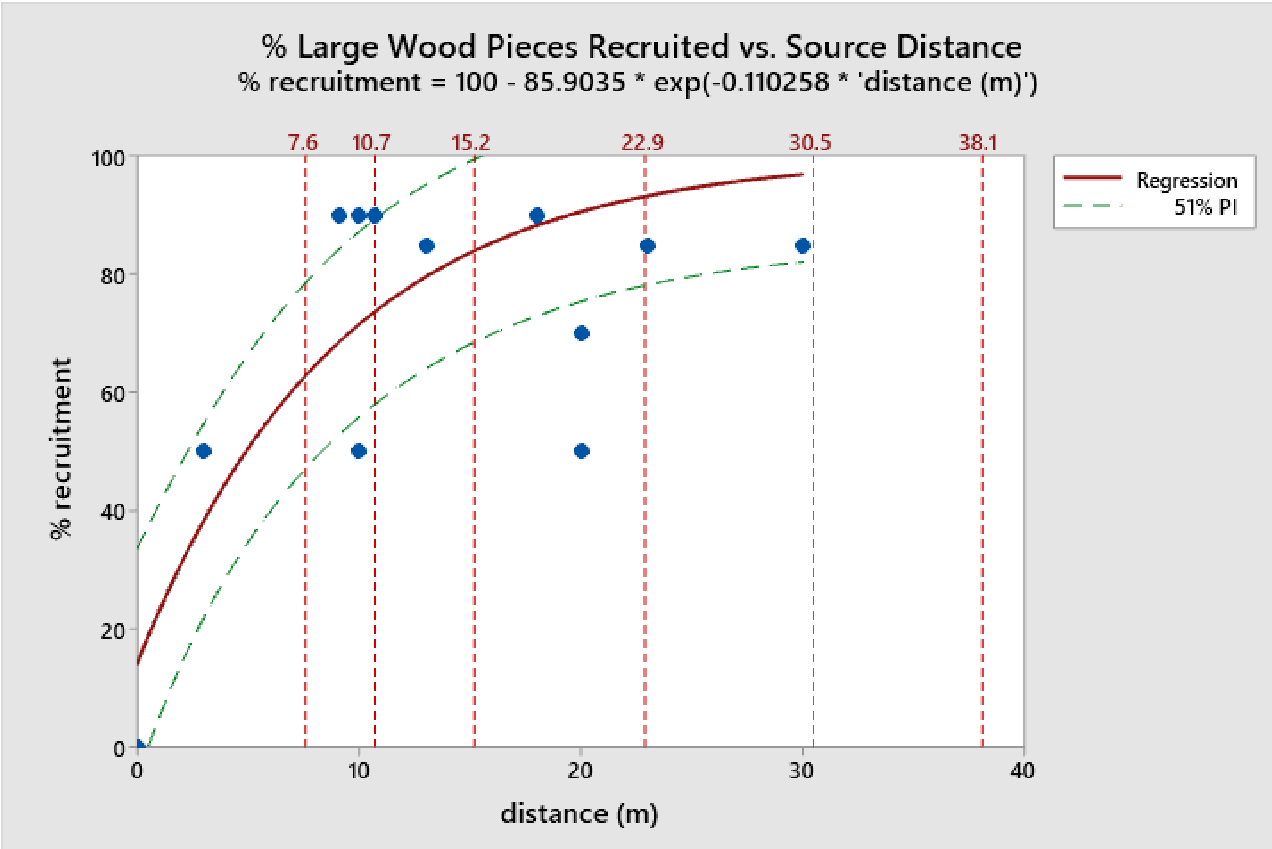
Percent Recruit ment	Distance of wood source m (ft.)	Forest Type	Metric	Other	Location	Author
				approx. 90 ft.		
82-85%	15 m (49.2 ft.)	Young Douglas fir	Volume	Stands thinned twice - 81 tpa then 34 tpa	W. OR	Burton et al. (2016, *published*)
90%	10.7 m (35 ft.)	Mature Conifer	Pieces	Mainstem excluded channel cutting	NW WA	**McKinely (1997, unpublished senior research paper)**
90%	9.1 m (30 ft.)	Mature Conifer	Pieces	Tributaries	NW WA	**McKinely (1997, unpublished senior research paper)**
85%	13 m (42.6 ft.)	Alder	Pieces	Sites dominated by Alder	W. WA & OR	**McDade et al. (1990, published)**
85%	18 m (59 ft.)	Model Scenario	Whole trees	73% hardwoods , and 27% conifers of mixed heights	OR Cascade	VanSickle and Gregory (1990, *published*)
90%	10 m (32.8 ft.)	Calif. Bay, Willow, Alder	Pieces	96.2% hardwoods (bay, willow, alder), 34% erosion	Central CA	**Opperman (2002, B.S. dissertation)**

Wood recruitment quantitative evaluation:

Eleven studies containing empirical data on large wood recruitment were reviewed. The data from of six these studies was found to be inappropriate for regression analysis either because it was based on modeled results, meta- analysis or because the data was incomparable (i.e., most of the empirical data was for large wood pieces, but some data was for wood volume or whole trees). There was insufficient empirical data on wood volume recruitment to conduct a separate analysis. The remaining dataset included data for wood pieces recruited from old growth, mature conifer, and hardwood stands in Cascade and Coast mountain ranges in WA, OR, and CA.

An asymptotic nonlinear regression using Minitab® software (from Grizzel et al, 2000; Johnston et al, 2011; McDade et al, 1990; McKinely, 1997; Opperman, 2002) was performed on data for % of wood recruited versus distance from the channel that the wood came from (Figure XXX). Note that a fictitious 0,0 point was included in the regression in order to force the curve towards the origin since wood pieces generally cannot be recruited from a negative distance from the channel edge (i.e., within the active channel). As discussed in the evaluation of pollutant parameters, a 51% prediction interval was applied in order to help describe variability in the regression. Table YYY provides estimates of large wood recruitment for select buffer widths, based on the regression equation.

Figure 10: Graph of % large wood piece recruitment vs. source distance for results in Table 34.



References lines at {7.6, 10.7, 15.2, 22.9, 30.5, 38.1m} correspond to distances of {25, 35, 50, 75, 100, 125ft}, respectively.

Table 32: Estimated recruitment of wood pieces by source distance based on the regression in above figure.[1]

Distance (ft)	25	35	50	75	100	125	150
% Pieces Recruited	62.9	73.5	84.0	93.1	97.0	98.7	99.5
Range, % Pieces Recruited*	47 - 79	58 - 90	69 - 100	78 - 100	82 - 100	**	**

[1]Based on a 51% prediction interval in Figure XXX.
** No estimate- this distance is beyond the range of the prediction interval.

The only relevant benchmark that was located is the resource objective in Washington State's 1999 Forest and Fish Report for instream large wood for streams in western Washington: "85%

of recruitment potential for a stand on the trajectory toward [desired future conditions]; additional recruitment from trees in the outer zone." Based on this, a reasonable objective for forested buffer effectiveness at providing large wood to streams is a buffer width that would provide at least 90% of potential wood recruitment relative to a fully forested riparian area. Based on the equation in Figure XXX, this would equate to a forested buffer width of roughly 19.5m (64ft). Note that this estimate is most relevant for streams of western Washington and that it seems likely that the effective buffer width would be lower for streams of eastern Washington which generally have a smaller riparian tree.

In many cases it will take an extended period of time to grow the trees that will contribute future large wood to streams. Additionally, there may be some situations where additional large wood is needed to meet objectives at a given site. In those cases, Ecology supports restoration projects that supplement large wood in streams.

Microclimate

Microclimates are created by the mutual influences (i.e., positive feedback loops) of the aquatic ecosystem and adjacent riparian ecosystem upon solar radiation, air temperature, wind speed, humidity, soil moisture, and soil temperature. The following summarizes some of the relevant literature regarding the effectiveness of riparian buffers at protecting stream/riparian microclimate. All of the literature was associated with evaluating the effects of timber harvest on stream and microclimates in forestlands.

Rykken et al. (2007) measured the magnitude and extent of microclimatic gradients associated with headwater streams in mature unmanaged forests in western Oregon and determined whether these patterns were maintained in clearcut harvested units with and without a 30-m (98.4 ft.) wide riparian buffer on each side of the stream. Streams had a strong effect on afternoon air temperature and relative humidity to a distance of 10m from the channel. The results indicated that a 30m buffer was ample for protecting the riparian microclimate gradient.

Anderson, P.D., et al (2007) studied the effect of timber harvesting on headwater stream and riparian microclimate in the Coast and western Cascade Mountain ranges of Oregon. The width of the unharvested buffer strips adjacent to the stream channel averaged either 69 m (226.4 ft., one site potential tree height, 22 m (54.3 ft, variable width), or 9 m (29.5 ft.) as measured from stream center. They found that microclimate gradients were strongest within 10 m (32.8 ft.) of stream center, and with thinning adjacent to 15m (49.2 ft.) or greater no-cut buffers, daily maximum air temperature above stream center was less than 1°C greater (statistically insignificant) and daily minimum relative humidity was less than 5% lower than for un-thinned stands. They cites Danehy and Kirpes (2000) as finding that humidity gradients on the more xeric eastern slope of the Cascades were changed the most within 5m of the stream, which was half that in this study. The authors suggested that "buffers of widths defined by the transition from riparian to upland vegetation or significant topographic slope breaks appear sufficient to mitigate the impacts of upslope thinning on the microclimate above the stream; there was no apparent increase in mitigation associated with wider buffers."

Brosofske, K. et al (1997) evaluated effects the effects of harvesting upon the microclimate of stream buffers in western Washington. The streams ranged in width from 2 to 4 meters and the riparian buffers ranged in width from 17 to 72 meters. Before harvest, surface temperature and humidity showed a gradient from near-stream conditions to interior forest conditions within 31 to 62 meters of the stream, air and soil temperature had a gradient length of 31 to 47m; after harvest, the temperature gradient increased and the humidity gradient decreased from near-stream into the harvested area. Stations in the buffer showed shifts towards the clear-cut values. Both pre and post-harvest, there were strong correlations between stream temperature and soil temperature 60m beyond the buffer edge. Solar radiation at the stream increased exponentially with decreasing buffer width. The authors concluded that a buffer of 45m or wider (possibly up to 300m) is needed to maintain the natural riparian microclimate against changes induced by forest canopy removal.

Based on his prior works and that of Brosofske et al. (1997), Chen et al. (1999) concluded that timber harvesting near the stream results in overall changes in microclimate at the stream, even when buffers are wide (i.e., up to 74 m) and that standardized values show that harvesting at 17 m (42. ft.) or more from the stream results in an increase in air temperature of 2-4^{o}C and a decrease in relative humidity of 2.5-13.8% at the stream. They also argue that the altered microclimate associated with the opening of canopies in riparian zones may result in modification of climate and landscape processes at the coarser scale of the drainage basin. For example, they suggest that increased air temperatures in the riparian zone may alter the channeling of air masses through river corridors.

According to the U.S. Forest Service and Bureau of Land Management (2012), microclimate gradients tend to be strongest within roughly 50ft of a stream. Headwater streams tend to have less diurnal variability in temperatures than streams downstream and have a cooler microclimate because they tend to be at higher elevations. Headwater streams in forested areas may therefore be more vulnerable to changes in microclimate than larger, lower elevation streams. There is evidence that for buffers in old-growth Douglas fir stands, air temperatures for thinned stands with variable width buffers were similar to intact old growth stands within 30m of the stream. The same has been found for buffers with a width equal to one-site potential tree height- within 30m of the stream, air temperatures were similar to intact stands. For the one-site potential tree height buffers, air temperatures increased with distance from the stream if the buffer was adjacent to patch cuts but did not increase if adjacent to thinned stands.

The agencies concluded that:

> For the purposes of employing the Strategy for forest treatments in Riparian Reserves, research indicates that the following microclimate elements are of relevance: 1) microclimate gradients over streams are the strongest and diminish rapidly moving upslope; especially when a 15m retention buffer is applied, 2) near-stream microclimate appears to be topographically controlled, and therefore considerations should be made for buffer widths utilizing slope breaks, 3) thinning beyond 15m is does not measurably affect microclimate, 4) stream thin-through treatments may have slight microclimate effects, 5) small patch openings greater than 15m from streams affects microclimate moderately, 6) where regeneration harvest is planned at the boundary of Riparian Reserves; edge effects may extend up to 15m into the buffer with subtle effects on microclimate gradients."

According to WDFW (Quinn et al, 2020):

> It is our belief that the effects of microclimate conditions on the thermal regime of streams with fully functioning riparian ecosystems are minor for two reasons: 1) microclimate (e.g., temp and humidity) rarely extend farther than one tree height into mature riparian forest (Moore et al. 2005; Rykken et al. 2007; Reeves at al. 2018), and 2) sensible heat exchanges comprise only a small portion of total heat flux in streams (Johnson 2004; Moore et al. 2005). In fact, net solar radiation effects on stream temperatures are generally about an order of magnitude greater than sensible and latent heat exchanges at the air-water interface (Moore et al. 2005; D. Caissie, Fisheries and Oceans Canada, personal communication). However, we also agree with Reeves et al. (2018), who note that the range of effects measured in different studies suggests substantial uncertainties regarding riparian ecosystem management with respect to microclimate.

In summary, it appears that a riparian buffer width of at least 50ft will provide a reasonable level of stream and riparian microclimate protection for small to medium sized streams on agricultural lands since the microclimate gradient tends to be most prominent within 50ft of a stream. The literature suggests, however, that for very small headwater streams, microclimate may be best protected by extending the riparian buffer out to the edge of the topographic break on either side of the stream. No microclimate research for larger streams (e.g. >30ft wide) was located; it may be that larger streams require a wider riparian buffer to maintain microclimate.

Site-Potential Tree Height Histograms by County

Introduction

The following graphs show the distribution of 200-year Site-Potential Tree Heights (SPTHs) for riparian areas in each county (except Benton and Franklin Counties).

The graphs were created by intersecting soil-type polygons from the Natural Resources Conservation Service (NRCS) with rivers and streams in the National Hydrography Dataset (NHD). For the tree species most likely to grow at a site, NRCS provides a site index value based on the most appropriate site index curves (e.g., King (1966) for west side Douglas-fir). A site index value is the tree height attained at the index's base age, typically either 50 or 100 years. We extrapolated tree heights from the base age to 200 years using the appropriate site index equation (Table A2-1). If a soil-type polygon contained site index values for more than one tree species, then we used the species that is expected to grow taller. In the graphs below, "no data" indicates that the soil-type polygon did not provide a site index value. This generally occurs where ecological site conditions are unsuitable for trees (e.g., arid sub-regions of the Columbia Plateau), or where current and expected future land use was judged by NRCS to never allow trees to become established (e.g., intensive agriculture). Federal and tribal lands are not covered by the standard NRCS soils data.

Means, medians, and quartiles of SPTH were calculated using stream miles. Stream miles roughly correspond to the amount of riparian area in a county. The mean 200-year SPTH of a county, for instance, was calculated as a stream-length weighted mean. The median represents the 200-year SPTH that is greater than the SPTHs along half the stream miles in a county and less than the SPTHs along the other half of stream miles.

Table 33: West Site index curves used in calculations of 200-year Site-Potential Tree Heights**.**

Tree Species	Site Index Curve
Douglas-fir	King (1966)
Western Hemlock	Wiley (1978)
Western Red Cedar	Kurucz (1978)
Red Alder	Worthington (1960)

Table 34: East Site index curves used in calculations of 200-year Site-Potential Tree Heights.

Tree Species	Site Index Curve
Douglas-fir	Cochran (1979a)
Rocky Mountain Douglas-fir	Monserud (1985)
Western Hemlock	Barnes (1962)
Ponderosa Pine	Meyer (1961)
Western Larch	Schmitt et al. (1976)
Grand Fir	Cochran (1979b)
Western White Pine	Haig (1932)
Engelmann Spruce	Alexander (1967a)
Lodgepole Pine	Alexander (1967b)
Black Cottonwood	BCFS (1977)

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Wiley, K.N., 1978. Site index tables for western hemlock in the Pacific Northwest. Weyerhaeuser Forestry Paper 17. Western Forestry Research Center, Weyerhaeuser Company, Centralia, Washington.

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WA Counties 3rd Quartile Measurements

Figure 11: Asotin County stream length-weighted 3rd quartile of 200-year SPTH: 115 ft

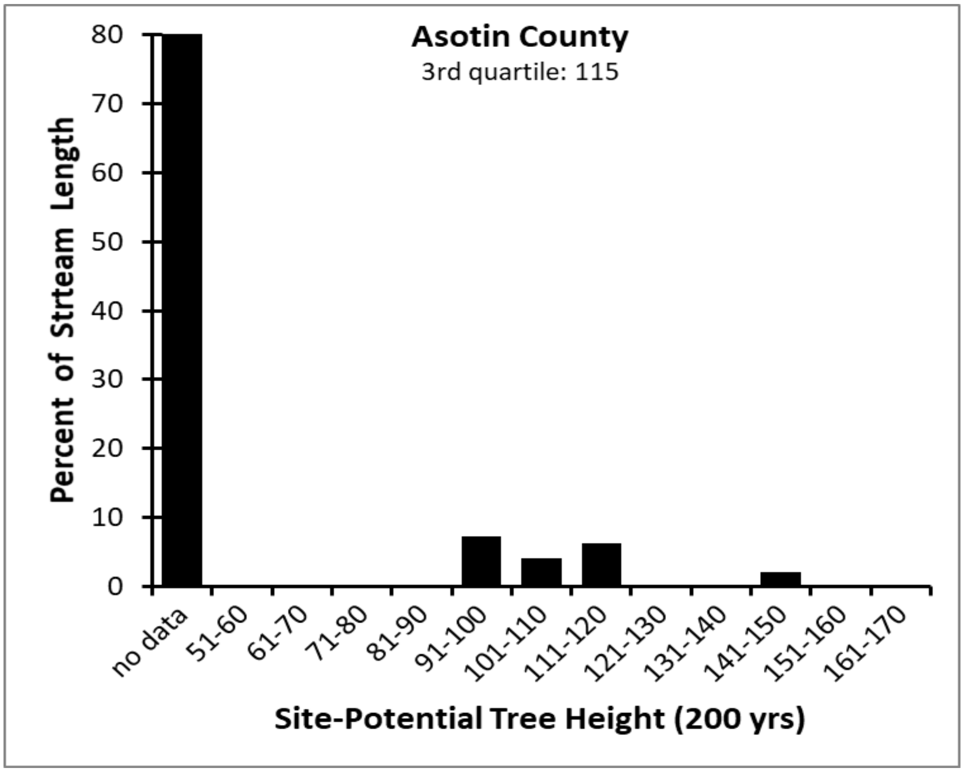


Figure 12: Chelan County stream length weighted 3rd quartile of 200-year SPTH: 160 ft

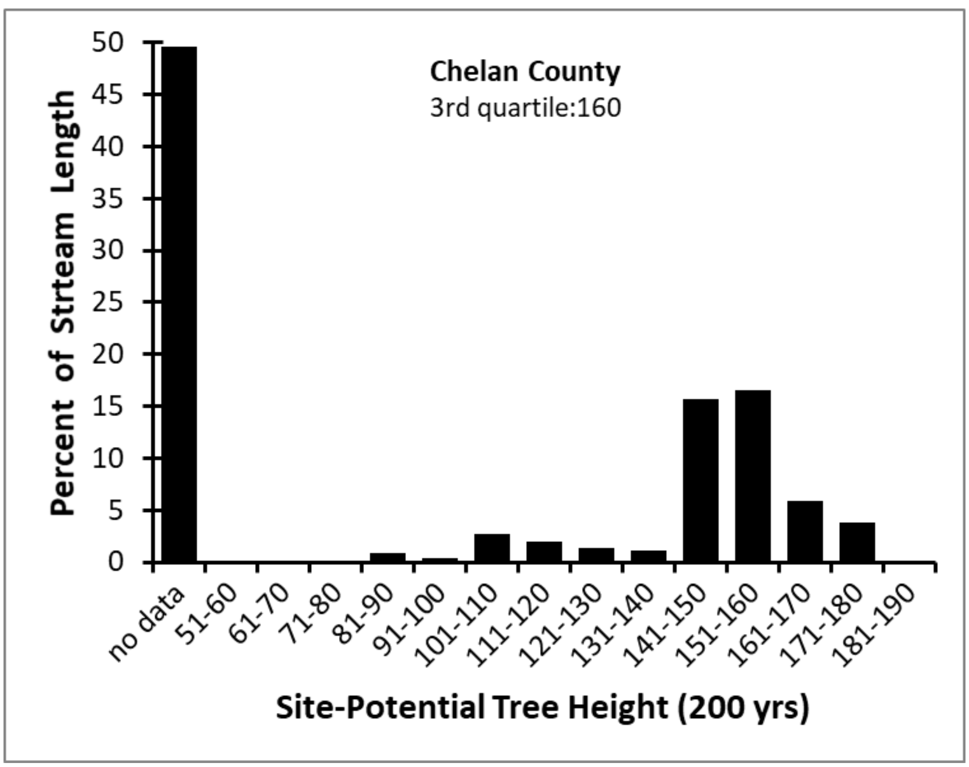


Figure 14: Clark County stream length weighted 3rd quartile of 200-year SPTH: 235 ft

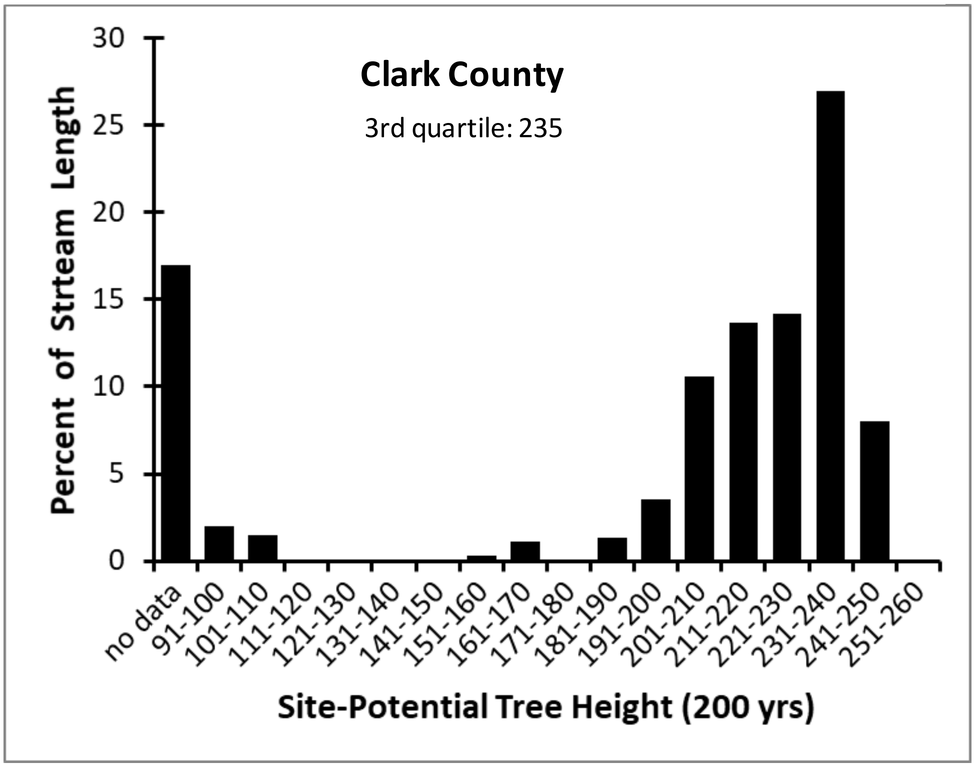


Figure 13: Clallam County stream length weighted 3rd quartile of 200-year SPTH: 137 ft

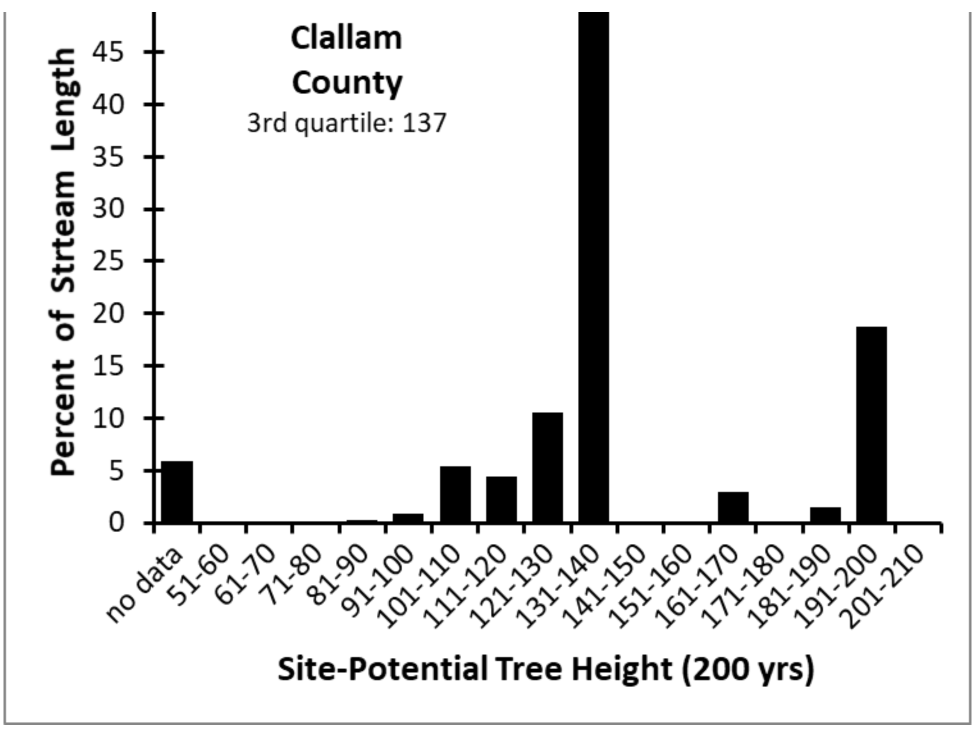


Figure 15: Columbia County stream length-weighted 3rd quartile of 200-year SPTH: 169 ft

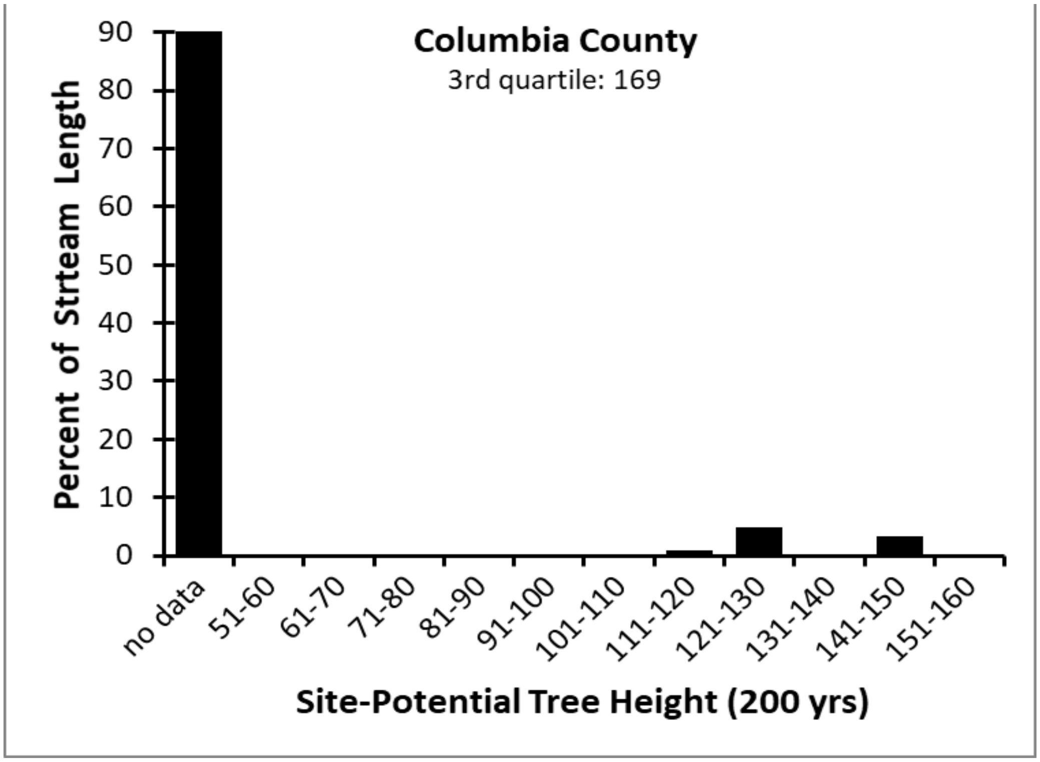


Figure16: Cowlitz County stream length-weighted 3rd quartile of 200-year SPTH: 235 ft

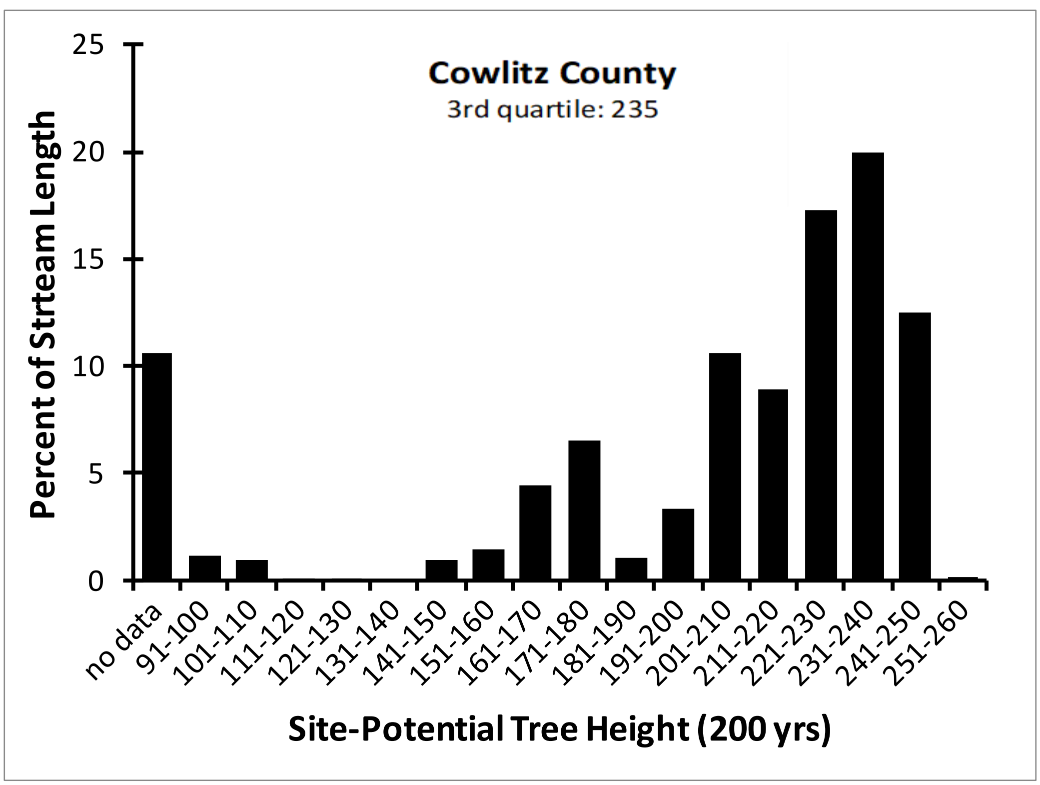


Figure17: Douglas County stream length-weighted 3rd quartile of 200-year SPTH: 126 ft

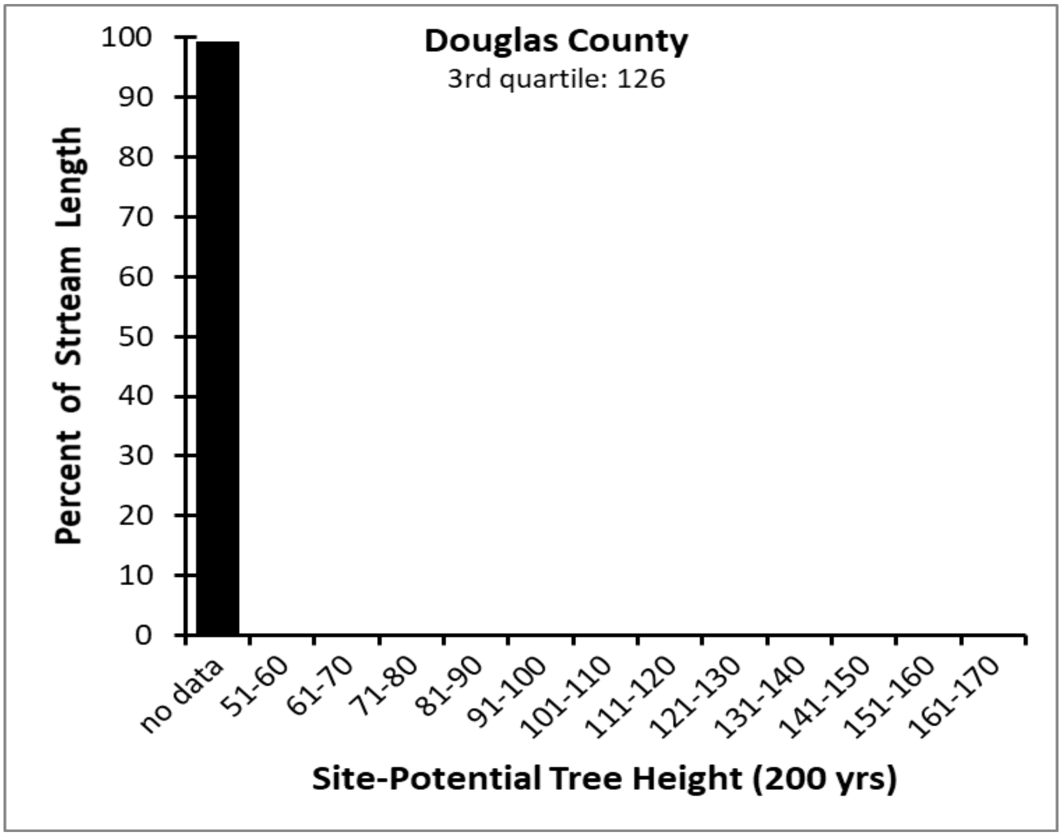


Figure 18: Ferry County stream length-weighted 3rd quartile of 200-year SPTH: 160 ft

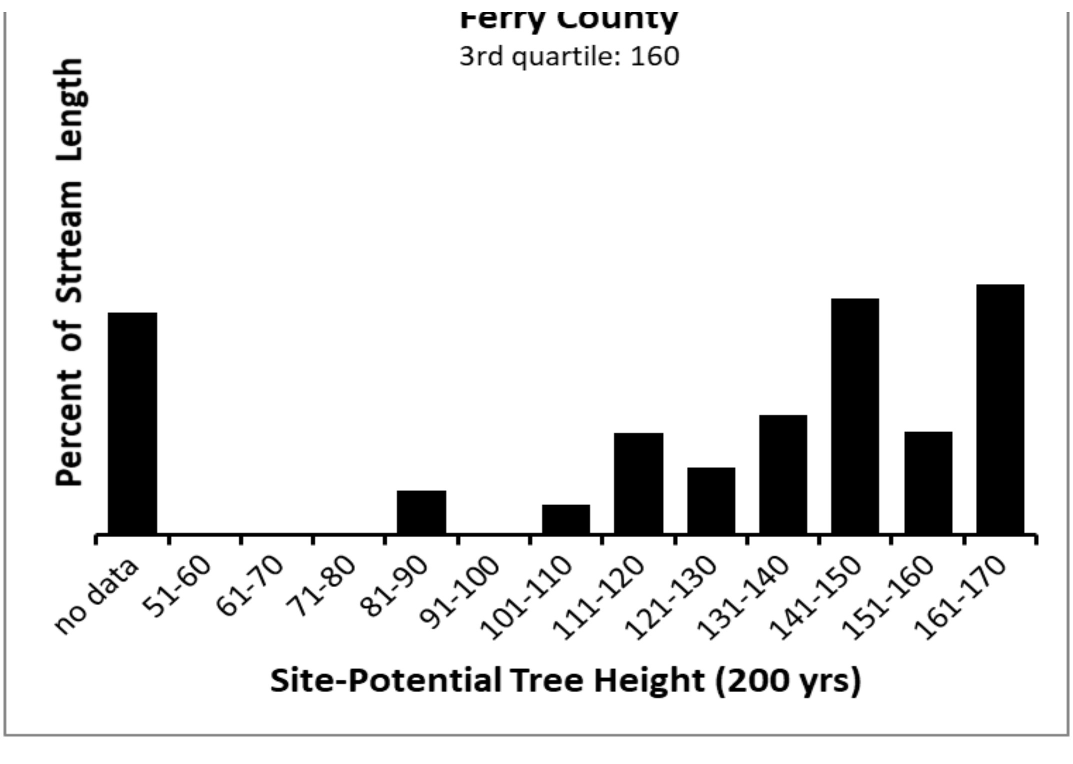


Figure 19: Garfield County stream length-weighted 3rd quartile of 200-year SPTH: 160 ft

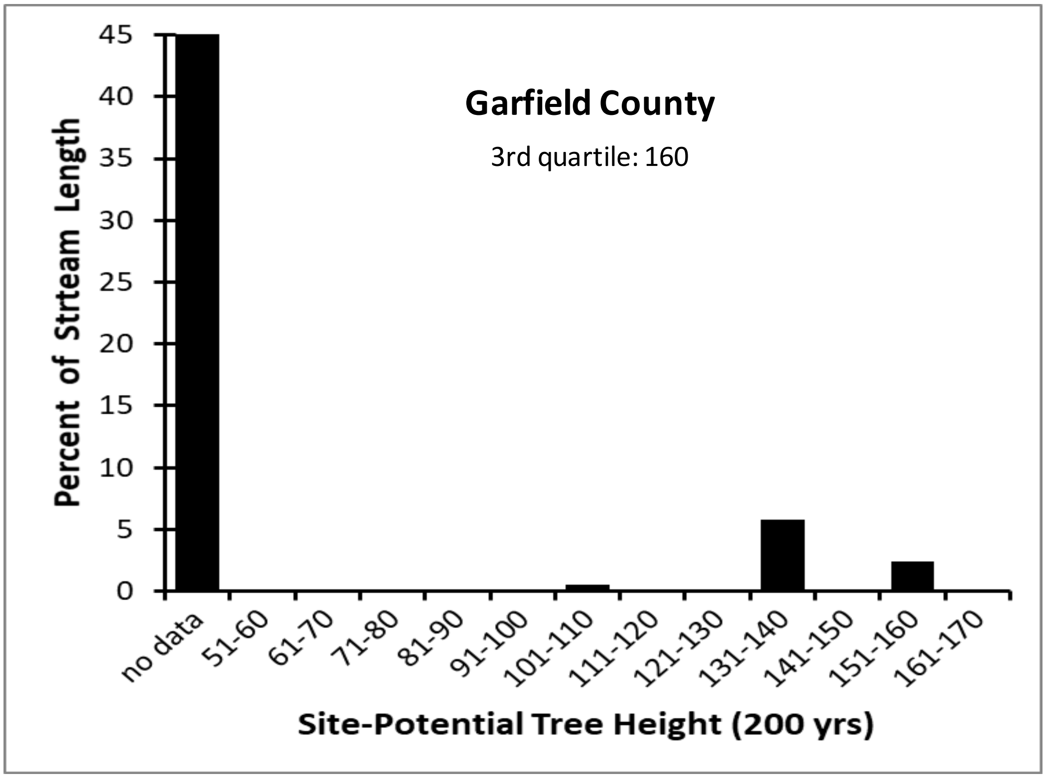


Figure20: Island County stream length-weighted 3rd quartile of 200-year SPTH: 204 ft

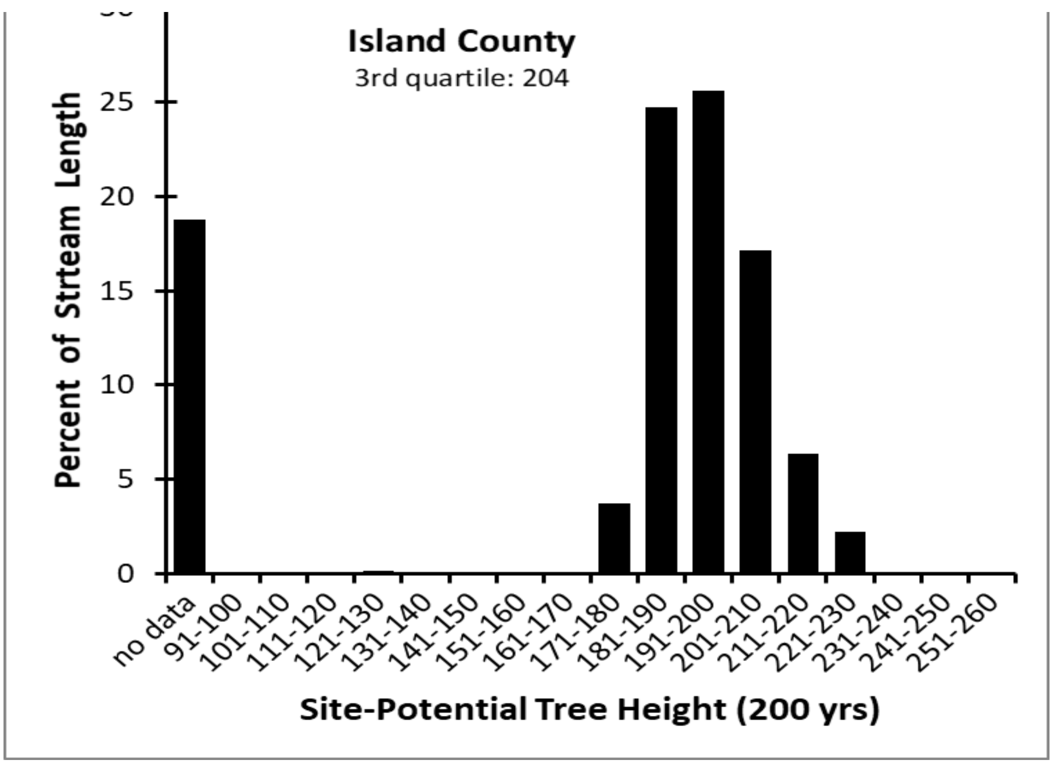


Figure21: Jefferson County stream length-weighted 3rd quartile of 200-year SPTH: 203 ft

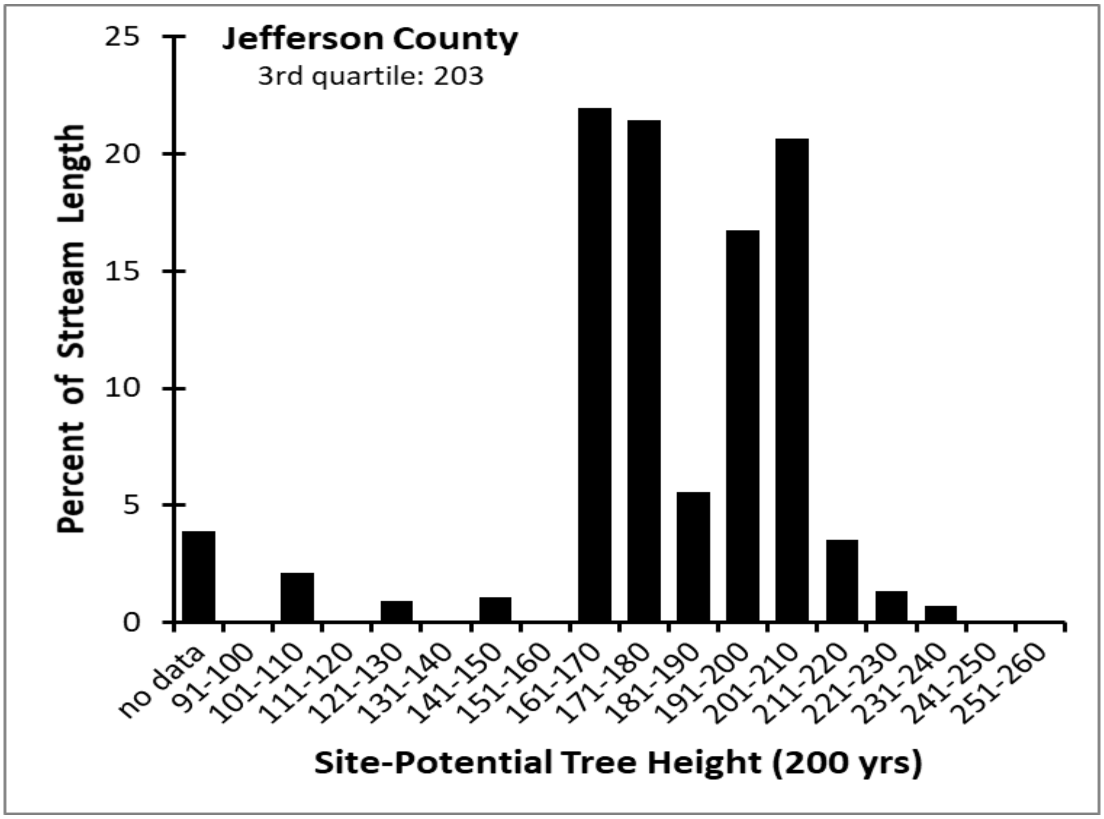


Figure22: King County stream length-weighted 3rd quartile of 200-year SPTH: 192 ft

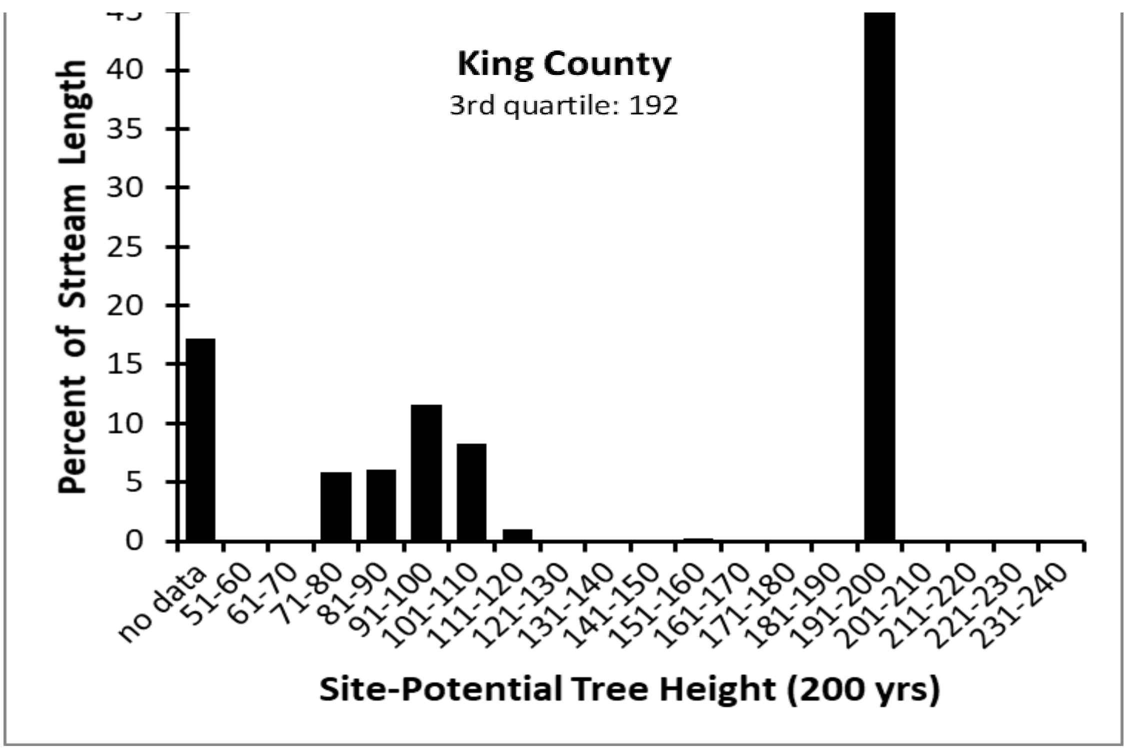


Figure23: Klickitat County stream length-weighted 3rd quartile of 200-year SPTH: 176 ft

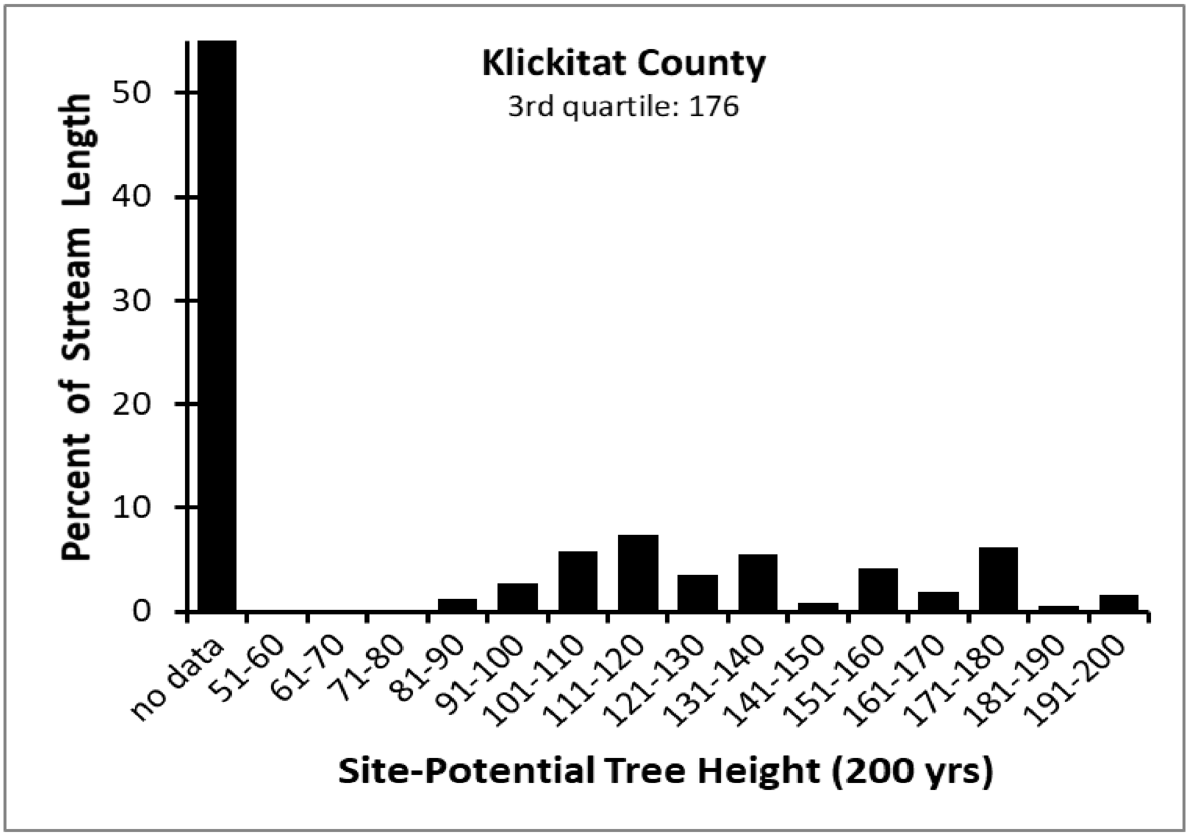


Figure24: Kittitas County stream length-weighted 3rd quartile of 200-year SPTH: 148 ft

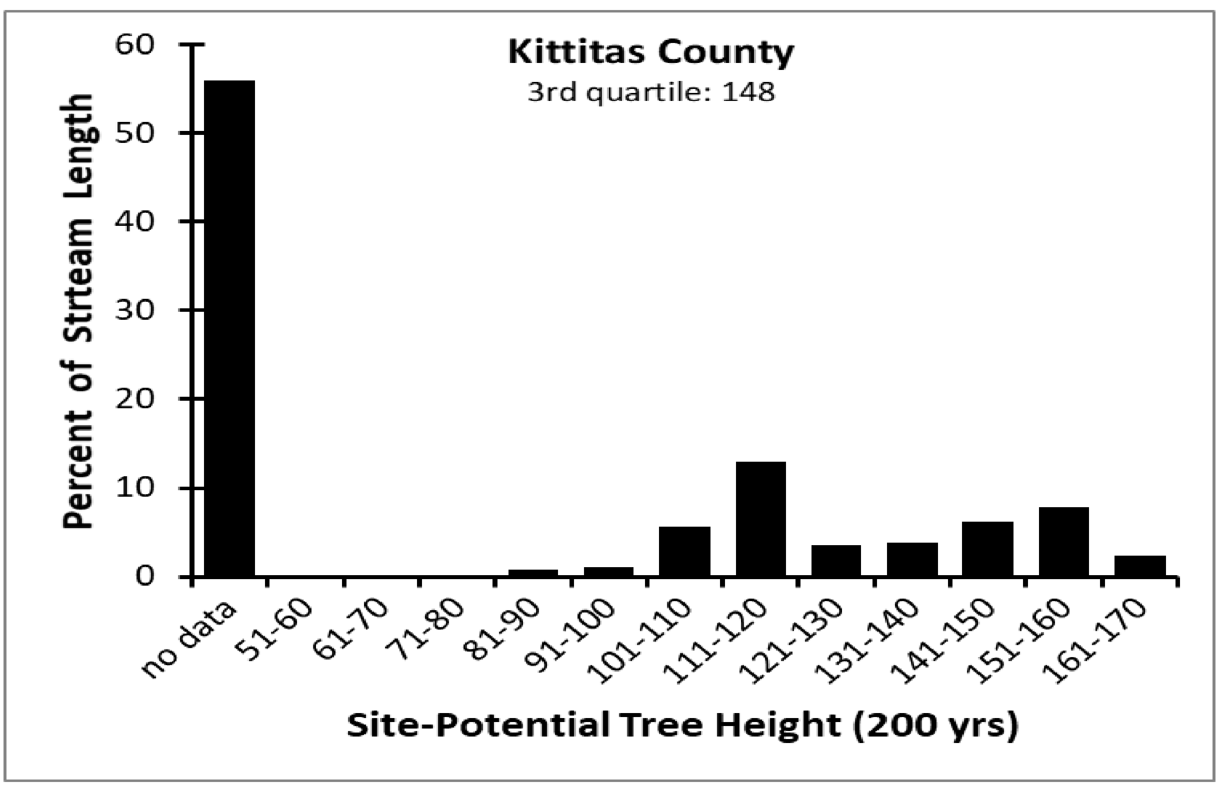


Figure 25: Lewis County stream length-weighted 3rd quartile of 200-year SPTH: 235 ft

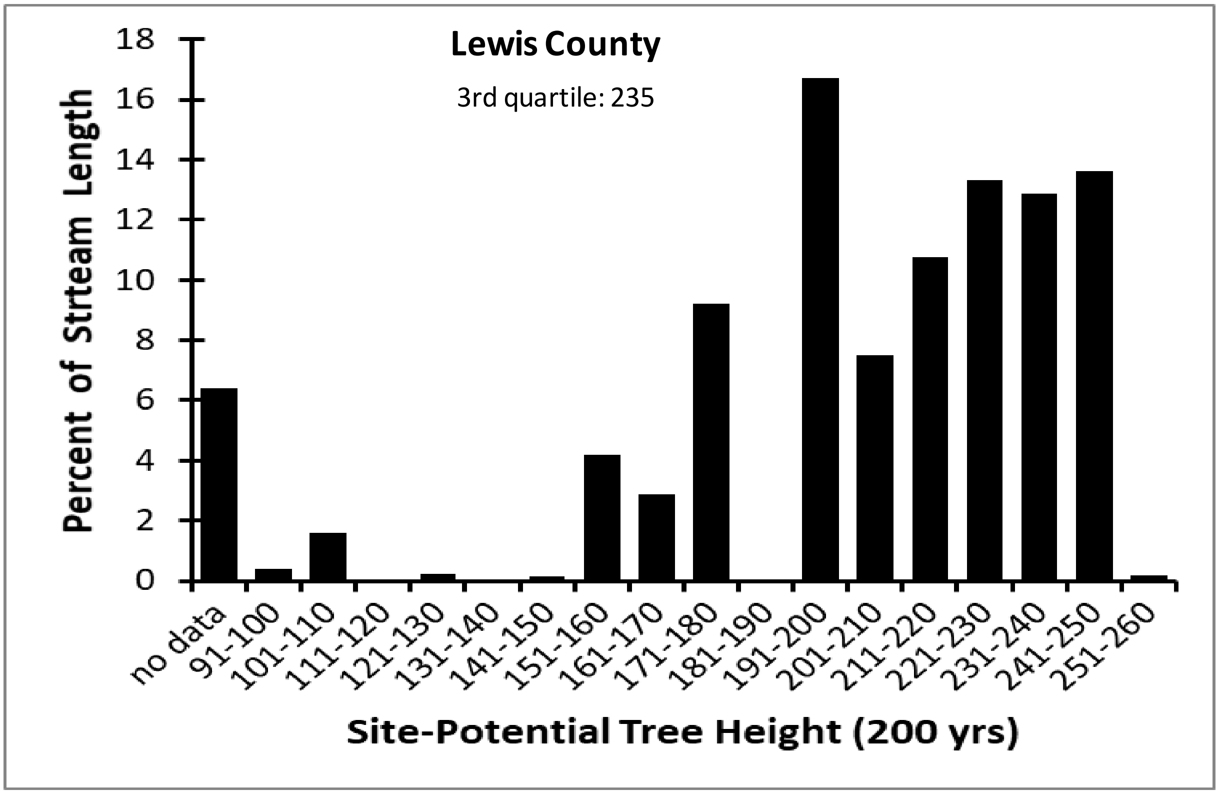


Figure 26: Lincoln County stream length-weighted 3rd quartile of 200-year SPTH: 133 ft

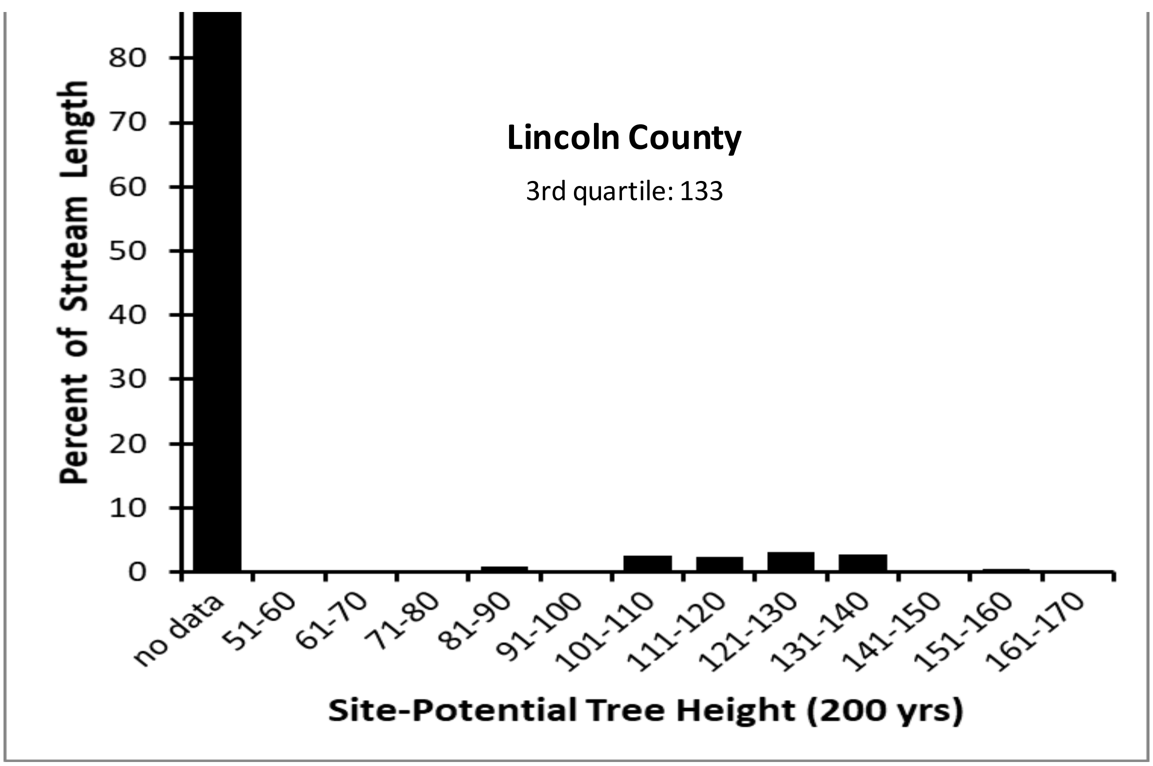


Figure 27: Mason County stream length-weighted 3rd quartile of 200-year SPTH: 225 ft

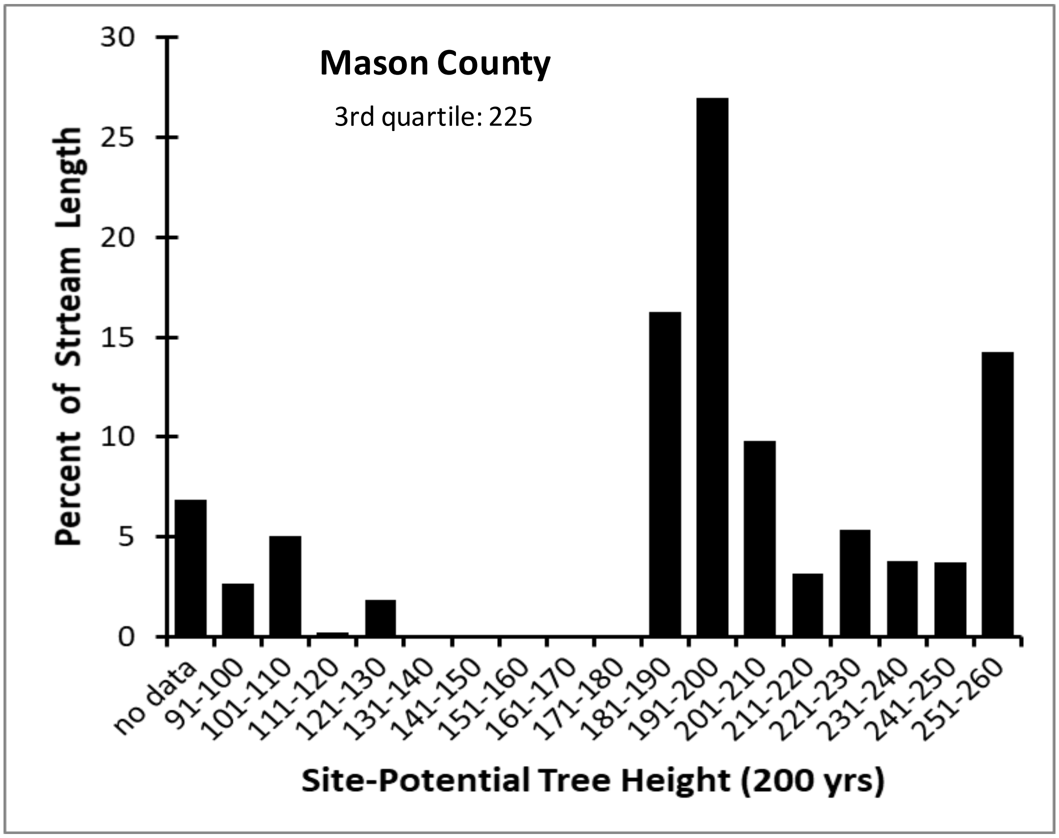


Figure 28: Okanogan County stream length-weighted 3rd quartile of 200-year SPTH: 149 ft

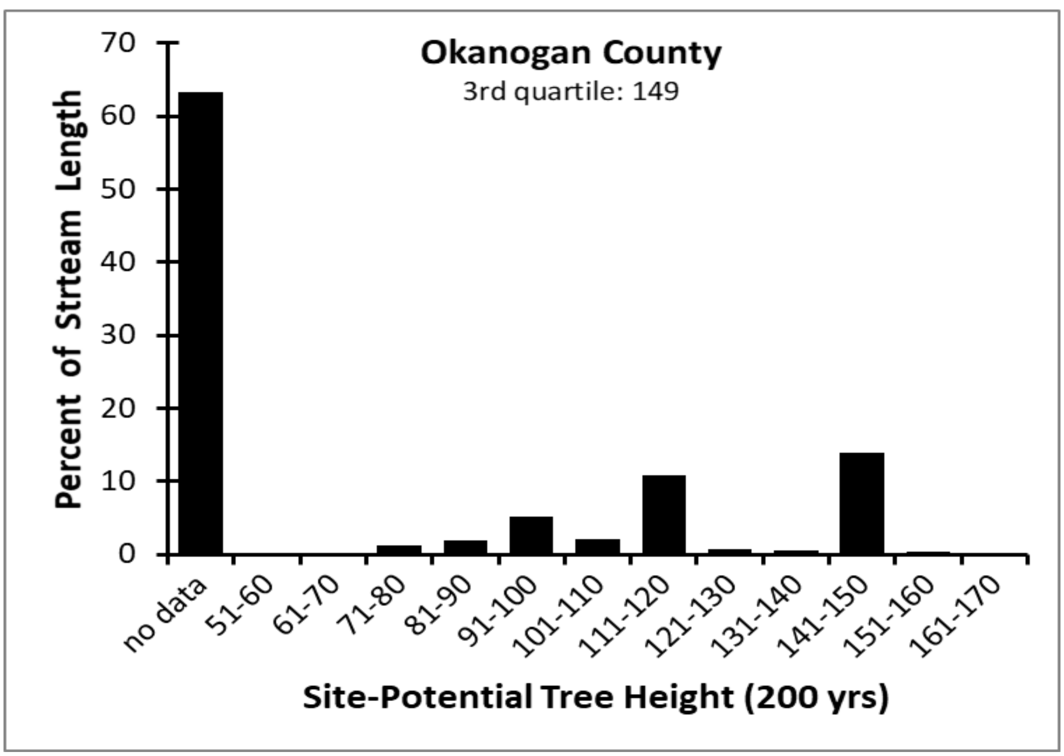


Figure 29: Pacific County stream length-weighted 3rd quartile of 200-year SPTH: 245 ft

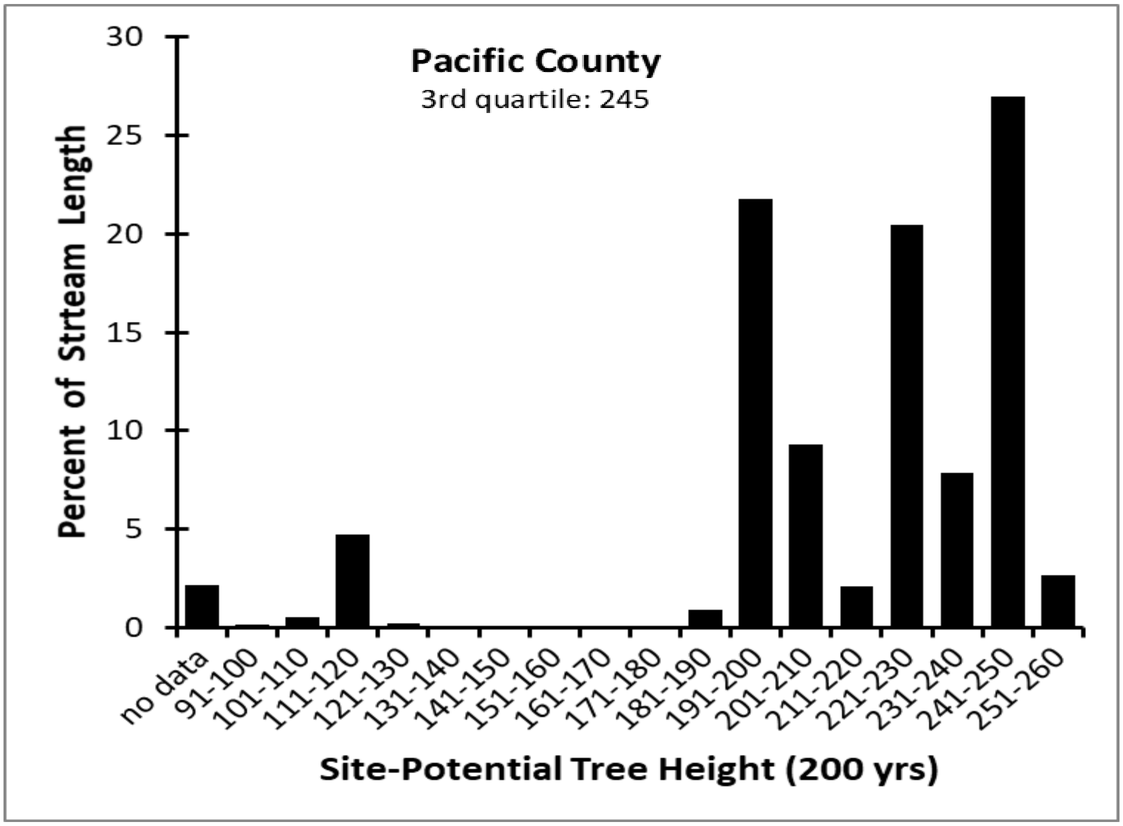


Figure 30: Pend Oreille County stream length-weighted 3rd quartile of 200-year SPTH: 160 ft

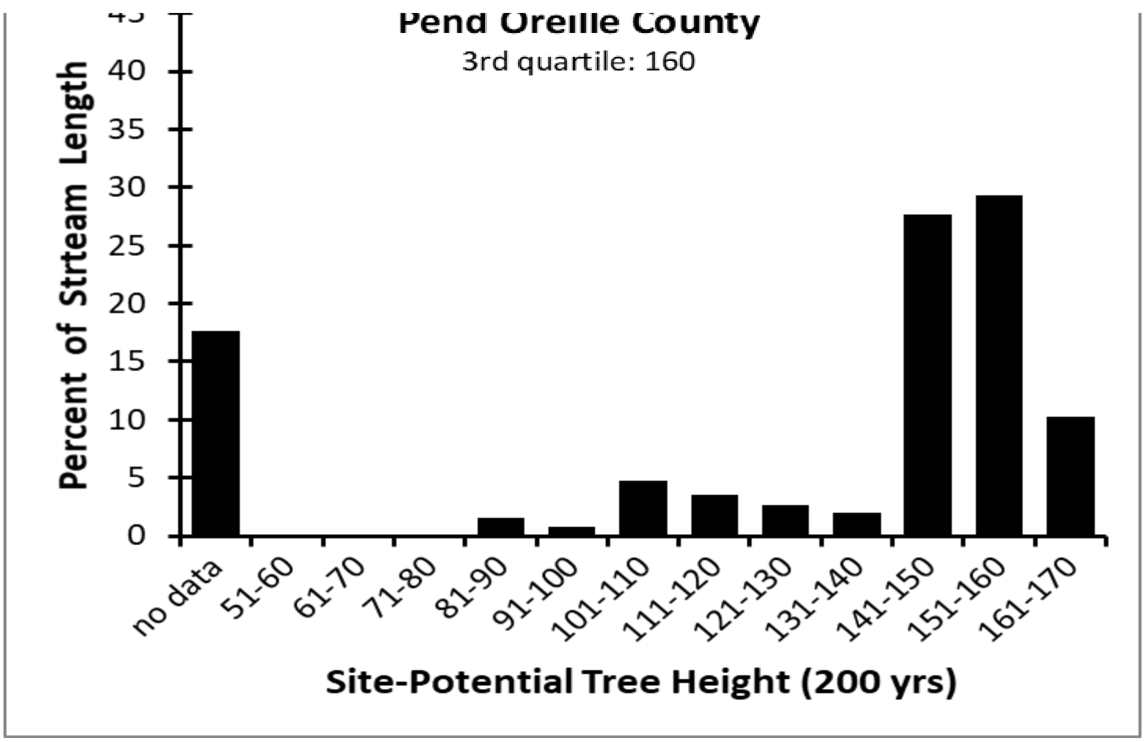


Figure 31: Pierce County stream length-weighted 3rd quartile of 200-year SPTH: 192 ft

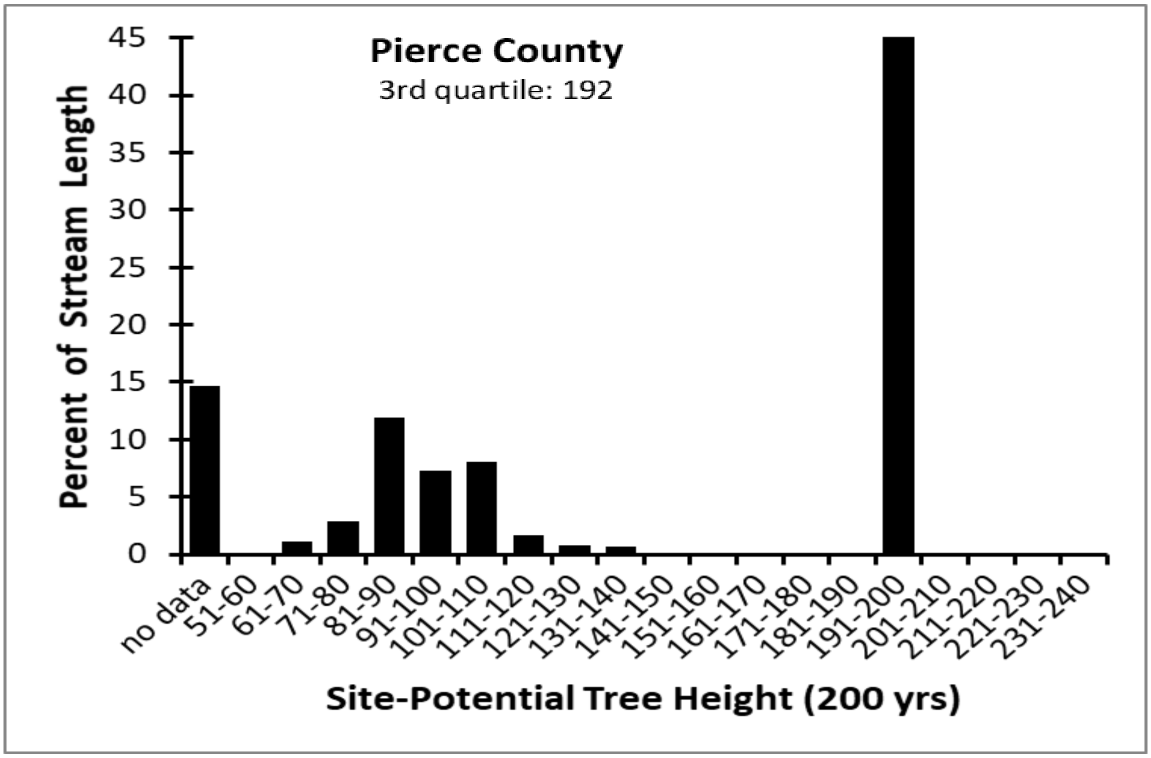


Figure 32: San Juan County stream length-weighted 3rd quartile of 200-year SPTH: 191 ft

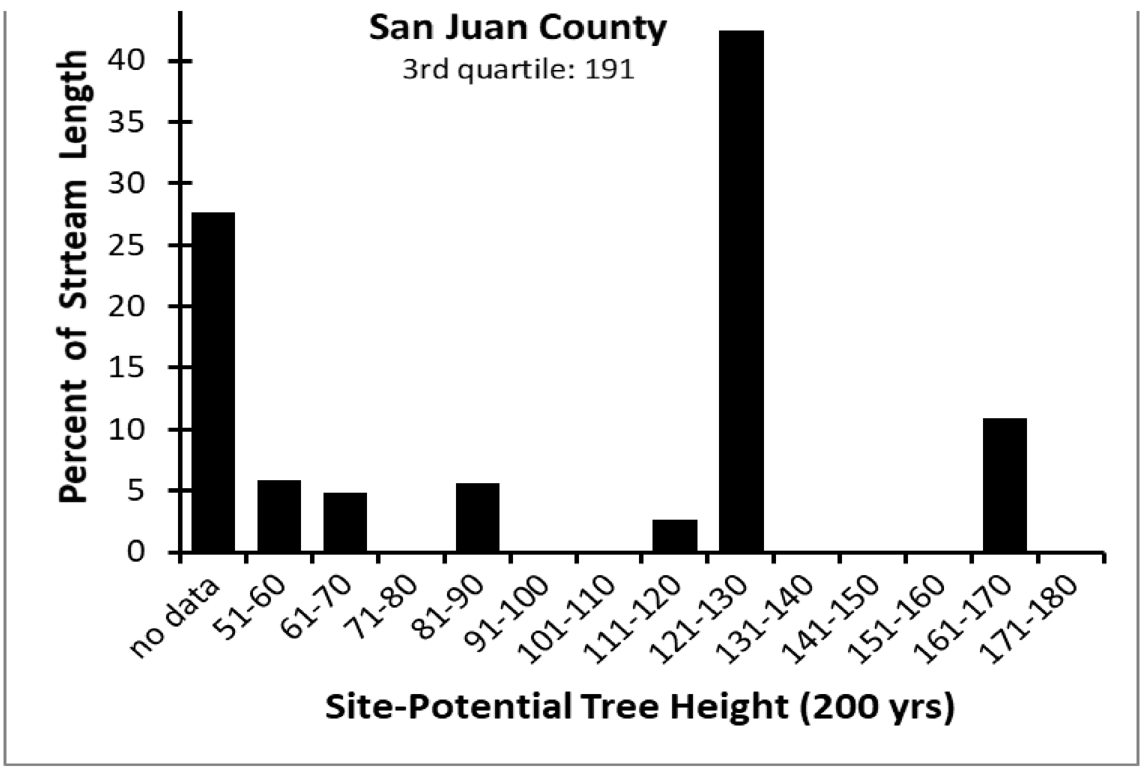


Figure 33: Skagit County stream length-weighted 3rd quartile of 200-year SPTH: 225 ft

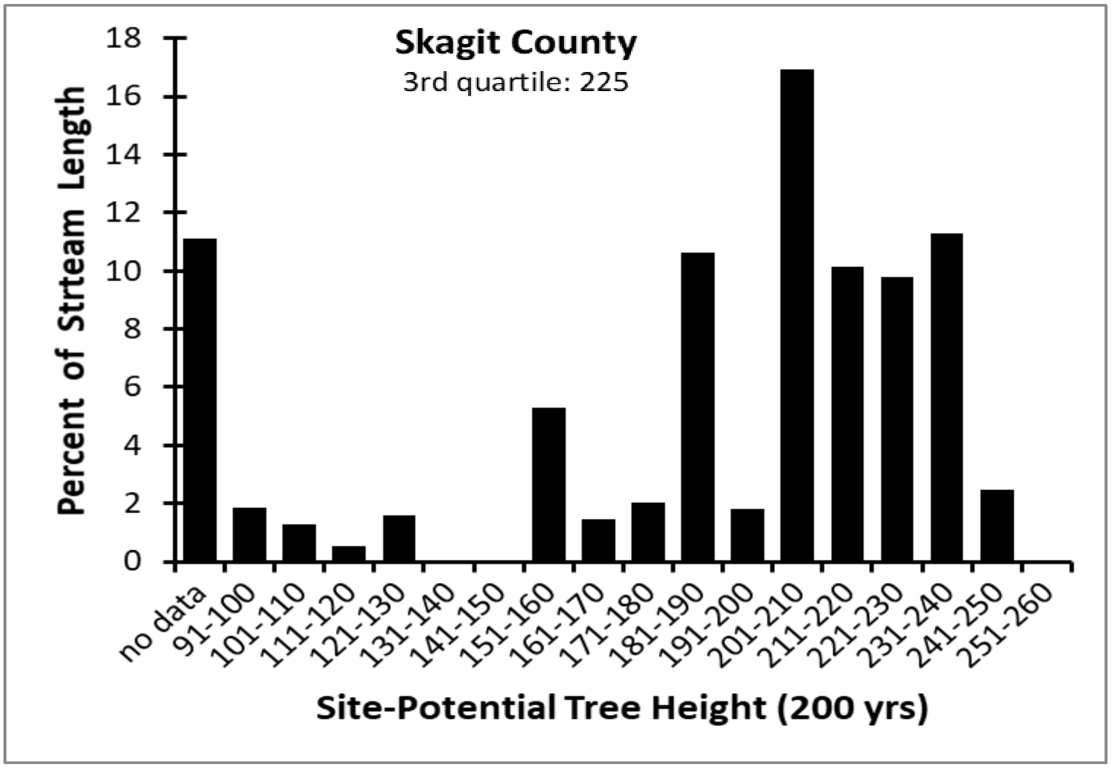


Figure 34: Skamania County stream length-weighted 3rd quartile of 200-year SPTH: 192 *ft*

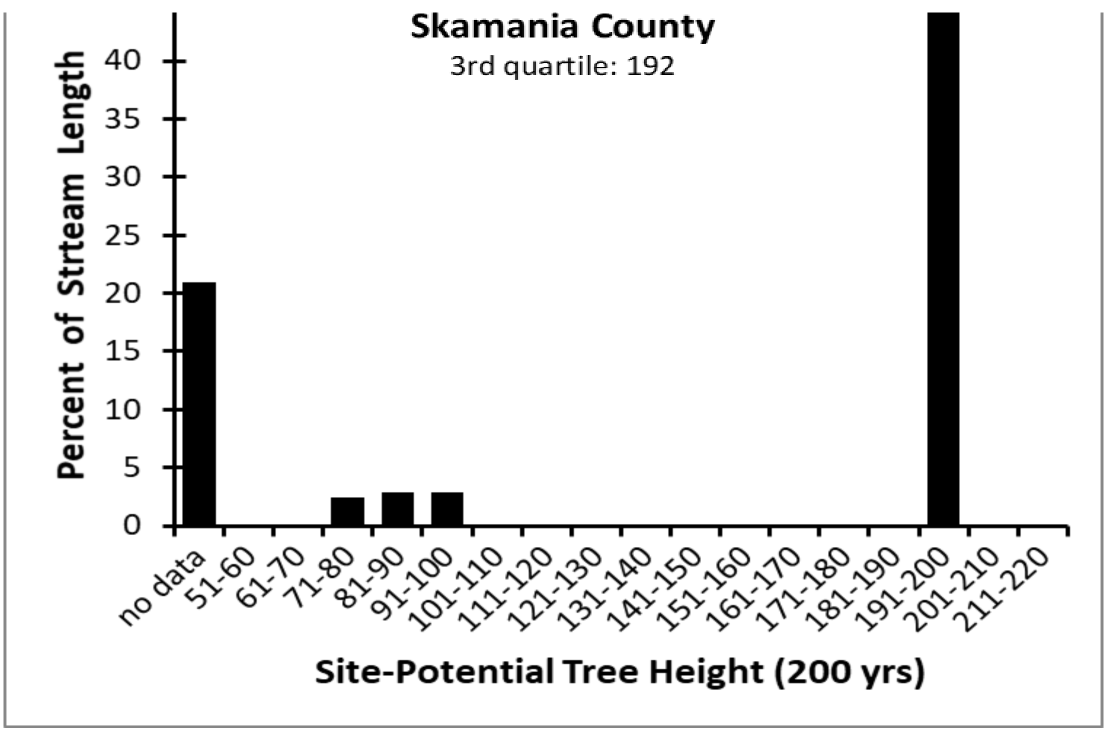


Figure 35: Snohomish County stream length-weighted 3rd quartile of 200-year SPTH: 235 ft

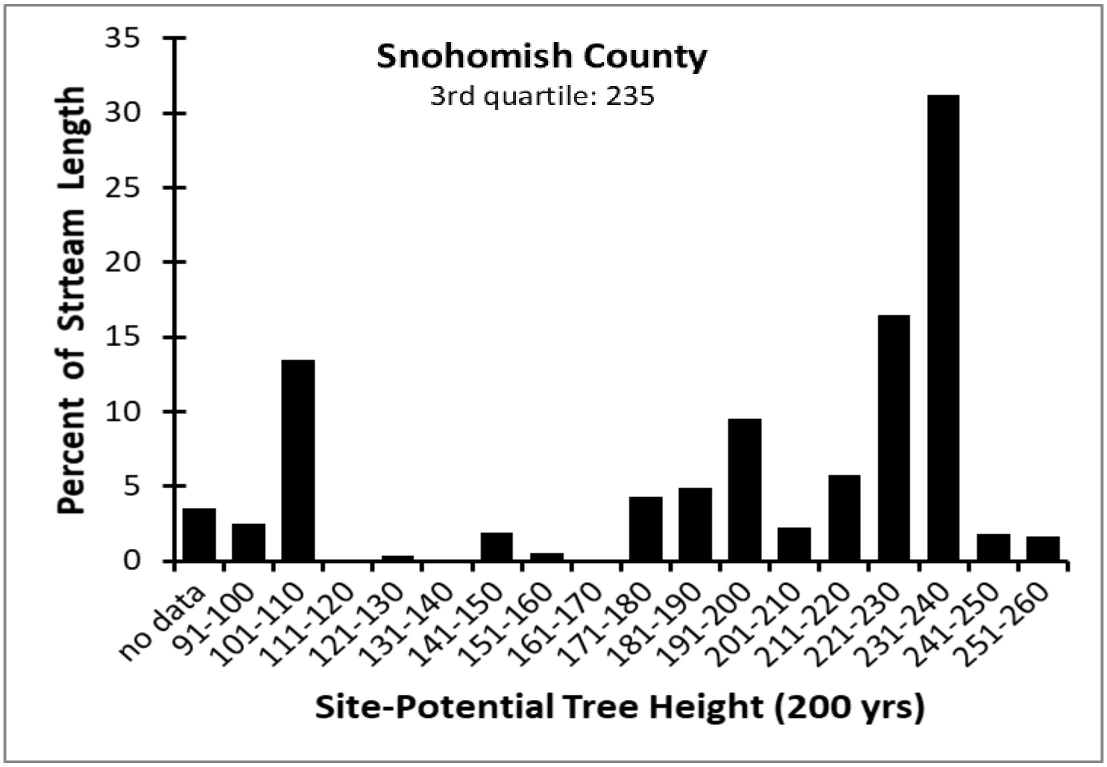


Figure 36: Spokane County stream length-weighted 3rd quartile of 200-year SPTH: 137 ft

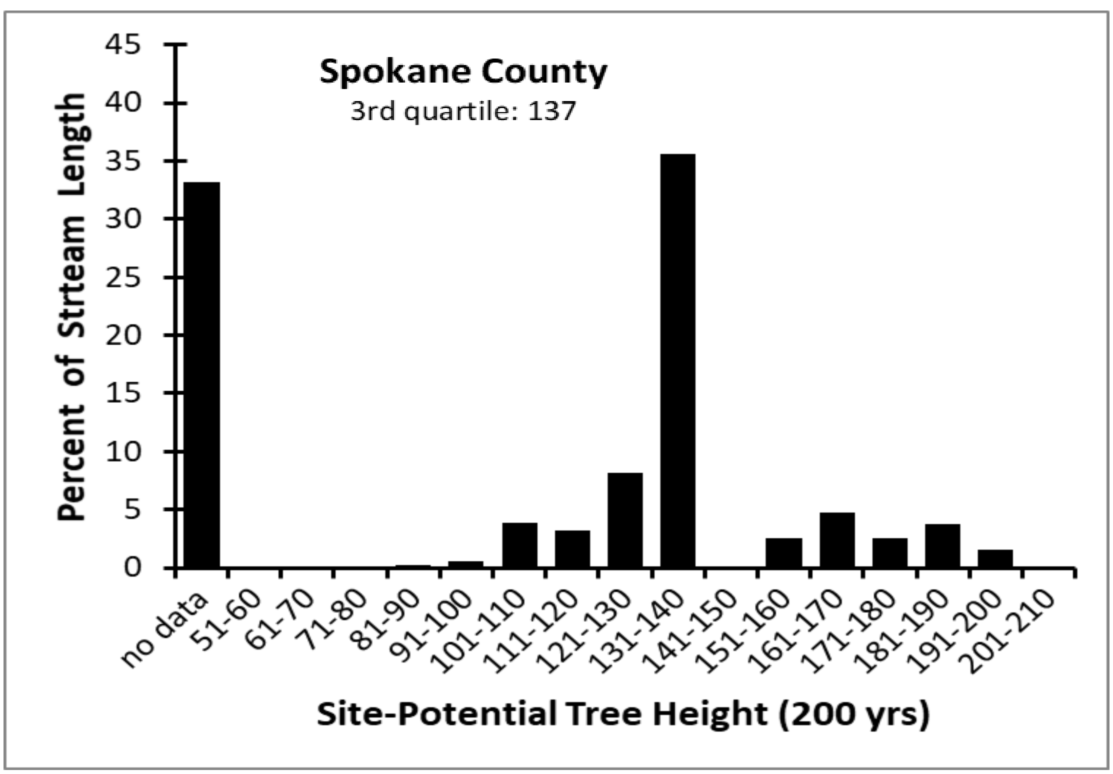


Figure 37: Stevens County stream length-weighted 3rd quartile of 200-year SPTH: 155 ft

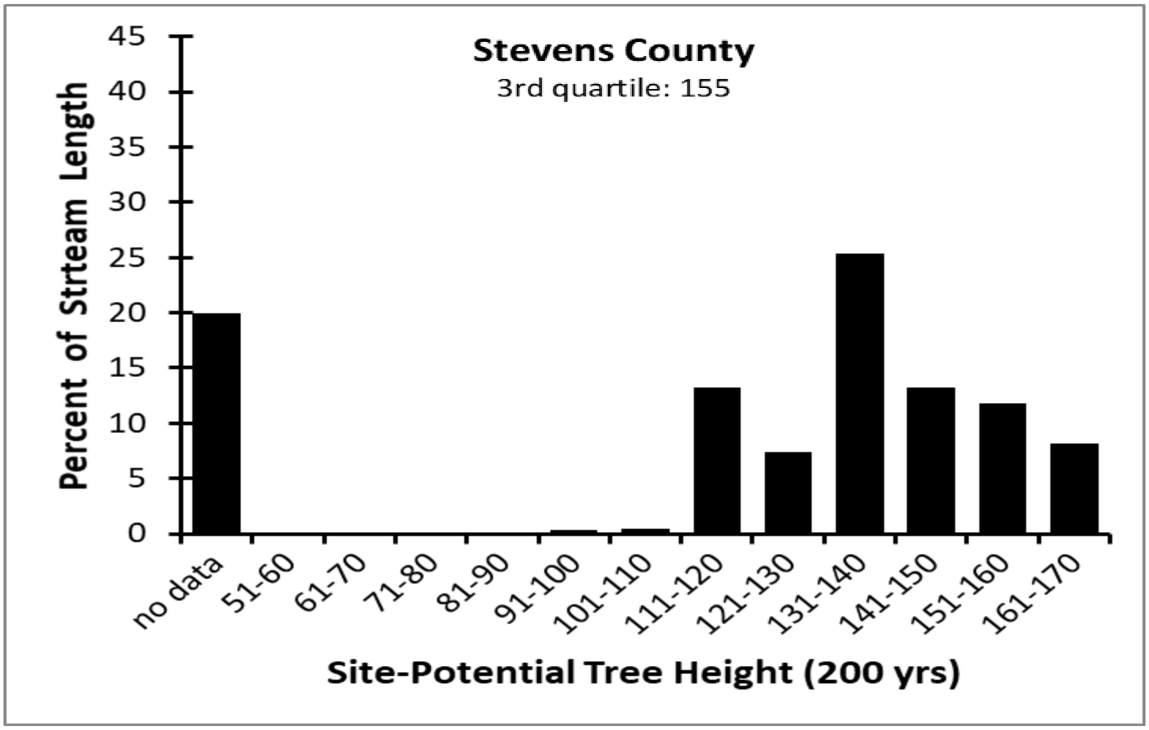


Figure 38: Thurston County stream length-weighted 3rd quartile of 200-year SPTH: 235 ft

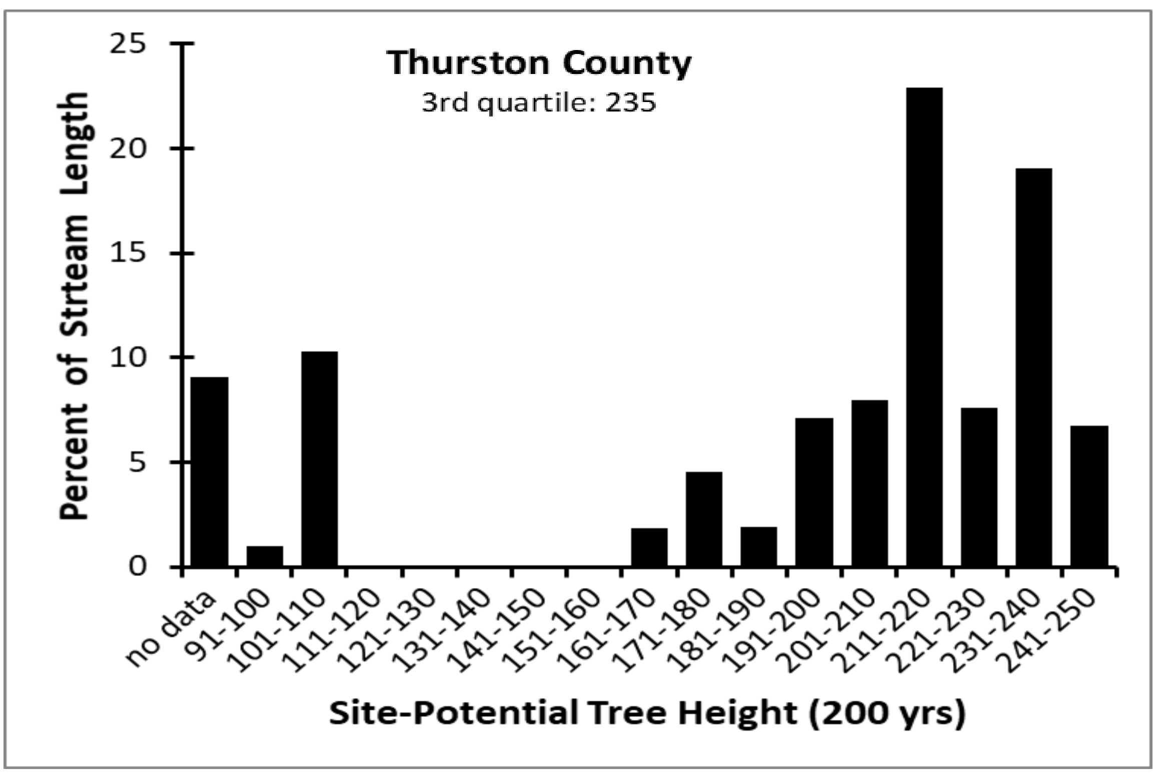


Figure 39: Wahkiakum County stream length-weighted 3rd quartile of 200-year SPTH: 245 ft

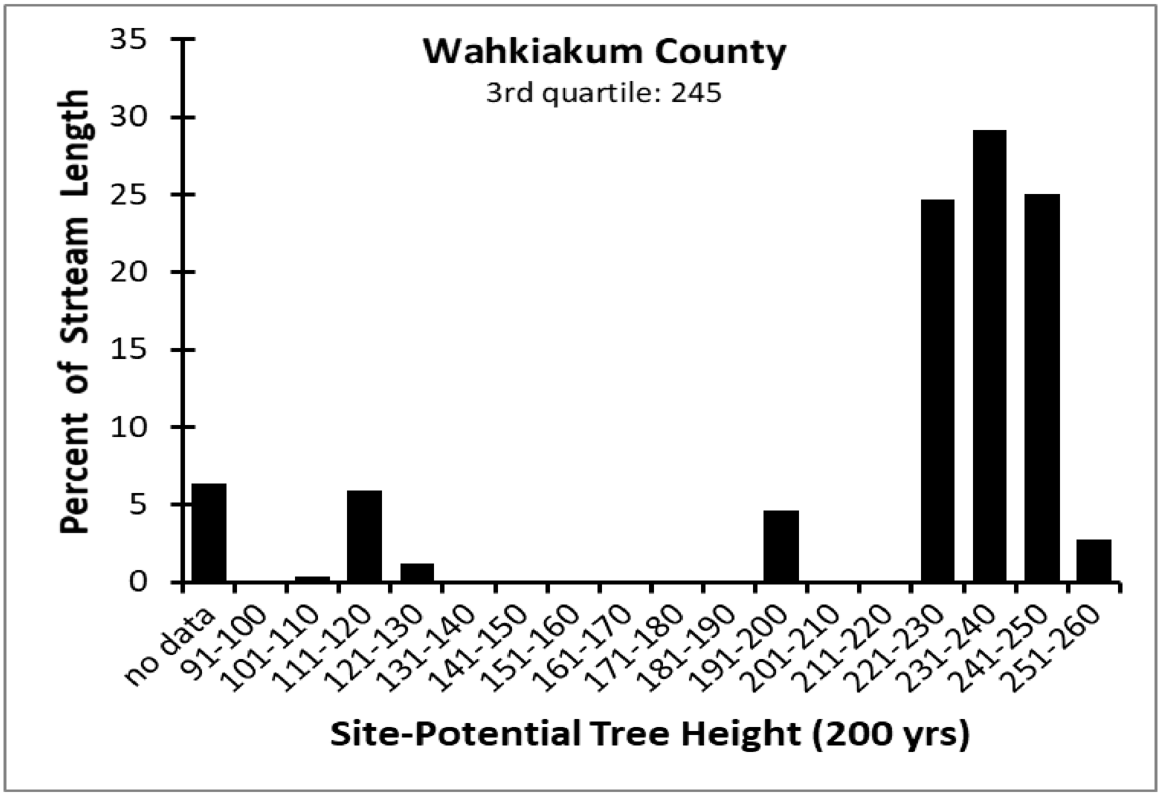


Figure 40: Walla Walla County stream length-weighted 3rd quartile of 200-year SPTH: 156 ft

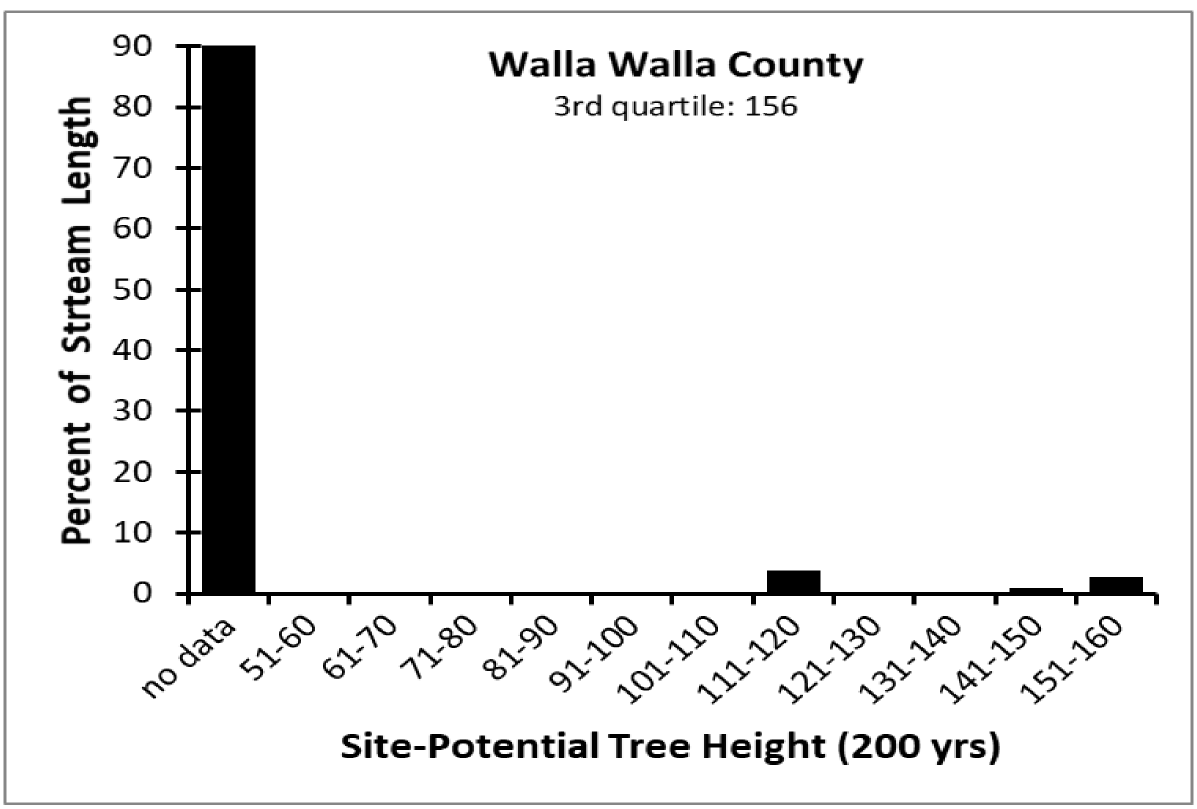


Figure 41: Whatcom County stream length-weighted 3rd quartile of 200-year SPTH: 204 ft

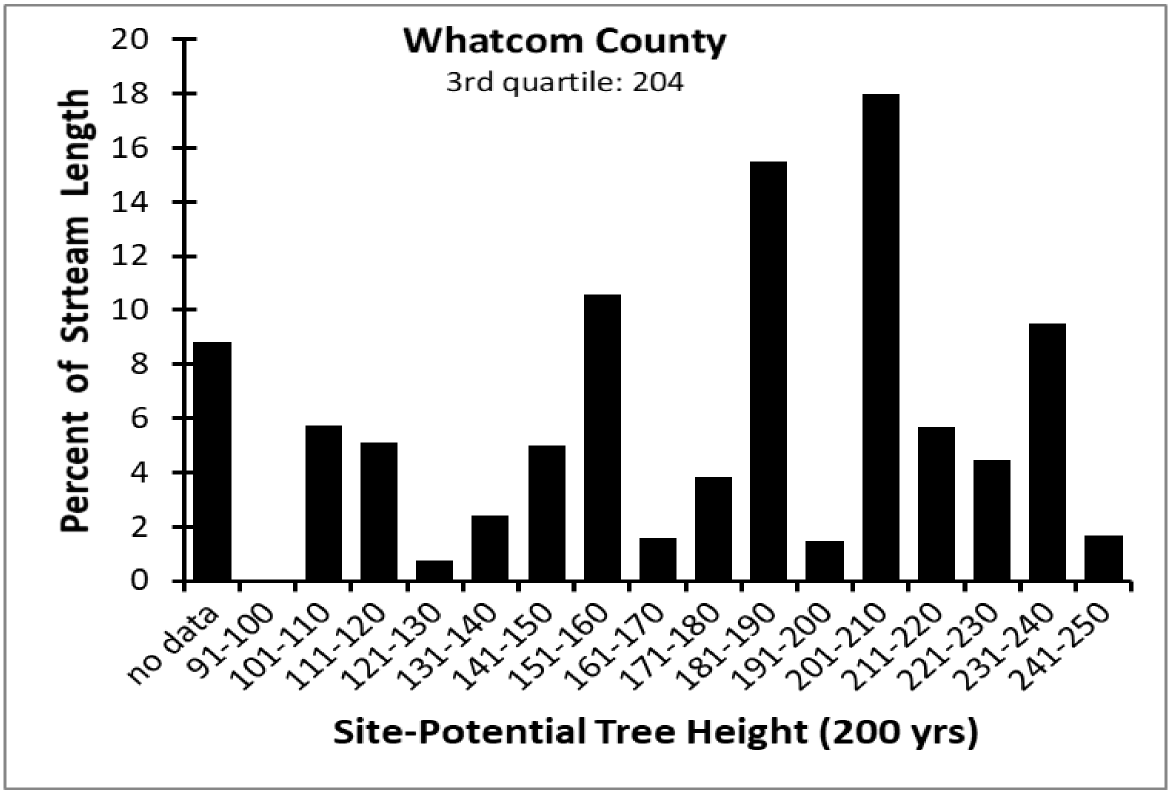


Figure 42: Whitman County stream length-weighted 3rd quartile of 200-year SPTH: 143 ft

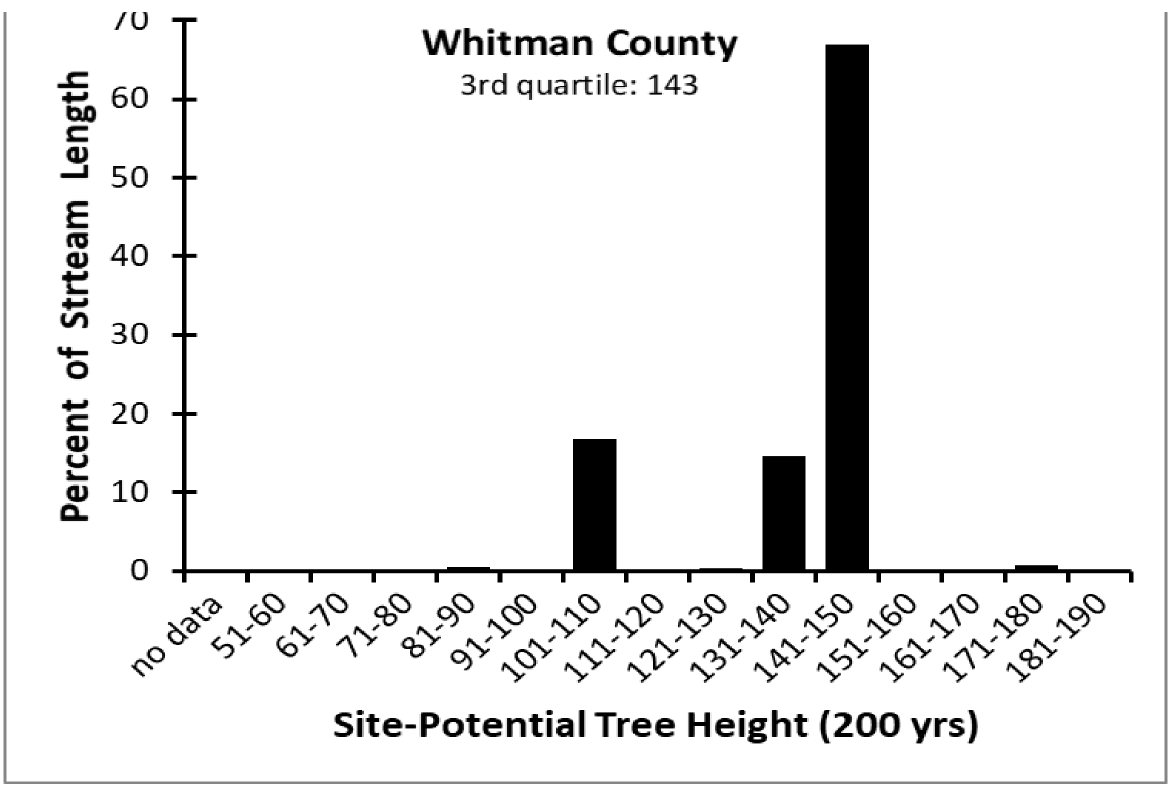


Figure 43: Yakima County stream length-weighted 3rd quartile of 200-year SPTH: 143 ft

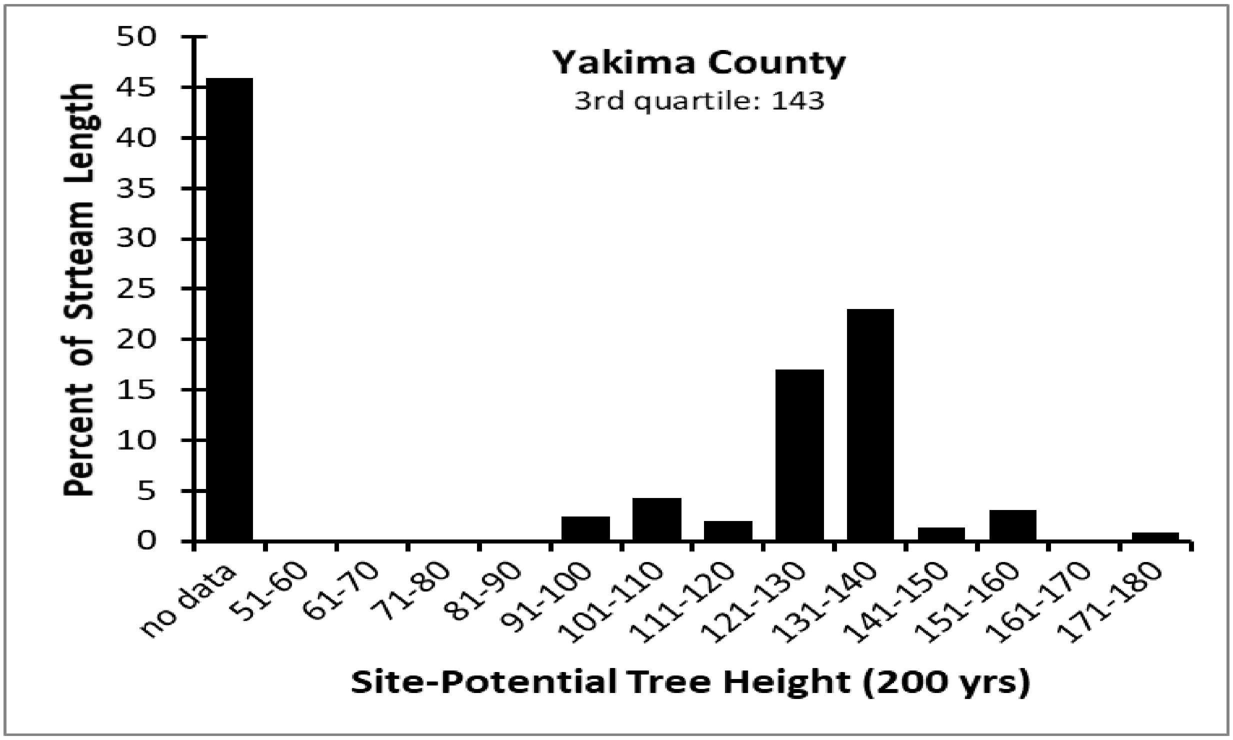


Figure 44: Stream length-weighted 3rd quartile of 200-year SPTH - Western & Eastern Counties

Counties in Western Washington	3rd Quartile (ft)
Clallam	137
Clark	235
Cowlitz	235
Grays Harbor	245
Island	204
Jefferson	203
King	192
Kitsap	204
Lewis	235
Mason	225
Pacific	245
Pierce	192
San Juan	191
Skagit	225
Skamania	192
Snohomish	235
Thurston	235
Wahkiakum	245
Whatcom	204
Average	**215**

Counties in Eastern Washington	3rd Quartile (ft)
Asotin	115
Chelan	160
Columbia	169
Douglas	126
Ferry	160
Garfield	160
Kittitas	176
Klickitat	148
Lincoln	133
Okanogan	149
Pend Oreille	160
Spokane	137
Stevens	155
Walla Walla	156
Whitman	143
Yakima	143
Average	**149**

Pesticide Properties

[1]*Based on Pesticide Movement Ratings designated by the National Pesticide Information Center.http://npic.orst.edu/ingred/ppdmove.htm.*

Augustijn-Beckers, P. W. M., A. G. Hornsby, and R. D. Wauchope. 1994. The SCS/ARS/CES pesticide properties database for environmental decision making II. Additional compounds. Reviews of Environ. Contamin. Toxicol. 137:1-82.

Wauchope, R. D., T. M. Buttler, A. G. Hornsby, P. M. Augustijn-Beckers, and J. P. Burt. 1992. The SCS/ARS/CES pesticide properties database for environmental decision making. Reviews of Environ. Contamin. Toxicol. 123:1-155.

Table 35: Pesticide Properties

Common Name	Pesticide Movement Rating	Soil (days)	Water Solubility (mg/l)	Sorption Coefficient (soil Koc)
1,2-Dichloropropane	Very High	700	2700	50
1,3-Dichloropropene	Moderate	10	2250	32
1-Naphthaleneacetamide	Moderate	10	100	100
2,4,5-T acid	High	30	278	80
2,4,5-T amine salts	Moderate	24	500,000	80
2,4,5-T esters	High	30	50	80
2,4-D acid	Moderate	10	890	20
2,4-D dimethylamine salt	Moderate	10	796,000	20
2,4-D esters or oil sol. amines	Moderate	10	100	100
2,4-DB acid	Very Low	5	46	440
2,4-DB butoxyethyl ester	Low	7	8	500
2,4-DB dimethylamine salt	Moderate	10	709,000	20
3-CPA sodium salt	Moderate	10	200,000	20

Common Name	Pesticide Movement Rating	Soil (days)	Water Solubility (mg/l)	Sorption Coefficient (soil Koc)
AMS (Ammonium sulfamate)	Moderate	14	684,000	30
Abamectin (Avermectin)	Very Low	28	5	5000
Acephate	Low	3	818,000	2
Acifluorfen sodium salt	Moderate	14	250,000	113
Acorlein	Very High	14	208,000	0.5
Alachlor	Moderate	15	240	170
Aldicarb	High	30	6000	30
Aldoxycarb (aldicarb sulfone)	High	20	10,000	10
Aldrin	Very Low	365	0.027	5000
Ametryn	Moderate	60	185	300
Aminocarb	Low	6	915	100
Amitraz	Very Low	2	1	1000
Amitrole	Moderate	14	360,000	100
Ancymidol	High	120	650	120
Anilazine	Extremely Low	1	8	1000
Arsenic acid	Extremely Low	10,000	17,000	100,000
Asulam sodium salt	Moderate	7	550,000	40
Atrazine	High	60	33	100
Azinphos-methyl	Low	10	29	1000
Barban	Very Low	5	11	1000
Benalaxyl	Low	30	37	1000

Common Name	Pesticide Movement Rating	Soil (days)	Water Solubility (mg/l)	Sorption Coefficient (soil Koc)
Bendiocarb	Very Low	5	40	570
Benefin	Extremely Low	40	0.1	9000
Benodanil	Low	25	20	700
Benomyl	Low	67	2	1900
Bensulfuron methyl	Low	5	120	370
Bensulide	Moderate	120	5.6	1000
Bentazon sodium salt	High	20	2,300,000	34
Bifenox	Extremely Low	7	0.398	10,000
Bifenthrin	Extremely Low	26	0.1	240,000
Bromacil acid	Very High	60	700	32
Bromacil lithium salt	Very High	60	700	32
Bromoxynil butyrate ester	Very Low	7	27	1079
Bromoxynil octanoate ester	Extremely Low	7	0.08	10,000
Butachlor	Low	12	23	700
Butylate	Low	13	44	400
CDAA (Allidochlor)	Moderate	10	20,000	20
Captafol	Very Low	7	1.4	3000
Captan	Very Low	2.5	5.1	200
Carbaryl	Low	10	120	300
Carbendazim (MBC)	Moderate	120	8	400
Carbofuran	Very High	50	351	22

Common Name	Pesticide Movement Rating	Soil (days)	Water Solubility (mg/l)	Sorption Coefficient (soil Koc)
Carbon disulfide	Very Low	1.5	2300	60
Carbophenothion	Extremely Low	30	0.34	50,000
Carboxin	Very Low	3	195	260
Chloramben salts	High	14	900,000	15
Chlorbromuron	Moderate	40	35	500
Chlordane	Extremely Low	350	0.06	20,000
Chlordimeform hydrochloride	Extremely Low	60	500,000	100,000
Chlorimuron ethyl	High	40	1200	110
Chlorobenzilate	Very Low	20	13	2000
Chloroneb	Low	130	8	1650
Chloropicrin	Extremely Low	1	2270	62
Chlorothalonil	Low	30	0.6	1380
Chloroxuron	Very Low	60	2.5	3000
Chlorpropham (CIPC)	Moderate	30	89	400
Chlorpyrifos	Very Low	30	0.4	6070
Chlorpyrifos-methyl	Very Low	7	4	3000
Chlorsulfuron	High	40	7000	40
Chlozolinate	Extremely Low	2	1	10,000
Cinmethylin	Moderate	30	63	300
Clofentezine	Extremely Low	40	0.1	11,000
Clomazone (dimethazone)	Moderate	24	1100	300

Common Name	Pesticide Movement Rating	Soil (days)	Water Solubility (mg/l)	Sorption Coefficient (soil Koc)
Clopyralid amine salt	Very High	40	300,000	6
Cryolite	Extremely Low	3000	420	10,000
Cyanazine	Low	14	170	190
Cycloate	Moderate	30	95	430
Cyfluthrin	Extremely Low	30	0.002	100,000
Cyhexatin	Very Low	50	<1	4000
Cypermethrin	Extremely Low	30	0.004	100,000
Cyromazine	High	150	136,000	200
DBCP	Very High	180	1000	70
DCNA	Low	60	7	1000
DCPA dacthal parent	Very Low	100	0.5	5000
DDD (TDE)	Extremely Low	1000	0.02	100,000
DDE	Extremely Low	1000	0.1	50,000
DDT	Extremely Low	2000	0.0055	2,000,000
DNOC sodium salt	High	20	100,000	20
DSMA (Methylarsonic acid disodium salt)	Very Low	180	250,000	7000
Dalapon sodium	Very High	30	900,000	1
Daminozide	High	21	100,000	30
Dazomet	Moderate	7	3000	10
Demeton	Moderate	15	60	70

Common Name	Pesticide Movement Rating	Soil (days)	Water Solubility (mg/l)	Sorption Coefficient (soil Koc)
Desmedipham	Low	30	8	1500
Di-allate	Low	30	14	500
Diazinon	Low	40	60	1000
Dicamba salt	Very High	14	400,000	2
Dichlobenil	Moderate	60	21.2	400
Dichlone	Extremely Low	10	0.1	10,000
Dichlormid	Moderate	7	5000	40
Dichlorprop (2,4-DP) ester	Low	10	50	1000
Dichlorvos	Extremely Low	0.5	10,000	30
Diclofop-methyl	Extremely Low	30	0.8	16,000
Dicofol	Very Low	45	0.8	5000
Dicrotophos	Moderate	20	1,000,000	75
Dieldrin	Extremely Low	1000	0.2	12,000
Dienochlor	Moderate	300	25	1000
Diethatyl-ethyl	Low	30	105	1400
Difenzoquat methylsulfate salt	Extremely Low	100	817,000	54,500
Diflubenzuron	Extremely Low	10	0.08	10,000
Dimethipin	Very High	120	3000	10
Dimethirimol	Very High	120	1200	90
Dimethoate	Moderate	7	39,800	20

Common Name	Pesticide Movement Rating	Soil (days)	Water Solubility (mg/l)	Sorption Coefficient (soil Koc)
Dimethylarsenic Acid	Low	50	2,000,000	1000
Dinitramine	Very Low	30	1.1	4000
Dinocap	Very Low	5	4	550
Dinoseb	High	30	52	30
Dinoseb phenol	Low	20	50	500
Dinoseb salts	Moderate	20	2200	63
Dioxacarb	Very Low	2	6000	40
Diphenamid	Moderate	30	260	210
Dipropetryn	Moderate	100	16	900
Diquat dibromide salt	Extremely Low	1000	718,000	1,000,000
Disulfoton	Low	30	25	600
Diuron	Moderate	90	42	480
Dodine acetate	Extremely Low	20	700	100,000
EPN	Very Low	15	0.5	4000
EPTC	Low	6	344	200
Endosulfan	Extremely Low	50	0.32	12,400
Endothall salt	Moderate	7	100,000	20
Endrin	Extremely Low	4300	0.23	10,000
Esfenvalerate	Very Low	35	0.002	5300
Ethalfluralin	Very Low	60	0.3	4000
Ethephon	Extremely Low	10	1,239,000	100,000

Common Name	Pesticide Movement Rating	Soil (days)	Water Solubility (mg/l)	Sorption Coefficient (soil Koc)
Ethion	Extremely Low	150	1.1	10,000
Ethofumesate	Moderate	30	50	340
Ethoprop	High	25	750	70
Ethylene Dibromide (EDB)	Very High	100	4300	34
Etridiazole	Moderate	103	50	1000
Fenac (chlorfenac) salt	Very High	180	500,000	20
Fenaminosulf	Very Low	2	20,000	40
Fenamiphos	High	50	400	100
Fenarimol	High	360	14	600
Fenbutatin oxide	Low	90	0.0127	2300
Fenfuram	Moderate	42	100	300
Fenitrothion	Very Low	4	30	2000
Fenoprop	Moderate	21	140	300
Fenoxaprop-ethyl	Extremely Low	9	0.8	9490
Fenoxycarb	Extremely Low	1	6	1000
Fenpropathrin	Very Low	5	0.33	5000
Fensulfothion	Moderate	30	1540	300
Fenthion	Low	34	4.2	1500
Fenuron	Very High	60	3850	42
Fenvalerate	Very Low	35	0.002	5300
Ferbam	Low	17	120	300

Common Name	Pesticide Movement Rating	Soil (days)	Water Solubility (mg/l)	Sorption Coefficient (soil Koc)
Fluazifop-butyl	Very Low	21	2	3000
Fluazifop-p-butyl	Very Low	15	2	5700
Fluchloralin	Very Low	60	0.9	3000
Flucythrinate	Extremely Low	21	0.06	100,000
Flumetralin	Extremely Low	20	0.1	10,000
Fluometuron	High	85	110	100
Fluridone	Low	21	10	1000
Fluvalinate	Extremely Low	7	0.005	1,000,000
Fomesafen sodium salt	Very High	100	700,000	60
Fonofos	Low	40	16.9	870
Formetanate hydrochloride salt	Extremely Low	100	500,000	1,000,000
Fosamine ammonium	Low	8	1,790,000	150
Fosetyl-aluminum	Extremely Low	0.1	120,000	20
Glufosinate ammonium salt	Low	7	1,370,000	100
Glyphosate isopropylamine salt	Extremely Low	47	900,000	24,000
Haloxyfop-methyl	High	55	43	75
Heptachlor	Extremely Low	250	0.056	24,000
Hexachlorobenzene (HCB)	Extremely Low	1000	0.005	50,000
Hexazinone	Very High	90	33,000	54
Hexythiazox	Very Low	30	0.5	6200

Common Name	Pesticide Movement Rating	Soil (days)	Water Solubility (mg/l)	Sorption Coefficient (soil Koc)
Hydramethylnon (amdro)	Extremely Low	10	0.006	730,000
Imazalil	Very Low	150	1400	4000
Imazamethabenz-methyl(m-isomer)	High	45	1370	66
Imazamethabenz-methyl(p-isomer)	Very High	45	857	35
Imazapyr acid	High	90	11,000	100
Imazapyr isopropylamine salt	High	90	500,000	100
Imazaquin acid	Very High	60	60	20
Imazaquin ammonium salt	Very High	60	160,000	20
Imazethapyr	Very High	90	200,000	10
Iprodione	Low	14	13.9	700
Isazofos	High	34	69	100
Isofenphos	Moderate	150	24	600
Isopropalin	Extremely Low	100	0.1	10,000
Isoxaben	Low	100	1	1400
Lactofen	Extremely Low	3	0.1	10,000
Lambda-cyhalothrin	Extremely Low	30	0.005	180,000
Lindane	Moderate	400	7	1100
Linuron	Moderate	60	75	400
MCPA dimethylamine salt	High	25	866,000	20
MCPA ester	Low	25	5	1000

Common Name	Pesticide Movement Rating	Soil (days)	Water Solubility (mg/l)	Sorption Coefficient (soil Koc)
MCPB sodium salt	High	14	200,000	20
MSMA (methanearsonic acid sodium salt)	Very Low	180	1,000,000	7000
Malathion	Extremely Low	1	130	1800
Maleic hydrazide acid	Moderate	30	6000	250
Maleic hydrazide potassium salt	High	30	400,000	20
Mancozeb	Low	70	6	2000
Maneb	Low	70	6	2000
Mecoprop (MCPP) dimethylamine salt	High	21	660,000	20
Mefluidide	Low	4	180	200
Mepiquat chloride salt	Extremely Low	1000	1,000,000	1,000,000
Metalaxyl	Very High	70	8400	50
Metaldehyde	Low	10	230	240
Metham (metam) sodium salt	Moderate	7	963,000	6
Methamidophos	Moderate	6	1,000,000	5
Methazole	Very Low	14	1.5	3000
Methidathion	Low	7	220	400
Methiocarb (mercaptodimethur)	Very Low	30	24	3000
Methomyl	High	30	58,000	72

Common Name	Pesticide Movement Rating	Soil (days)	Water Solubility (mg/l)	Sorption Coefficient (soil Koc)
Methoxychlor	Extremely Low	120	0.1	80,000
Methyl bromide	Very High	55	13,400	22
Methyl isothiocyanate	Moderate	7	7600	6
Methyl parathion	Very Low	5	60	5100
Metiram	Extremely Low	20	0.1	500,000
Metolachlor	High	90	530	200
Metribuzin	High	40	1220	60
Metsulfuron-methyl	High	30	9500	35
Mevinphos	Low	3	600,000	44
Mexacarbate	Low	10	100	300
Mirex	Extremely Low	3000	0.00007	1,000,000
Molinate	Moderate	21	970	190
Monocrotophos	Very High	30	1,000,000	1
Monolinuron	High	60	735	200
Monuron	Very High	170	230	150
Myclobutanil	Moderate	66	142	500
NAA ethyl ester	Low	10	105	300
NAA sodium salt	Moderate	10	419,000	20
Naled	Extremely Low	1	2000	180
Napropamide	Moderate	70	74	700
Naptalam sodium salt	High	14	231,000	20

Common Name	Pesticide Movement Rating	Soil (days)	Water Solubility (mg/l)	Sorption Coefficient (soil Koc)
Napthalene	Low	30	30	500
Neburon	Low	120	5	2500
Nicosulfuron	High	21	22,000	30
Nitrapyrin	Low	10	40	570
Nitrofen	Extremely Low	30	1	10,000
Norflurazon	Low	30	28	700
Oryzalin	Low	20	2.5	600
Oxadiazon	Very Low	60	0.7	3200
Oxamyl	Low	4	282,000	25
Oxycarboxin	Moderate	20	1000	95
Oxydemeton methyl	High	10	1,000,000	10
Oxyfluorfen	Extremely Low	35	0.1	100,000
Oxythioquinox (quinomethionate)	Very Low	30	1	2300
PCNB	Very Low	21	0.44	5000
Paclobutrazol	High	200	35	400
Paraquat dichloride salt	Extremely Low	1000	620,000	1,000,000
Parathion (ethyl parathion)	Very Low	14	24	5000
Pebulate	Low	14	100	430
Pendimethalin	Very Low	90	0.275	5000
Pentachlorophenol	Very High	48	100,000	30

Common Name	Pesticide Movement Rating	Soil (days)	Water Solubility (mg/l)	Sorption Coefficient (soil Koc)
Perfluidone	High	30	500,000	30
Permethrin	Extremely Low	30	0.006	100,000
Petroleum oil	Low	10	100	1000
Phenmedipham	Very Low	30	4.7	2400
Phenthoate	Low	35	11	1000
Phorate	Low	60	22	1000
Phosalone	Very Low	21	3	1800
Phosmet	Low	19	20	820
Phosphamidon	High	17	1,000,000	7
Picloram salt	Very High	90	200,000	16
Piperalin	Very Low	30	20	5000
Pirimicarb	Moderate	10	2700	60
Pirimiphos-ethyl	Moderate	45	93	300
Pirimiphos-methyl	Low	10	9	1000
Primisulfuron-methyl	High	30	70	50
Prochloraz	Moderate	120	34	500
Procymidone	Very Low	7	4.5	1500
Prodiamine	Extremely Low	120	0.013	13,000
Profenofos	Very Low	8	28	2000
Profluralin	Extremely Low	110	0.1	10,000
Promecarb	Moderate	20	91	200

Common Name	Pesticide Movement Rating	Soil (days)	Water Solubility (mg/l)	Sorption Coefficient (soil Koc)
Prometon	Very High	500	720	150
Prometryn	Moderate	60	33	400
Pronamide	Low	60	15	800
Propachlor	Low	6.3	613	80
Propamocarb hydrochloride	Extremely Low	30	1,000,000	1,000,000
Propanil	Extremely Low	1	200	149
Propargite	Very Low	56	0.5	4000
Propazine	High	135	8.6	154
Propham (IPC)	Low	10	250	200
Propiconazole	Moderate	110	110	650
Propoxur	High	30	1800	30
Pyrazon (chloridazon)	Moderate	21	400	120
Pyrethrins	Extremely Low	12	0.001	100,000
Quizalofop-ethyl	Moderate	60	0.31	510
Resmethrin	Extremely Low	30	0.01	100,000
Rotenone	Extremely Low	3	0.2	10,000
Secbumeton	High	60	600	150
Sethoxydim	Low	5	4390	100
Siduron	Moderate	90	18	420
Simazine	High	60	6.2	130
Simetryn	High	60	450	200

Common Name	Pesticide Movement Rating	Soil (days)	Water Solubility (mg/l)	Sorption Coefficient (soil Koc)
Sodium chlorate	Very High	200	100,000	10
Streptomycin sulfate	Extremely Low	1	20,000	339
Sulfometuron-methyl	Moderate	20	70	78
Sulprofos	Extremely Low	140	0	12,000
TCA	Very High	21	1,200,000	3
Tebuthiuron	Very High	360	2500	80
Temephos	Extremely Low	30	0.001	100,000
Terbacil	Very High	120	710	55
Terbufos	Very Low	5	5	500
Terbutryn	Low	42	22	2000
Tetrachlorvinphos	Very Low	2	11	900
Thiabendazole	Low	403	50	2500
Thidiazuron	Low	10	20	110
Thifensulfuron-methyl	Moderate	12	2400	45
Thiobencarb	Low	21	28	900
Thiocyclam-hydrogen Oxalate	Extremely Low	1	84,000	20
Thiodicarb	Low	7	19	350
Thiophanate methyl	Very Low	10	3.5	1830
Thiram	Low	15	30	670
Tolclofos-methyl	Low	30	0.3	2000
Toxaphene	Extremely Low	600	3	100,000

Common Name	Pesticide Movement Rating	Soil (days)	Water Solubility (mg/l)	Sorption Coefficient (soil Koc)
Tralomethrin	Extremely Low	27	0.001	100,000
Triadimefon	Moderate	26	71.5	300
Triadimenol	Moderate	300	47	1000
Triallate	Low	82	4	2400
Tribenuron methyl	Moderate	12	280	46
Tribufos	Very Low	10	2.3	5000
Trichlorfon	High	10	120,000	10
Trichloronate	High	139	50	400
Triclopyr amine salt	Very High	46	2,100,000	20
Triclopyr ester	Low	46	23	780
Tricyclazole	Low	21	1600	1000
Tridiphane	Very Low	28	1.8	5600
Triflumizole	Moderate	14	12,500	40
Trifluralin	Very Low	60	0.3	8000
Triforine	Moderate	21	30	200
Trimethacarb	Low	20	58	400
Triphenyltin hydroxide	Extremely Low	75	1	23,000
Vernolate	Low	12	108	260
Vinclozolin	Moderate	20	1000	100
Zineb	Low	30	10	1000
Ziram	Moderate	30	65	400

Riparian Management Zone Annotated Bibliography

(An asterix following a citation means that only the abstract was acquired)

Section 1: Pollutant-Specific Primary Literature Sources

"Value" in this bibliography refers to the feasibility of using extracted data from the study in a quantitative analysis of buffer effectiveness. The general characteristics of data that were considered in the consideration of value include: accuracy, precision, comparability, completeness, and representativeness, and bias. Value scores range from 0 to 3, with 3 having the highest data quality.

Nitrogen (bolded citation means extractable data)

1. Addy, K.L., Gold, A.J., Groffman, P.M. and Jacinthe, P.A. (1999) Ground water nitrate removal in subsoil of forested and mowed riparian buffer zones. *J. Environ. Qual.* 28:962-970.

   Value: 0 for buffer-nitrogen data analysis because of methodology, 1 for factors influencing nitrogen removal. Location: Rhode Island. Type: Experimental.

   This study compared denitrification rates in the shallow groundwater below forested riparian buffers and mowed herbaceous buffers. Soils were poorly drained, fine to medium sands of glaciofluvial origin (sandy, mixed, mesic, Typic Humaquepts). Site A forested area was dominated by 35-45 yr old red maple; mowed area dominated by sedges and clover. Site B (had been historically cultivated) forested area was dominated by 18 to 23yr old, speckled alder; mowed area dominated by sedges, bluegrass, bromegrass. Soil cores were removed from each area and used to experimentally simulate the riparian areas. Shallow groundwater was periodically collected and pumped through the mesocosms. A mass balance approach was used to evaluate denitrification rates. Significant differences in nitrate removal was found between sites A and B- despite similar soil type, drainage class, and soil morphology; no significant difference was found in nitrate removal between forest and mowed herbaceous buffers. The authors noted that tree roots were found in the subsoil below all herbaceous areas, which may have influenced nitrate removal. Differences in N removal between sites A and B may have been influenced by the presence of nitrogen-fixing alder on Site B. The authors state that water table dynamics, land use legacy, adjacent vegetation, and distribution of subsurface carbon may influence spatial variability in nitrate removal. The authors suggest that "robust" nitrate removal can occur within relatively short distances under a variety of vegetation and climate conditions.

2. Alexander, R.B., Boyer, E.W., Smith, R.A., Schwarz, G.E., and Moore, R.B. 2007. The role of headwater streams in downstream water quality. *JAWRA*, Vol. 43, No. 1. *

   Abstract: "Knowledge of headwater influences on the water-quality and flow conditions of downstream waters is essential to water-resource management at all governmental levels; this includes recent court decisions on the jurisdiction of the Federal Clean Water Act (CWA) over upland areas that contribute to larger downstream water bodies. We review current

watershed research and use a water-quality model to investigate headwater influences on downstream receiving waters. Our evaluations demonstrate the intrinsic connections of headwaters to landscape processes and downstream waters through their influence on the supply, transport, and fate of water and solutes in watersheds. Hydrological processes in headwater catchments control the recharge of subsurface water stores, flow paths, and residence times of water throughout landscapes. The dynamic coupling of hydrological and biogeochemical processes in upland streams further controls the chemical form, timing, and longitudinal distances of solute transport to downstream waters. We apply the spatially explicit, mass-balance watershed model SPARROW to consider transport and transformations of water and nutrients throughout stream networks in the northeastern United States. We simulate fluxes of nitrogen, a primary nutrient that is a water-quality concern for acidification of streams and lakes and eutrophication of coastal waters and refine the model structure to include literature observations of nitrogen removal in streams and lakes. We quantify nitrogen transport from headwaters to downstream navigable waters, where headwaters are defined within the model as first-order, perennial streams that include flow and nitrogen contributions from smaller, intermittent and ephemeral streams. We find that first-order headwaters contribute approximately 70% of the mean-annual water volume and 65% of the nitrogen flux in second-order streams. Their contributions to mean water volume and nitrogen flux decline only marginally to about 55% and 40% in fourth- and higher-order rivers that include navigable waters and their tributaries. These results underscore the profound influence that headwater areas have on shaping downstream water quantity and water quality. The results have relevance to water-resource management and regulatory decisions and potentially broaden understanding of the spatial extent of Federal CWA jurisdiction in U.S. waters."

3. Anbumozhi, V., Radhakrishnan, J., and Yamagi, E. 2005. Impact of riparian buffer zones on water quality and associated management considerations. *Ecological Engineering.* 24: 517-523.

   Value: 0- location/rigor/relevance. Type: observational; Location: Japan, Indonesia, India. The study evaluated water quality relative to riparian land use. Water quality was better where riparian buffers existed. This reference is not particularly useful.

4. Bingham, S.C., Westerman, P.W., and Overcash, M.R. 1980. Effect of grass buffer zone length in reducing the pollution from land application areas. *Trans. ASAE* 23: 330-336.

   Value: 0 for buffer-nitrogen data analysis due to experimental methodology (land application, distribution system, use of area ratios, reporting in concentrations rather than mass). Location: North Carolina. Type: Experimental, control-treatment. This study evaluated the removal of nitrogen and phosphorus from runoff containing poultry manure by grassed buffers of differing lengths. The experiment collected runoff from natural rainfall upon a land application area receiving regular poultry litter applications and used a constructed distribution system to deliver it to buffer plots. Soils were Cecil Series, with clay loam surface and clay subsurface. Plots were graded to 6 to 8% slopes, which caused some

reduced surface horizon thickness on some plots and may have affected infiltration rates. Tall fescue was the dominant vegetation on the plots. Source area lengths were 8.7 to 13m. For nitrate, a buffer area length to waste area length ratio greater than 1.0 generally decreased runoff nitrate concentrations below control concentrations; for total P, a ratio of 1.0 to 2.0 was required. The authors caution that these results cannot necessarily be scaled up to larger areas or where land application areas and buffers do not have similar soils and vegetation.

5. **Borin, M., Vianello, M., Morari, F., and Zanin, G. 2005. Effectiveness of buffer strips in removing pollutants in runoff from a cultivated field in north-east Italy. *Agriculture, Ecosystems and Environment.* 105: 101-114.**

   Value: 3 for surface flow buffer-nitrogen analysis due to rigor, methods. Location: NE Italy. Type: Experimental. Terrain is flat, with a shallow water table (1-3m deep). Mean annual temperature is approx. 12°C and precip averages 32.7 inches (but precip during study was 28.2in, 14% lower). Fields in this area average 1.4 acres. Crops include corn, soybeans, sugar beets and winter wheat. The authors evaluate the effectiveness of a **6m wide buffer** at reducing suspended solids, nitrogen and phosphorus exports from crop fields. Hillslope dimensions were 35m long at 1.8% slope. The buffer was composed of two rows of alternating trees and shrubs (1.5 and 4.5m from the ditch) planted 8 years prior and fescue grass sown throughout the buffer. Soils were loamy, with sand increasing to 50-60% at 1.4m depth. Soil infiltration rates ranged from 2.8 x 10-3 cm s-1 to 2.7 x10-4 cm s-1 in compacted areas; hydraulic conductivity averaged 1.2 x 10-3 cm s-1. Fertilizer application rates ranged from 16 to 150 kg/ha for nitrogen and 0 to 20kg/ha for phosphorus, depending on the crop rotation (winter wheat, maize, and soybean).

   Buffer strips reduced runoff volumes by an average of 80%. No significant difference in export concentrations found for total N (annual median ranged from 5 to 12mg/L). Nitrate (annual median ranged from 1.37 to 3.73 mg/L) and ammonia (annual median ranged from 0.36 to 1.36mg/L) concentrations were significantly higher in runoff exiting the buffer strip. However, **in terms of total mass losses, the buffer reduced losses by: 78% for total N loss by (2.9 vs. 13.4kg/ha), 58% for nitrate, 63% for ammonia.** Relatively few run-off events were responsible for a large proportion of the total pollutant loads.

6. **Borin, M. and Bigon, E. 2002. Abatement of NO3-N concentration in agricultural waters by narrow buffer strips. *Environmental Pollution.* 117: 165-168.**

   Value: 3 for surface flow buffer-nitrogen data analysis. Location: NE Italy. Type: Experimental

   This study examines nitrate abatement by a grass/tree buffer bordering wheat and corn cropland. The buffer consisted of 5m of grass and 1m of deciduous trees. Soils were loamy in upper 0.8 to 1.0m, sandy loam below, with low permeability strata below that. The water table at the field-buffer interface fluctuated between 0.4 and 0.8m below the surface. The soil organic matter content in the upper 0.5m was 2.1%, which is high. Most of the nitrate removal occurred below the field. Overall, the average nitrate concentration reduction through the buffer was 52%. The shallow water table and high organic matter content likely resulted in higher denitrification within the buffer. Tree size in the buffer did not appear to affect nitrate removal.

7. **Burns, D.A. and Nguyen, L. 2002. Nitrate movement and removal along a shallow groundwater flow path in a riparian wetland within a sheep-grazed pastoral catchment: results of a tracer study. *New Zealand Journal of Marine and Freshwater Research*. 36: 371-385.**

   Value: 2 for groundwater buffer-nitrogen data analysis, reductions in concentration rather than mass reported. Location: New Zealand. Type: Observational.

   This study examined nitrate removal by a wetland adjacent to grazed pasture. Upland and wetland soils were steep and clayey (wetland 17% slope, uplands 17 to 84% slope). In the shallow groundwater, 92% of nitrate removal occurred over a 1m distance, although almost all removal occurred in the first 0.3m. However, when rainfall events resulted in surface runoff through the wetland, the wetland did not reduce nitrate in the runoff. The authors assert that wetland soils should be prevented from compaction in order to preserve the rates of nitrate removal.

8. Burt, T.P., Matchett, L.S., Goulding, K.W.T., eta l. 1999. Denitrification in riparian buffer zones: the role of floodplain hydrology. *Hydrological Processes.* 13: 1451-1463.*

   Abstract: "The broad purpose of the study described here was to assess the role of denitrification in riparian zones in ameliorating groundwater pollution through nitrate loss, and as a potential source of nitrous oxide to the atmosphere. A suitable riparian zone was identified at Cuddesdon Mill on the River Thame floodplain near Oxford, England. Measurements were made of water and nitrate moving from arable land through the riparian zone and into the river. Techniques to measure denitrification were tested and applied, and the factors controlling denitrification measured. While there was considerable potential for denitrification at the site, this was not realized because much of the water moving off the farmland bypassed the riparian zone, entering the river directly via springs or through gravel lenses beneath the floodplain soil. Management of this site would not reduce nitrate leaching unless the floodplain hydrology could be substantially modified, and the main conclusion is that nitrate buffer zones will only operate efficiently where the hydrology of the site is appropriate."

9. Cey, E.E., Rudolph, D.L., Aravena, R., and Parkin, G. 1999. Role of riparian zone in controlling the distribution and fate of agricultural nitrogen near a small stream in southern Ontario. *Journal of Contaminant Hydrology.* 37: 45-67.*

Abstract: "Uncultivated riparian areas can play an important role in reducing nutrient loading to streams in agricultural watersheds. Groundwater flow and geochemistry were monitored in the riparian zone of a small agricultural watershed in southern Ontario. Hydraulic and geochemical measurements were taken along a transect of monitoring wells extending across the riparian area into an agricultural field. Chloride and nitrate concentrations in groundwater samples collected from the agricultural field were much higher than in samples from the riparian area. A sharp decline in both nitrate and chloride concentrations was observed near the field-riparian zone boundary. It appears that increased recharge within the riparian zone, as compared to the artificially drained field, caused nitrate-rich groundwater from the field to be diverted downward beneath the riparian zone, thus limiting the input of agrochemicals to the riparian area and consequently protecting the stream from potential contamination. Geochemical data also indicated that nitrate was attenuated in the downward moving groundwater. Patterns of dissolved oxygen concentrations and redox potential in the subsurface coincided with the pattern defined by groundwater nitrate. These patterns indicated that conditions within the riparian zone and at depth near the field-riparian zone boundary were conducive to denitrification. A linear relation between the $\delta\ ^{15}N$ and $\delta\ ^{18}O$ values of nitrate from the monitored transect also supported denitrification as the primary nitrate removal mechanism. This study provides a new conceptual model of how riparian zones may prevent nitrate contamination of streams and highlights the need for a complete understanding of both groundwater flow and geochemistry in riparian environments."

10. **Chaubey, I., Edwards, D.R., Daniel, T.C., Moore Jr. P.A., and Nichols, D.J. 1994. Effectiveness of vegetative filter strips in retaining surface-applied swine manure constituents. *Transactions of the American Society of Agricultural Engineers.* 37: 845-850.**

    Value: 2 of 3 for data analysis- simulated rainfall rather than natural. Location: Arkansas. The authors investigated the efficacy of filter strips in attenuating nitrogen, phosphorus, suspended solids, and fecal coliform in runoff containing liquid swine manure. See summary in the sediment section.

11. **Chaubey, I., Edwards, D.R., Daniel, T.C., Moore Jr. P.A., and Nichols, D.J. 1995. Effectiveness of vegetative filter strips in controlling losses of surface-applied poultry litter constituents. *Transactions of the American Society of Agricultural Engineers.* 38: 1687-1692.**

    Value: 2 of 3 for data analysis- simulated rainfall rather than natural. Location: Arkansas. The authors investigated the efficacy of filter strips in attenuating nitrogen, phosphorus, and suspended solids in runoff containing poultry litter. See summary in the sediment section.

12. **Clausen, J.C., Guillard, K., Sigmund, C.M., and Dors, K. M. 2000. Water quality changes from riparian buffer restoration in Connecticut. *Journal of Environmental Quality.* 29: 1751-1761.**

Value: 1 of 3 for data analysis- groundwater upwelling confounds the removal estimates for nitrate. Location: Connecticut. The authors investigated how TSS, nitrogen, and phosphorus changed when half of a 35 by 250m plot of corn was converted to fescue grass along a first order stream. See the summary in sediment section.

13. **Correll, D.L., Jordan, T.E., and Weller, D.E. 1997. Failure of agricultural riparian buffers to protect surface waters from groundwater nitrate contamination. Pp. 162-165, In: Groundwater/Surface Water Ecotones: Biological and Hydrological Interactions and Management Options. J. Gibert, J. Mathieu and F. Fournier (Eds.). Cambridge: Cambridge Univ. Press. Daniels, R.B., Gilliam, J.W. 1996. Sediment and chemical load reduction by grass and riparian filters. *Soil Science Society of America Journal*. 60: 246-251.**

    Value: 2 for groundwater buffer-nitrogen data analysis, because mass removal not reported. Location: Maryland. Type: Observational. This study examined nitrate removal as shallow groundwater moved from cropland through a floodplain buffer at two different sites. One floodplain site had mixed deciduous hardwoods, the other mown grass. At both sites the shallow groundwater moved through sandy subsoil. Nitrate below the forest buffer declined from 25mg/L at the crop field edge to 17mg/L (32% reduction) over a distance of 48m. For the mown grass buffer nitrate declined from 25mg/L to 14mg/L (44% reduction) over a distance of 37m. Some dilution may have occurred through the addition of groundwater from farther source areas; evidence that groundwater flow rate was higher for the forested buffer could mean that nitrate mass removal was higher than in the grass buffer despite a lesser decline in the concentration.

14. **Daniels, R.B. and Gilliam, J.W. 1996. Sediment and chemical load reduction by grass and riparian filters. *Soil Sci. Soc. Am. J*. 60: 246-251.**

    Value: 1 or 2 for data analysis- because surface flow evaluation only. Location: North Carolina Piedmont. The study evaluated the effectiveness of grassed and forested buffers at removing sediment and nutrients from agricultural runoff at two sites. See summary provided in the sediment section.

15. Dickey, E.C. and Vanderholm, D.H. 1981. Vegetative filter treatment of livestock feedlot runoff. *Journal of Environmental Quality.* 10: 279-284.

    Value: 0 for buffer- nitrogen data analysis because utilizes engineered filtration systems. Location: Illinois. Type: Observational/experimental. This study examines nutrient and pathogen removal from feedlot runoff using constructed overland and channelized flow filter systems. The overland flow area was 12 by 91m. The filtered outflow showed a mass reduction of 97.7% for ammonia and 96.7% for total kjeldahl nitrogen. This reference is not particularly useful for evaluating buffer effectiveness.

16. Dickey, E.C. and Vanderholm, D.H. 1989. Performance and design of vegetative filters for feedlot runoff treatment. *Biological Systems Engineering: Papers and Publications*. 267.

    This paper describes the same study as Dickey and Vanderholm (1981).

17. **Dillaha, T.A., Reneau, R.B., Mostaghimi, S., and Lee, D. 1989. Vegetative filter strips for agricultural nonpoint source pollution control. *Transactions of the American Society of Agricultural Engineers*. 32: 513-519.**

Value: 1 or 2 out of 3, due to surface flow evaluation only. Location: SW Virginia. Abstract: A rainfall simulator was used to evaluate the effectiveness of vegetative filter strips (VFS) for the removal of sediment, nitrogen (N), and phosphorus (P) from cropland runoff. See summary in the phosphorus section.

18. **Dillaha, T.A., Sherrad, J.H., Lee, D., Mostaghimi, S., Shanholtz, V.O. 1988. Evaluation of vegetative filter strips as best management practices for feed lots. *Journal of Water Pollution Control Federation*. 60: 1231-1238.**

Value: 1 or 2 out of 3, due to surface flow evaluation only. Location: SW Virginia. The effectiveness of reducing sediment and nutrients in runoff from a simulated feedlot was evaluated. See summary in the phosphorus section.

19. Dodds, W.K. and Oakes, R.M. 2006. Controls on nutrients across a prairie stream watershed: land use and riparian cover effects. *Environmental Management*. 37: 634-646

Value: 0 for buffer-nitrogen data analysis, 3 for watershed process info. Location: Kansas. Type: Observational. This study examined land use at multiple spatial scales relative to instream concentrations of total phosphorus, total nitrogen and nitrate. 28 sampling sites were distributed throughout a mixed land use watershed with a 1010km^2 drainage area. Headwater basins had tallgrass livestock pasture while lower elevations had a mix of cropland and tallgrass prairie. Confined livestock areas and point source were not observed near sample sites and large CAFOs (animals) did not occur upstream of sample sites. Small headwaters streams were periodically dry or frozen in winter, which limited sample numbers and restricted comparisons to other sites. Catchment-wide and riparian land cover was evaluated for each sample site, as well as riparian land cover within 2km upstream of each sample site. The four major land cover types were forest, cropland, grassland, and urban. Almost all areas of alluvial soils had cropland cover. Riparian land cover at the sub-catchment and local scales was correlated with nitrogen and nitrate concentrations, whereas total P was not. Increasing agricultural intensity was correlated with greater N concentrations. Total N and nitrate levels were most strongly associated with riparian land cover in the sub-catchment above a site. Total P levels were not correlated with catchment or riparian land cover. The dominant pathway for nitrate delivery to surface waters is via subsurface flow. Nitrate levels drove spatial patterns of total N. Where nitrate delivery is primarily via groundwater flowing beneath the plant rooting zone, implementing riparian buffers may not reduce nitrogen levels in streams.

20. Dosskey, M.G.G., Hoagland, K.D., and Brandle, J.R. 2007. Change in filter strip performance over ten years. *Journal of Soil and Water Conservation*. 62: 21-32.

Value: 0 for data analysis- doesn't report results in a useable format. Location: Nebraska. The study sought to determine if the age of buffer strip establishment has an influence upon its ability to remove pollutants from agricultural runoff. For the 7.5m plots

(downgradient of an additional 7m grassed field border, Nitrate + Nitrite removal ranged from about 80 to 90% during years two through eight of the study, for all three of the plot types vegetated with grass or grass+ woody vegetation. See summary in sediment section.

21. Doyle, R.C., Wolf, D.C., and Bezdicek, D.F. 1975. Effectiveness of Forest Buffer Strips in Improving the Water Quality of Manure Polluted Runoff. In *Managing Livestock Wastes Proceedings of the 3rd International Symposium on Livestock Wastes ASAE*, St. Joseph, MI pp. 299-302.

    Value: 1 of 3 for data analysis- evaluated changes in concentrations rather than mass and equated infiltration with removal. Location: Maryland. Type: Experimental. This study examined the effectiveness of a buffer at removing nitrogen, phosphorus, fecal coliform (FC), and fecal streptococcus (FS) from runoff containing dairy manure. See summary in pathogens section.

22. Eghball, B., Gilley, J.E., Kramer, L.A, and Moorman, T.B. 2000. Narrow grass hedge effects on phosphorus and nitrogen in runoff following manure and fertilizer application. *Journal of Soil and Water Conservation*. 55: 172-176.

    Value: 0 for surface flow buffer-nitrogen data analysis due to methods- simulated rainfall with source water containing high level of nitrate. Location: Iowa. Type: experimental. This study examined removal of nutrients in surface runoff by a narrow grass hedge bordering a corn field where feedlot manure and fertilizer application occurred. Soils were Monona silt loams with a 12% slope. 0.75m switchgrass hedges were employed as the filter strip. The target N application rate was 9.4 Mg/hectare. Some field plots were cultivated while others were in no-till. On cultivated fields manure and fertilizer were disked into the soil after application. Simulated rainfall was employed at an initial rate of 6.4cm/hr for one hour at existing soil moisture conditions, followed by a second trial at the same rate 24hrs later. The irrigation water contained 9mg/L of nitrate and 0.29mg/L dissolved P. Reductions for manure application to no-till plots: 47% for dissolved P, 48% for bioavailable P (BAP), 38% for particulate P (PP), 40% for TP, 4% for nitrate, and 60% for NH4-N. Reductions for manure application under disked conditions: 21% for dissolved P, 29% for bioavailable P (BAP), 43% for particulate P (PP), 38% for TP, 4% for nitrate, and 52% for NH4-N. Reductions for fertilizer application to no-till plots: 26% for dissolved P, 28% for bioavailable P (BAP), 22% for particulate P (PP), 24% for TP, -2% for nitrate, and 39% for NH4-N. Reductions for fertilizer application under disked conditions: -15% for dissolved P, -6% for bioavailable P (BAP), 24% for particulate P (PP), 22% for TP, 21% for nitrate, and 61% for NH4-N. More P was lost in plots with manure than fertilizer, but the amount lost was 0.3% for the manure and 3.3% for the fertilizer. More N was lost from fertilizer plots than manure plots, with 10.4% of N lost from fertilizer plots and 2.1% from manure plots.

23. Fajardo, J.J., Bauder, J.W., and Cash, S.D. 2001. Managing nitrate and bacteria in runoff from livestock confinement areas with vegetative filter strips. *Journal of Soil and Water Conservation*. 56: 185-191.

Value: 1 for buffer-nitrogen data analysis due to methods: an extreme runoff volume was used, and source area was livestock confinement area. See summary in pathogen section.

24. Gilley, J.E., Sindelar, A.J., and Woodbury, B.L. 2016. Removal of cattle manure constituents in runoff from no-till cropland as affected by setback distance. *Biological Systems Engineering: Papers and Publications.* 489.

    Value: 0 for buffer-nitrogen data analysis, because the reductions data are not presented in a useable format. Location: Nebraska. Type: Experimental. This study evaluated the removal of nutrients from manure applied to no-till cropland for multiple filter strip widths with runoff generated by simulated rainfall. Soil was Aksarben silty clay loam with 19% sand, 46% silt, 35% clay with a mean slope of 6.2%. Cropland was in wheat, cover crop, soybean, sorghum rotation. Manure was applied to upper 4.9m of the plots. Filter lengths were 0.0, 3.0, 6.1, 12.2, 18.3m. The irrigation water used for simulated rainfall had concentrations of dissolved P, total P, and nitrate at 0.16, 0.16, and 15.8mg/L, respectively. Simulated rainfall was applied at approximately 52mm/hr until steady state flow occurred. Trials were run with and without manure, and with and without additional inflow to increase the overland flow rate. Simulated rainfall was used to saturate the plots 24hrs before the trials were run. The trials without inflow had an average overland flow rate of 25.6L/min. The inflow trials involved adding water to plots to test the filters at flow rates of 49.4, 64.3, and 87.6L/min. There were no nitrate mass reductions for any width filter. Unfortunately, the data are not presented in a way that is useable- the data in table do not match the data in figures and an adequate explanation is not provided to interpret the results.

25. Groffman, P.M., Axelrod, E.A., Lemunyon, J.L., and Sullivan, M. 1991. Denitrification in grass and forest vegetated filter strips. *Journal of Environmental Quality*. 20: 671-674.*

    Abstract: “Denitrification was measured in two grass and two forest vegetated filter strips (VFS) in Rhode Island. The grass plots were established on a well-drained soil and were planted to either tall fescue (Festuca arundinacea) or reed canarygrass (Phalaris arundinacea). One forest site was on an excessively well-drained soil and was dominated by oak (Quercus sp.), and the other was on a poorly drained soil and was dominated by red maple (Acer rubrum). Denitrification was measured using soil cores under aerobic and anaerobic conditions with a range of treatments: no amendment, acetylene, water, nitrate (NO−3), NO−3 plus C. Unamended rates of denitrification were low in all plots. Nitrate and NO−3-plus-C amended rates were consistently higher in the grass plots than in the forest plots. Nitrate-plus carbon-amended rates were higher than NO−3-amended rates in all plots, but the differences were significant ($P < 0.05$) in the forest plots only. Denitrification enzyme activity (DEA) was measured in 14 additional forest sites of varying natural drainage classes and was related to soil moisture ($r2 = 0.56$, $P < 0.01$) and pH ($r2 = 0.43$, $P < 0.01$) at these sites. The results suggest that the ability of VFS to support denitrification varies strongly with vegetation, soil type and pH, and that denitrification in VFS may be amenable to management.”

26. Hay, V., Pittroff, W., Tooman, E.E., and Meyer, D. 2006. Effectiveness of vegetative filter strips in attenuating nutrient and sediment runoff from irrigated pastures. *The Journal of Agricultural Science*. 144: 349-360.

    Value: 0 for buffer-nitrogen data analysis because insufficient data is presented. Location: California. Type: Experimental, control-treatment. This study examines the effectiveness of filter strips at removing TSS, P, N, and fecal coliforms from flood irrigated pasture. See pathogens section for summary.

27. **Haycock, N.E. and Pinay, G. 1993. Groundwater nitrate dynamics in grass and poplar vegetated riparian buffer strips during the winter. *Journal of Environmental Quality*. 22: 273-278.**

    Value: 3 for groundwater buffer-nitrogen data analysis. Location: England. Type: Observational. This study examined retention of nitrate in grass and forest buffers during the winter. A 12m strip of pasture, followed by fertilized cropland was upslope of the buffers. Shallow calcareous soils upslope of the sites were underlain by an unconfined limestone aquifer. The authors note that the floodplain sites were not "underdrained", the meaning of which is unclear. The grass floodplain site was 22m in width, with a maximum saturated width of 16m. The forest buffer was vegetated with poplar and was 26m wide with a maximum saturated width of 20m. The topography upslope of the grass floodplain was gradual, while at the forested site, there were two terraces, followed by a gradual slope upwards. All water flow was shallow subsurface flow- no deeper groundwater or overland flow. At low and moderate groundwater flow rates, a sharp decline in nitrate occurred at both sites within approximately the first 10m of buffer. At high groundwater flow rates, nearly 100% of nitrate was reduced in the first 5m of the forest buffer, but in the grass buffer the nitrate decline took 17m to reach an 84% reduction. The data suggest that high groundwater flow rates caused denitrification to extend upslope of the riparian area as soils became saturated, but that the grassed site was less efficient at removal than the forested site. The authors suggest that greater N reductions below the forest buffer may have been due to greater carbon supply from the trees. **Multiple studies are cited as finding that most of the nitrate removal was in the first several meters of a buffer- this is why caution must be applied so as not to attribute the full removal amount to the full buffer width unless the authors explicitly state that it took the full buffer width to remove the nitrate.** It is suggested that nitrate removal requires infiltration of runoff and that nitrate will not be removed from surface flow.

28. **Heathwaite, A.L., Griffiths, P., and Parkinson, R.J. 1998. Nitrogen and phosphorus in runoff from grassland with buffer strips following application of fertilizers and manures. *Soil Use and Management*. 14: 142-148.***

    Value: 3 for nitrogen-buffer data analysis. Abstract: "We examined whether nitrogen (N) and phosphorus (P) export was enhanced from grassland receiving inorganic fertilizer and manures typical of intensive livestock production. Buffer strips were included in the study to determine if they could reduce nutrient export. Hillslope plots receiving granular inorganic fertilizer, liquid cattle slurry and solid cattle manure (FYM) were compared using rainfall simulation for 4 storms on consecutive days at 22 mm h-1 and 35 minutes duration. The plots were hydrologically isolated in a randomized block layout of 4 treatments × 3 replicates and measured 30 × 5m; the upper 20m received either fertilizer, slurry or FYM, **while the lower 10 m acted as an unfertilized grass buffer strip. Nitrogen and P export in surface runoff from grassland receiving inorganic fertilizer exceeded that from FYM or slurry treatments**; concentrations up to46mgN1--1 and 15 mgP1–1 were recorded.

Sixty-eight % and 62% of the N from FYM and slurry respectively, was exported in organic form. Seventy-four % (FYM) and 39% (slurry) of the P was in particulate or dissolved organic form. The buffer strip reduced N export in surface runoff by 94% and P export by 98% from inorganic fertilizer plots. A 75% reduction in N export was recorded from the buffer zone below slurry plots but only a 10% reduction in P, with most P remaining in the particulate or dissolved organic fraction. There was no significant difference in N export from the buffer zone between the inorganic fertilizer treatment and the untreated control."

29. Hill, A.R., Vidon, P.G.F., and Langat, J. 2004. Denitrification potential in relation to lithology in five headwater riparian zones. *Journal of Environmental Quality*. 33: 911-919*

    Abstract: "The influence of riparian zone lithology on nitrate dynamics is poorly understood. We investigated vertical variations in potential denitrification activity in relation to the lithology and stratigraphy of five headwater riparian zones on glacial till and outwash landscapes in southern Ontario, Canada. Conductive coarse sand and gravel layers occurred in four of the five riparian areas. These layers were thin and did not extend to the field-riparian perimeter in some riparian zones, which limited their role as conduits for ground water flow. We found widespread organic-rich layers at depths ranging from 40 to 300 cm that resulted from natural floodplain processes and the burial of surface soils by rapid valley-bottom sedimentation after European settlement. The organic matter content of these layers varied considerably from 2 to 5% (relic channel deposit) to 5 to 21% (buried soils) and 30 to 62% (buried peat). Denitrification potential (DNP) was measured by the acetylene block method in sediment slurries amended with nitrate. The highest DNP rates were usually found in the top 0- to 15-cm surface soil layer in all riparian zones. However, a steep decline in DNP with depth was often absent and high DNP activity occurred in the deep organic-rich layers. Water table variations in 2000-2002 indicated that ground water only interacted frequently with riparian surface soils between late March and May, whereas subsurface organic layers that sustain considerable DNP were below the water table for most of the year. These results suggest that riparian zones with organic deposits at depth may effectively remove nitrate from ground water even when the water table does not interact with organic-rich surface soil horizons."

30. Houlahan, J.E. and Findlay, C.S. 2004. Estimating the 'critical' distance at which adjacent land-use degrades wetland water and sediment quality. *Landscape Ecology*. 19: 677-690.

Value: 0 for buffer-nitrogen data analysis. Location: Ontario, Canada. This study used modelling to evaluate the relationship between land use and nutrient concentrations in wetland water and sediment. Total P and Total Kjeldahl nitrogen showed significant negative correlations with forest cover, whereas nitrate did not. The study attempted to link wetland nutrient levels with buffer widths based on landscape scale correlations, but the supporting evidence is weak. For example, the authors found that as the expanse of forest cover surrounding a wetland increases, total P decreases, and the effect of forest cover on wetland phosphorus levels can be detected out to 2250m. This led them to suggest that buffers thousands of meters wide may be necessary to control sediment and nutrient loads. However, there was no analysis of whether the forest out to 2000m and beyond was even in the watershed containing the wetlands.

31. Jacobs, T.C. and Gilliam, J.W. 1985. Riparian losses of nitrate from agricultural drainage waters. *Journal of Environmental Quality*. 14: 472-478.*

Value: 1 for nitrogen removal process info. Abstract: "Increased nutrient levels in surface streams and eutrophication of some Coastal Plain waters has led to inquiries about both the amount and control of nitrate losses from agricultural fields. Nitrate concentrations in shallow groundwaters beneath cultivated fields and in the drainage waters from those fields were examined to determine the fate of nitrogen lost to drainage waters. From a Middle Coastal Plain watershed where well- and moderately well-drained soils dominate agricultural fields, 10 to 55 kg ha^{-1} yr^{-1} NO_3-N moved from the fields in subsurface drainage water. However, most fields are bordered by forested buffers between the cultivated areas and streams which consist of poorly and very poorly drained soils covered by dense vegetation. The evidence strongly indicated that a substantial part of the nitrate in the drainage water was denitrified in the buffer strip and that assimilation by vegetation was insignificant. Buffer strips of < 16 m were effective for inducing significant losses of nitrate before drainage water reached the stream. A field containing subsurface drainage tubing which emptied into open ditches moved more nitrogen into surface water than those fields without subsurface drainage improvements. From a Lower Coastal Plain watershed, a dense clay layer below the surface horizon reduced subsurface drainage resulting in total losses from the field of only 6 to 12 kg ha^{-1} yr^{-1} NO_3-N. These losses were mostly in surface runoff. The extensive floodplain of the natural stream had a high capacity to reduce large quantities of N but the low total loss from the watershed is largely a result of low input to the drainage water from nonpoint sources. Soils included in this study were Typic Paleudults, Arenic Paleudults, Aquic Hapludults, and Aeric Paleaquults."

32. Jordan, T.E., Correll, D.L., and Weller, D.E. 1993. Nutrient interception by a riparian forest receiving inputs from adjacent cropland. *Journal of Environmental Quality*. 22: 467-473.

Value: 2 for groundwater buffer-nitrogen data analysis, 1 for nitrogen removal process info. Location: Maryland. Type: Observational. This study evaluated nutrient removal from shallow groundwater beneath a forested buffer adjacent to cropland. Soils were sandy, becoming gravelly near the interface with a clayey formation multiple meters thick starting about 0.5 m below the surface horizons. The riparian buffer existed from the stream on the floodplain for about 30m, where it extended up the hillslope about 20m to the upper edge of the terrace and the edge of the cropland, which was about 5m higher elevation than the floodplain. The max groundwater elevation was about 4m below the surface of the terrace and less than 0.25m below the surface of the floodplain. Nitrate concentrations declined from about 8mg/L to 0.4mg/L in the first 30m of the buffer, with the steepest decline occurring between 25 and 30m into the buffer, which was where the terrace leveled out into the floodplain and where the elevation of the shallow groundwater was within 0.25m of the soil surface. Between station 22.5 and 309 there was a decrease in nitrate concentration of approx. 83%. Cl tracer indicated that dilution was not responsible for the decline in concentration.

33. Kozlowski, D.F., Hall, R.K., Swanson, S.R. and Heggem, D.T. 2016 Linking management and riparian physical functions to water quality and aquatic habitat. *Journal of Water Resource and Protection*, 8. pp 797-815.

    Value: 0 for buffer-nitrogen data analysis. Type: Observational, before-after. Location: Nevada. This paper provides a retrospective before/after comparison of wetland/riparian assessments (1994 vs. 2006) and water quality data (before/after 1994) for a watershed (Maggie Creek) in which prescriptive livestock management was implemented in 1994. See summary in sediment section.

34. **Kuusemets, V., Mander, Ü., Lõhmus, K., and Ivask, M. 2001. Nitrogen and phosphorus variation in shallow groundwater and assimilation in plants in complex riparian buffer zones. *Water Science and Technology*. Vol. 44 No. 11-12. pp 615-622.**

    Value: 3 for groundwater buffer-nitrogen data analysis, because addresses groundwater. Location: Estonia.

    This study examined nitrogen and phosphorus removal from shallow groundwater through buffers at two different sites. The Viiratsi site was located in an area with glacial moraines and the buffer occurred adjacent to a pig farm where waste was applied to fields. The buffer consisted of an 11m strip of grassland and young alder, a 12m wide wet grassland, and a 28m wide grey alder forest on clay soils. The Porijogi site consisted of cropland and grassland where agriculture had ceased 2 years prior, followed by a buffer consisting of an 11m wide wet grassland on clay soils, and 20m of grey alder forest, also on clay soils. The groundwater table was 1 to 2m below the fields, and 0.1 to 0.8m below the riparian buffers. Soil and plant biomass were sampled for nutrient analysis. At the Viiratsi site, total nitrogen concentration declined from an average of 19.1mg/L below the field to an average of 2.9mg/L at the end of the buffer; a 38% reduction in total N occurred in the first 2m of the buffer, followed by a 69% reduction below the wet meadow, and a 33% decrease below the alder forest (cumulative reduction of 86%). Total P concentration had a cumulative decrease of 84% through the buffer system. N uptake at the Viiratsi site was much higher in the wet meadow than in the alder stand. At the Porijogi site, total P concentration decreased by 78% from the lowermost abandoned field on through the buffer, while total N declined by 35%. Both N and P soil contents increased in the wet meadow portions of the buffers.

35. **Lee, K-H., Isenhart, T.M., and Schultz, R.C. 2003. Sediment and nutrient removal in an established multi-species riparian buffer. *Journal of Soil and Water Conservation*. 58: 1-8.**

    Value: 2. Type: Experimental, control-treatment. Location: Iowa. The authors investigated sediment and nutrient removal in buffers of different widths and vegetation composition. See sediment section for summary.

36. **Lee, K-H., Isenhart, T.M., Schultz, R.C., and Mickelson, S.K. 2000. Multispecies riparian buffers trap sediment and nutrients during rainfall simulations. *Journal of Environmental Quality*. 29: 1200-1205.***

    Value: 2. Type: Experimental, control-treatment. Location: Iowa. See sediment section for abstract.

37. **Lee, K-H. 1999. Effectiveness of a multi-species riparian buffer system for sediment and nutrient removal. *Retrospective Theses and Dissertations*. 12148. IA State University. Ames, IA. https://lib.dr.iastate.edu/rtd/12148.**

    Value: 2. Type: Experimental, control-treatment. Location: Iowa. The author investigated sediment and nutrient removal in buffers of different widths and vegetation composition. See sediment section for summary.

38. **Lim, T.T., Edwards, D.R., Workman, S.R., Larson, B.T., and Dunn, L. 1998. Vegetated filter strip removal of cattle manure constituents in runoff. *Transactions of the American Society of Agricultural Engineers*. 41: 1375-1381**

    Value: 1 of 3 for data analysis, due to study methods (near worst case scenario, and for lack of comparable parameter- TKN). Type: Experimental, before-after treatment. Location: Kentucky. The authors studied the influence of vegetated filter strip (VFS) length on the reductions (concentrations and mass) in the transport of nitrogen, phosphorus, suspended and total solids, and fecal coliform from plots treated with cattle manure. See sediment section for summary.

39. **Lowrance, R. and Sheridan, J.M. 2005. Surface runoff water quality in a managed three zone riparian buffer. *Journal of Environmental Quality*. 34: 1851-1859.**

    Value: 1 for buffer-nitrogen data analysis due to some comparability issues. Type: Observational. Location: Georgia. This study evaluates the performance of a three-zone riparian buffer at removing N and P from cropland runoff. Both riparian and upland soils were loamy sands, but the upland soil had a plinthic subsurface horizon, and the riparian soil had a high-water table for a large portion of the year. Zone 3 of the buffer (upland most zone) was an 8m strip of warm and cool season grass. Zone 2 was a 45 to 60m wide swath of pine. Zone 1 was a 15m wide strip of hardwoods. One section of zone 2 was clearcut, another cut to ½ basal area, and the third left alone. Surface runoff samples were collected between December 1992 and December 1996. Samples could not be collected from water exiting Zone 1, so they were collected at the upslope edge of that zone; therefore, the results only represent filtering through the grass zone, the pine zone, and the two combined. Results for all three zone 2 treatments combined are as follows: the grass buffer reduced the nitrate load by 68%, whereas the grass and pine zones combined had a lower reduction at 44%; total N was reduced by 67% by the grass zone and 37% for the grass and pine zones combined; both total P and dissolved P loads were reduced 67% by the grass zone and 56% for the grass and pine zones combined. Groundwater was not sampled, so it is unknown how much of the reductions in surface N and P loads translated into actual reductions to the stream; it was observed that runoff increased at position 4, just inside zone 1 possibly due to exfiltrating groundwater, such that N and P loads likely also increased.

40. Lowrance, R., Williams, R.G., Inamdar, I. P., Bosch, D.D., and Sheridan, J.M. 2001. Evaluation of coastal plain conservation buffers using the riparian ecosystem management model. *JAWRA* Vol. 37, No. 6.

    Value: 0 for buffer-nitrogen data analysis. Location: Georgia. Type: model. This study employed a USDA riparian model to evaluate nutrient removal rates (under 2 different loading scenarios) for 14 different NRCS buffer configurations (4.6m to 51.8m widths) associated with three zone buffers (z1- hardwoods, z2- pines, z3-grass) at an experimental farm in Georgia. Riparian soils were moderately deep loamy sands with a plinthic subsurface horizon that greatly restricted water percolation. The water table depth among seasons varied from 0 to 200cm. The 4.6m buffer had a large amount of seepage directly to the streams due to limited storage capacity. As buffer width increased, increase storage capacity resulted in lower seepage discharge, proportionally greater subsurface flow, and lower overall discharge to streams due to increased evapotranspiration. Surface runoff was also greatest for the narrower buffers. Beyond a width of 7.6m, buffer width no longer affected discharge and seepage. Pines and grass had higher evapotranspiration rates than hardwoods and so their addition to the buffers resulted in lower buffer discharge. Under both normal and high runoff loading rates, sediment removal was greater than 90% for buffers at least 16.8m wide and sediment removal did not increase substantially beyond that width. For high nitrogen loading rates, the narrowest buffer had an N discharge rate 20 times greater than the widest buffer (a 5% nitrogen reduction vs. a >95% reduction). Nitrate output from buffers was roughly proportional to the amount of seepage and subsurface flow. Removing at least 50% of nitrogen for both the high and normal loading scenarios required a buffer width of at least 10.7m. Most of the phosphorus output from buffers was delivered to the stream as dissolved P via surface runoff. The 51.8m buffer reduced the dissolved P load by 55% whereas the 4.6m buffer reduced it by 24%. For total P, the 4.6m buffer reduced loads by 62% while the 51.8m buffer reduced loads by 90%. For wider buffers, the high loading scenario resulted in greater N and P reductions because the buffer outputs were roughly equal between the high and normal loading scenarios, despite higher inputs for the high loading scenario. The per hectare denitrification rate decreased with increasing buffer size (suggesting nitrate supply was limiting) resulting in the 10.7 to 16.8m buffers having the greatest per hectare rates; these buffers were saturated most of the year and likely had a water storage volume balanced with the nitrate supply. A decrease in seepage from the 4.6m to the 10.7m buffers was coincided with an increase in denitrification. Denitrification rates were double or more for the high loading scenarios than the normal loading scenarios for all but the narrowest buffer. Adding pines or grass to the buffers reduced per hectare N and P uptake rates.

41. **Lowrance, R., Hubbard, R.K., and Williams, R.G. 2000. Effects of a managed three zone riparian buffer system on shallow groundwater quality in the southeastern Coastal Plain. *Journal of Soil and Water Conservation*. 55: 212-220.***

    Same sites as Lowrance, 2005. Abstract: "Riparian Forest buffers can help improve agricultural water quality. USDA guidelines are for riparian forest buffers of three zones. Zone 1 is permanent woody vegetation near the stream. Trees can be harvested in Zone 2, which is upslope from Zone 1. Zone 3 is a grass filter upslope from Zone 2 at field edge. In order to test USDA guidelines, a site was established in the southeastern Coastal Plain near Tifton, Georgia, with an 8 m wide grass buffer (Zone 3) situated between a field and a mature Riparian Forest. In the Zone 2 forest, mostly 50-year-old pine trees, one block was harvested by clearcut, one block was thinned, and one block was left as a mature forest control. Care was taken to minimize soil disturbance during the timber harvest operation. The Zone 1 forest [15 m wide (49 ft)] was left undisturbed. Shallow groundwater wells were used to monitor the effects of the managed riparian forest buffer on N, P, and Cl concentrations. Groundwater nitrate concentrations decreased from 11 to 22 mg L-1 adjacent to the field to less than 2 mg L-1 at 5 m (16 ft) into the forest. Nitrate concentration decreased under the grass filter strip as well as in the forest. Nitrate concentrations increased in one corner of the riparian forest near the stream. This increase may be due to flow patterns of groundwater that bypasses the riparian forest buffer. Chloride concentrations increased under the buffer indicating that the nitrate removal was due to biological processes such as plant uptake and denitrification rather than dilution. Concentrations of other potential pollutants such as ortho-p, ammonium, and organic N moved in very small quantities and did not show consistent spatial patterns. There was no effect due to harvesting of the Zone 2 forest on either nutrient concentrations or water table elevations. These results indicate that Zone 2 trees, along small streams in the southeastern coastal plain, can be harvested with little effect on groundwater nutrient movement to streams."

42. Lowrance, R., Todd, R., Fail Jr., J., Hendrickson, Jr., O., Leonard, R., and Asmussen, L. 1984. Riparian forests as nutrient filters in agricultural watersheds. *BioScience*. 34: 374-377.

Value: 0 for buffer-nitrogen data analysis. Location: Georgia coastal plain. Type: In this study, the role of riparian buffers in an estimated nitrogen and phosphorus budget was examined for a small agricultural watershed. It was estimated that 80 to 96% of water flow occurred as subsurface flow. An aquiclude forced infiltrated precipitation to flow laterally to streams as shallow groundwater. Inputs, outputs, and vegetation storage of N and P were measured. By itself, the amount of denitrification occurring in the shallow groundwater in riparian buffers was enough to offset the amount of N entering the buffers from upland crop fields. Other inputs of N were from precipitation and plant mediated bacterial N-fixation. The budget suggested that more phosphorus was uptaken by riparian vegetation than was supplied form the upland crop fields.

43. Lowrance, R.R., Todd, R.L. and Asmussen, L.E. 1983. Waterborne nutrient budgets for the riparian zone of an agricultural watershed. *Agriculture Ecosyst. Environ*. 10:371-384.*

Abstract: "Agroecosystems in the southeastern United States Coastal Plain typically have uplands in agriculture with mixed hardwood forests along the stream channels. This study determined the inputs and outputs of waterborne nutrients for the riparian forest ecosystem of an agricultural watershed. Quantities of phreatic groundwater and precipitation nutrient inputs and phreatic and surface nutrient outputs were determined during 1979. Based on input/output budgets, these streamside forests were shown to be effective in retaining N, P, Ca, and Mg. Partial conversion of the riparian forest to cropland was projected to increase NO3-N and NH4-N loads by up to 800%. Total replacement of riparian forest with crops would increase loads of all nutrients studied except organic N, DMRP, and total P. Land managers can maintain the nutrient filtering capacity of the streamside forest by selective harvesting of hardwoods and by maintaining the present hydrologic regime."

44. Lupon, A., Bernal, S., Poblador, S., Marti, E., and Sabater, F. 2016. The influence of riparian evapotranspiration on stream hydrology and nitrogen retention in a subhumid Mediterranean catchment. Hydrol. Earth Syst. Sci., 20, 3831-3842.*

Abstract: "Riparian evapotranspiration (ET) can influence stream hydrology at catchment scale by promoting the net loss of water from the stream towards the riparian zone (i.e., stream hydrological retention). However, the consequences of stream hydrological retention on nitrogen dynamics are not well understood. To fill this gap of knowledge, we investigated changes in riparian ET, stream discharge, and nutrient chemistry in two contiguous reaches (headwater and valley) with contrasted riparian forest size in a small forested Mediterranean catchment. Additionally, riparian groundwater level (h_{gw}) was measured at the valley reach. The temporal pattern of riparian ET was similar between reaches and was positively correlated with h_{gw} (ρ=0.60) and negatively correlated with net riparian groundwater inputs (ρ <-0.55). During the vegetative period, stream hydrological retention occurred mostly at the valley reach (59% of the time), and was accompanied by in-stream nitrate release and ammonium uptake. During the dormant period, when the stream gained water from riparian groundwater, results showed small influences of riparian

ET on stream hydrology and nitrogen concentrations. Despite being a small component of annual water budgets (4.5 %), our results highlight that riparian ET drives stream and groundwater hydrology in this Mediterranean catchment."

45. Lynch, J.A., Corbett, E.S., and Mussallem, K. 1985. Best management practices for controlling nonpoint-source pollution on forested watersheds. *Journal of Soil and Water Conservation*. 40: 164-167.

    Value: 0 for nitrogen data analysis- this is a logging effects study, not nitrogen removal study. Type: Experimental, control-treatment. Location: Pennsylvania. See summary in sediment section.

46. Lynch, J.A. and Corbett, E.S. 1990. Evaluation of best management practices for controlling nonpoint pollution from silvicultural operations. *JAWRA* Vol. 26 No. 1.

    Value: 0 for nitrogen data analysis- this is a logging effects study, not nitrogen removal study. Type: Experimental, control-treatment. Location: Pennsylvania. The study evaluated the efficacy of forest harvesting BMPs at preventing nitrate, temperature, suspended sediments, and turbidity in streams. See summary in sediment section.

47. Magette, W.L., Brinsfield, R.B., Palmer, R.E., Wood, J.D. 1989. Nutrient and sediment removal by vegetated filter strips. *Transactions of the American Society of Agricultural Engineers*. 32: 663-667.

    Value: 0 because this is a worst-case scenario study that forced simulated runoff through the entire buffer; consequently, nitrogen concentrations exceeded initial application amounts in every test run. Type: Experimental, control-treatment. Location: mid-Atlantic Coastal Plain- Maryland. The authors evaluated sediment and nutrient retention by vegetated filters strips under simulated rainfall. See sediment section for summary.

48. **Mander, Ü., Kuusemets, V., Lõhums, K., Mauring, T. 1997. Efficiency and dimensioning of riparian buffer zones in agricultural catchments. *Ecological Engineering*. 8: 299-324.**

    Value: 2 for groundwater buffer data analysis. Location: Estonia. This study is associated with Kuusemets et al. 2001. The authors perform a meta-analysis of nutrient retention in riparian zones and also present an efficiency assessment for nutrient retention for sites in Estonia and the U.S. Biological processes removing nitrogen from runoff in riparian ecosystems include vegetation uptake and storage; microbial transformation of inorganic nitrogen into organic nitrogen and storage in soils; and microbial mediated denitrification into nitrogen gas. A table is presented with published rates of nitrogen removal for different processes and ecosystems. Denitrification rates in riparian areas have been found to range from <1 to 1600kg per hectare per year. Vegetation uptake of nitrogen in riparian areas has been found to range from <10 to 350 kg per hectare per year, with the highest amount in riparian meadows. Processes resulting in the capture of phosphorus in riparian zones include: 1) soil adsorption; 2) plant uptake of dissolved organic phosphorus; 3) microbial uptake; and 4) organic phosphorus incorporation into peat. A table is presented with published rates of phosphorus removal for different processes and ecosystems. Soil adsorption has been found to range from 0.1 to 236 kg P per hectare per year and vegetation uptake from <10 to 350 kg per hectare per year. Between the Estonian two sites (Porijogi- 20m buffer and Viiratsi- 28m buffer) the buffer removal efficiency ranged from 2.9 to 4.1% per meter for nitrogen and 2.9 to 3.5% for phosphorus. These rates translate to a theoretical 100% retention for a buffer width between approximately 24 and 34.5 m. Field results: For the Porijogi site with a 20m alder buffer N and P retention were 81 and 67% respectively, while for the Viiratsi site with a 28m alder buffer it was 80 and 81% for N and P respectively. Note: this paper is somewhat difficult to follow.

49. Mankin, K.R., Barnes, P.L., Harner, J.P., et al. 2006. Field evaluation of vegetative filter effectiveness and runoff quality from unstocked feedlots. *Journal of Soil and Water Conservation*. 61: 209-217.

    Value: 0 for buffer-nitrogen data analysis because the study results are not comparable to other study data since it was conducted on feedlot runoff management systems having a runoff collection and distribution system. Location: Kansas. Type: Observational. See Pathogens section for abstract.

50. Mayer, P.M, Reynolds, Jr., R.K., McCutchen, M.D., Canfield, T.J. 2007. Meta-analysis of nitrogen removal in riparian buffers. *J. Environ. Qual.* 36: 1172-1180.

    Value 1 or 2. The authors performed a meta-analysis of nitrogen removal from surface and subsurface flow through buffers. They used much, if not all the same data as in the 2005 EPA review of nitrogen removal by buffers. Their analysis found that subsurface nitrogen removal was not related to buffer width and that a small, but significant (R^2 = 0.21) reduction in nitrogen from surface flow was explained by buffer width. Based on the poor model results, their predictions for buffer widths needed to remove nitrogen from surface flow are not valuable. The results are confounded by inclusion of incomparable/inaccurate study data. For example, it is not appropriate to attribute a full buffer width to an observed nitrate removal if most of the denitrification occurs in a narrow portion of the full buffer width. This greatly skews the buffer width estimates. This is evident through careful review of studies associated with data points presented in the 2005 EPA document, which were also included in this study. Nitrogen removal from surface flow was likely due to infiltration of surface runoff, but this is not the same as removal, since nitrate is known to be readily transported via shallow subsurface flow. Prior studies had already shown that nitrogen removal from surface flow is ineffective, so it is unclear why the authors decided not to more fully evaluate removal for subsurface flow. The authors suggest that buffer width is a surrogate for the intensity of processes driving nitrogen removal in buffers. Such processes include soil physics, subsurface hydrology, and subsurface biogeochemistry (e.g. organic carbon supply, nitrate inputs). This study should have parsed apart buffer effectiveness for subsurface flow based on differences in the factors noted above; this would likely have reduced the variability in their regression analyses.

51. McKergow, L.A., Weaver, D.M., Prosser, I.M., Grayson, R., and Reed, A.E.G. 2003. Before and after riparian management: sediment and nutrient exports from a small agricultural catchment, Western Australia. *Journal of Hydrology*. 270: 253-272.

    Value: 1. Type: Observational, Chronosequence. Location: western Australia. This study evaluated changes in sediment and nutrients delivered to a stream as a result of riparian livestock fencing. See sediment section for summary.

52. **Mihara, M. 2006. The effect of natural weed buffers on soil and nitrogen losses in Japan. *Catena*. 65: 265-271.**

    Value: 2 for buffer-nitrogen data analysis. Type: Experimental. Location: Japan. See summary in sediment section.

53. Neilen, A.D., Chen, C.R., Parker, B.M., Faggotter, S.J., and Burford, M.A. 2017. Differences in nitrate and phosphorus export between wooded and grassed riparian zones from farmland to receiving waterways under varying rainfall conditions. *Science of the Total Environment*, 598. pp. 188-197.

    Value: 0 for buffer-nitrogen data analysis, 2 for nutrient transport process info. Location: Australia. Type: Observational. This study examined variation in nitrate and phosphorus exports through grassed vs. wooded riparian buffers and under differing amounts of rainfall. Soils were loamy sands derived from oxidized basalts. The results suggested that woody buffers exported less P than grassed buffers regardless of rainfall amount. P appeared to be retained by physical rather than biological processes. Under high rainfall conditions, grassed buffers had lower nitrate export than wooded buffers. N leaching increased in wooded buffers under high rainfall. Wooded buffers did not reduce nitrate exports. It was inferred that during low rainfall, soil microbial processes were more important for N removal than vegetative uptake.

54. **Newbold, J.D., Herbert, S., Sweeney, B.W, Kiry, P. and Alberts, S.J. 2010. Water quality functions of a 15-year-old riparian forest buffer system. *JAWRA*, 46: 2: 299-310.**

    Value: 2 for buffer-nitrogen data analysis, due to rigor, comparability. Type: Experimental, treatment-control. Location: Pennsylvania. The study evaluated the long-term effectiveness of a three-zone buffer at removing suspended solids, nitrogen and phosphorus from runoff. See sediment section for summary.

55. Núñez Delgado, A., Periago, E.L., and Diaz-Fierros, F. 1997. Effectiveness of buffer strips for attenuation of ammonium and nitrate levels in runoff from pasture amended with cattle slurry or inorganic fertiliser. Pp. 134-139, In: *Buffer Zones: Their Processes and Potential in Water Protection*. N. Haycock, T. Burt, K. Goulding and G. Pinay (Eds.). Harpenden, UK: Quest Environmental.

    Value: 0 for buffer-nitrogen data analysis due to methods (lack of control) how results were presented. Location: Spain. This study evaluated nitrate and ammonia removal by filter strips for manure slurry versus inorganic fertilizer. The article is difficult to follow in terms of the methods and results and thus not very useful.

56. Omernik, J.M., Abernathy, A.R., and Male, L.M. 1981. Stream nutrient levels and proximity of agricultural and forest land to streams: some relationships. *Journal of Soil and Water Conservation*. 36: 227-231.*

    Abstract: "The effectiveness of forested buffer strips for controlling nutrient loss from agricultural land to streams is not well documented. To clarify this effectiveness, an attempt was made to determine whether considering the proximity of two land use types (agriculture and forest) to streams improved the ability to predict nutrient levels over simply using the proportion of watersheds occupied by each land use. Results indicated that considering the proximity of these land uses did not improve this predictive ability. One reason may be that the long-term effects of near-stream vegetation in reducing stream nutrient levels is negligible."

    Another explanation is that nitrogen removal is not strongly tied to buffer width, but rather subsurface characteristics- things such as soils types, hydraulic conductivity, the depth to groundwater, and biogeochemical processes.

57. Parsons, J.E., Daniels, R.B., Gilliam, J.W., and Dillaha, T.A. 1994. Reduction in sediment and chemical load agricultural field runoff by vegetative filter strips. *UNC-WRRI-94-286*. University of North Carolina. Raleigh, NC.

    Value: 0 because data not presented in a complete or readily useable format. Type: Experimental, treatment-control. Location: Coastal Plain and Piedmont, North Carolina. The authors investigated the performance of grass filters followed by riparian buffers at reducing sediment and nutrients from crop fields after natural rainfall events. See summary in sediment section.

58. **Patty, L., B. Real, and J.J. Gril. 1997. The use of grassed buffer strips to remove pesticides, nitrate and soluble phosphorus compounds from runoff water. *Pesticide Sci*.49:243-251.**

    Value: 3 for nitrogen-buffer analysis. Location: France. Type: Experimental, control-treatment, before-after. See summary in toxics section.

59. Peterjohn, W.T.; Correll, D.L. 1984. Nutrient dynamics in an agricultural watershed: observations on the role a riparian forest. Ecology. 65: 1466-1475.*

    Abstract: "Nutrient (C, N, and P) concentration changes were measured in surface runoff and shallow groundwater as they moved through a small agricultural (cropland) watershed located in Maryland. During the study period (March 1981 to March 1982), dramatic changes in water—borne nutrient loads occurred in the riparian forest of the watershed. From surface runoff waters that had transited 50 m of riparian forest, an estimated 4.1 Mg of particulates, 11 kg of particulate organic—N, 0.83 kg of ammonium—N, 2.7 kg of nitrate—N and 3.0 kg of total particulate—P per ha of riparian forest were removed during the study year. In addition, an estimated removal of 45 kg°ha—1°yr—1 of nitrate N occurred in subsurface flow as it moved through the riparian zone. Nutrient uptake rates for the cropland are riparian forest were estimated. These systems were then compared with respect to their pathways of nutrient flow and ability to retain nutrients. The cropland appeared to retain fewer nutrients than the riparian forest and is thought to incur the majority of its nutrient losses in harvested crop. The dominant pathway of total—N loss from the riparian forest seemed to be subsurface flux. Total phosphorus loss from the riparian forest appeared almost evenly divided between surface and subsurface losses. Nutrient removals in the riparian forest and thought to be of ecological significance to receiving waters and indicate that coupling natural systems and managed habitats within a watershed may reduce diffuse—source pollution."

60. Pinay, G. and DeCamps, H. 1988. The role of riparian woods in regulating nitrogen fluxes between the alluvial aquifer and surface water: a conceptual model. *Regulated Rivers: Research and Management* Vol. 2. 507-516.

    Value: 0 for buffer-nitrogen data analysis- no useable data. Location: France. Type: Observational. This study evaluates nitrate removal through a forested buffer under three differing levels of subsurface saturation and presents a conceptual model for removal processed. The study indicated that the riparian forest had a much greater denitrification potential than was observed, and that the observed rate was limited by the nitrate supply. The authors surmised that a 30m buffer was sufficient to eliminate all nitrate in groundwater derived from the upland agricultural fields.

    Non-saturated sites: The soil was never completely saturated. In winter, the surficial aerobic zone allows for mineralization of nitrogen to nitrate, which can be denitrified at low to high rates in the deeper anaerobic zone between the groundwater and aerobic zone (e.g. 6 to 45mg/m2 N2 per day). During summer, nitrate supplied by groundwater inflow can be denitrified (at a high rate e.g. 50mg/m2 N2 per day) or absorbed by plants, the latter of which is only a temporary removal process since litter returns nitrogen back to the soil. The limiting factor in this situation can be carbon supply or nitrate supply (as the potential denitrification rate was much higher than what was observed).

    Temporarily saturated site: the elevation of the alluvial aquifer fluctuates by season, creating periods when soil conditions change from aerobic to anaerobic. During spring high water conditions, the nitrate supply is limited because most organic N is converted to ammonia, thereby limiting denitrification to low rates (e.g. 2mg/m2 N2 per day. Therefore, dissolved reduced iron and manganese are used as terminal acceptors of electrons rather than nitrate. A declining aquifer elevation in summer crates aerobic conditions allowing nitrate to form, which is absorbed by plants or denitrified at a high rate (e.g. 30 to 40mg/m2 N2 per day. However, due to high microbial activity, the nitrate supply is outstripped by demand and nitrate never accumulates in the soils.

Permanently saturated sites: There was no allochthonous nitrate inputs from the aquifer. Submerged sediments were anaerobic and accumulated ammonia and organic matter. Continually reduced conditions prevent mineralization of the nitrogen in the organic matter to nitrate, thereby leading to low denitrification rates (e.g., 1mg/m2 N2 per day).

61. **Rosa, D.J., Clausen, J.C., and Kuzovkina, Y. 2017. Water quality changes in a short-rotation woody crop riparian buffer. *Biomass and Bioenergy*, 107. 370-375.**

    Value: 2 for groundwater nitrogen-buffer data analysis. Type: Experimental, treatment-control. Location: Connecticut. The authors studied how suspended solids and nutrient concentrations were affected by short-rotation biomass crops of willows used as riparian buffers. See summary in sediment section.

62. Schellinger, G.R. and Clausen, J.C. 1992. Vegetative filter treatment of dairy barnyard runoff in cold regions. *Journal of Environmental Quality*. 21: 40-45*

    Value: 0 for buffer-pathogen data analysis because the study results are not comparable-the study involved an engineered runoff management system. Location: Vermont. See summary in pathogens section.

63. **Schmitt, T.J., Dosskey, M.G.G., and Hoagland, K.D. 1999. Filter strip performance and processes for different vegetation widths and contaminants. *Journal of Environmental Quality*. 28: 1479-1489.**

    Value: 3 for surface runoff nitrogen-buffer data analysis. Type: Experimental, before-after. Location: Nebraska. The effectiveness of different filter strip designs at removing permethrin, atrazine, alachlor, nitrate, and phosphorus was evaluated. See summary in toxics section.

64. Schoonover, J.E., Williard, K.W.J., Zaczek, J.J. et al. 2005. Nutrient attenuation in agricultural surface runoff by riparian buffer zones in southern Illinois, USA. *Agroforestry Systems*. 64: 169-180.*

    Value: 0 for nitrogen-buffer data analysis because infiltration of runoff containing dissolved nitrogen in does not equate to nitrogen removal.

    Abstract: "Nutrients in overland flow from agricultural areas are a common cause of stream and lake water quality impairment. One method of reducing excess nutrient runoff from non-point sources is to restore or enhance existing riparian areas as vegetative buffers. A field scale study was conducted to assess the ability of remnant giant cane (Arundinaria gigantea (Walt.) Muhl.) and forest riparian buffer zones to attenuate nutrients in agricultural surface runoff from natural precipitation events. Two adjacent, 10.0 m wide riparian buffers were instrumented with 16 overland flow collectors to monitor surface runoff for nitrate, ammonium, and orthophosphate. Measurements were taken at 3.3 m increments within each buffer. The forest buffer significantly reduced incoming dissolved nitrate-N, dissolved ammonium-N, total ammonium-N, and total orthophosphate masses in surface runoff by 97, 74, 68, and 78, respectively within the 10.0 m riparian buffer. Nutrient reductions within the cane buffer were 100 for all three nutrients due to relatively high infiltration rates. Significant reductions of total ammonium- N and total orthophosphate were detected by 3.3 m in the cane buffer and at 6.6 m in the forest buffer. Results suggest that both giant cane and forest vegetation are good candidates to incorporate into riparian buffer restoration designs for southern Illinois as well as in other regions within their native range with similar climatic and physiographic conditions."

65. Schoonover, J.E. and Williard, K.W.J. 2003. Ground water nitrate reduction in giant cane and forest buffer zones. *JAWRA*. 39 (2) 347-354.

Value: 3 for groundwater buffer-nitrogen data analysis, due to rigor- results reported as concentrations but chloride tracer was used to quantify changes in nitrate due to dilution and evapotranspiration. Location: Illinois. Type: Observational.

This study examined the removal of nitrate (derived from upland row crop (no-till corn-soybean rotation) agriculture) from shallow groundwater as it moved through a buffer strip of either giant cane or box elder/green ash forest. The contributing area of fields was 0.26ha. Soils were Hamond silt loams underlain by limestone and having a 1% surface slope. The water table ranged from 1.0 to 4.0 m below the soil surface. Groundwater nitrate concentrations were sampled at distances of 0.0, 3.3, 6.6, and 10.0m into the buffer. Chloride was added to the fertilizer to quantify changes in nitrate concentrations due to dilution or evapotranspiration. For the cane buffer nitrate concentrations were reduced by 90% at 3.3m, 97% at 6.6m, and 99% at 10.0m; however, the chloride levels indicated significant dilution occurred in the first 3.3m and last 3.3m of the buffer while substantial evapotranspiration occurred in the middle 3.3m. For the 10m cane buffer overall, 40% of the 99% reduction could be attributed to dilution. For the forest buffer, the nitrate reductions were 62% at 3.3m and 82% at 6.6m (no results given for 10m distance). Changes in chloride were statistically non-significant, although an increase in chloride concentration at the 6.6m distance did suggest some evapotranspiration. Nitrate reductions were lower during winter when vegetation was dormant and microbial activity was likely reduced, but during summer a drop in the water table likely reduced vegetative uptake of nitrate.

The article provides a table comparing the results of different studies in terms of buffer widths and nitrate removal effectiveness; this table suggests that buffer width alone is a poor predictor of removal rates. For example, one study found a 5m buffer to be associated with a 98% nitrate removal rate, while another study found that a 90m forested buffer was associated with a removal rate of just 45%. As the authors indicate, some of the differences in removal are probably due to the depth of groundwater examined since shallower groundwater tends to have a larger supply of organic carbon, which fuels greater denitrification rates.

66. Smith, C.M. 1989. Riparian pasture retirement effects on sediment, phosphorus and nitrogen in channellised surface run-off from pastures. *N. Z. J. Mar. Freshwater Res*. 23:139-146.

Value: 0 for nitrogen-buffer data analysis because infiltration of runoff containing dissolved nitrogen does not equate to removal. Type: Observational, before-after. Location: New Zealand. An examination of changes in suspended solids and nutrients in channelized flow before and after livestock exclusion from riparian strips. See sediment section for summary.

67. Snyder, N.J., Mostaghimi, S., Berry, D.F., Reneau, R.B., Hong, S., McClellean, P.W., and Smith, E.P. 1998. Impact of riparian forest buffers on agricultural nonpoint source pollution. *Journal of the American Water Resources Association*. 34: 385-395.

Value: 2 for groundwater buffer-nitrogen data analysis, study results reported as concentrations, but dilution and evapotranspiration were unaccounted for. Location: Virginia. Type: Observational.

This study examined removal of nitrate, ammonia, and phosphate through a forested riparian buffer bordering an upland crop field. The field and upper portion of the woodland (0-6% slopes for both) was 10m higher in elevation than the riparian area and uplands drop off steeply (10-20+% slope) into the riparian forest. Depth to groundwater was 10m below the field and as low as 0 in the riparian area where seeps discharged from the hillslope. The ag field was in a corn-soybean rotation with winter cover cropping. The deep and well-drained upland soils were of the Suffolk series (coarse-loamy, siliceous, thermic Typic) Hapludults. The hillslope soils wee of the Rumford series (coarse-loamy, siliceous, thermic Typic Hapludults) and had a clay horizon. Below the forested hillslope, the riparian area was forested wetland with deep, poorly draining soils of the Bibb series (coarse-loamy, siliceous, acid thermic Typic Fluvaquents) and Levy series (fine, mixed, acid thermic Typic Hydroquents). The water table seasonally came to within 15 to 46cm of the surface of the Bibb soils and frequently exceeded the surface of the Levy soils. Groundwater nitrate in the forest and wetlands were 30 to 70% less than below the ag field, and reductions varied by season. The total buffer width was about 140m. 65m into the buffer just before the steep slope began there was an overall average reduction in nitrate of 43%. About 105m into the buffer the overall average reduction was 54%; at about 120m it was 50%; at about 125m it was 50%; at about 130m it was 57%. In the stream at a distance of about 140m the concentration was 48% less than below the field, but this level may have been influenced by nutrient and water sources other than the buffer transect being studied. Phosphate and ammonia concentrations changed very little over the width of the buffer. The greatest nitrate reductions were close to the wetland edge or within the wetland where groundwater movement was slow. Nitrate levels appeared to be slightly greater during winter and spring.

68. Spruill, T.B. 2004. Effectiveness of riparian buffers in controlling ground-water discharge of nitrate to streams in selected hydrogeologic settings of the North Carolina Coastal Plain. *Water Science and Technology*. 49(3): 63-70.

Value: 0 for buffer-nitrogen data analysis because it was an uncontrolled study. Location: North Carolina. Type: Observational. This study examined removal of nitrate from groundwater through buffers adjacent to crop fields with corn-soybean rotations. Four sites were evaluated. Two with well-draining riparian soils and two with poorly draining soils. Nitrate concentrations tended to be lower in the poorly draining soils. 50% or more of the nitrate reaching streams was denitrified as the groundwater discharged through streambeds, even in areas with no buffer. Nitrate levels were negatively correlated with dissolved organic carbon levels, which were highest beneath buffers and in streambeds.

69. Srivastava, P., Edwards, D.R., Daniel, T.C. [and others]. 1996. Performance of vegetative filter strips with varying pollutant source and filter strip lengths. *Transactions of the American Society of Agricultural Engineers*. 39: 2231-2239.

Value: 0 for nitrogen-buffer data analysis because only surface runoff was examined and infiltration of dissolved nitrogen does not equate to removal. Location: Arkansas. Type: Experimental, control-treatment. This study examined removal of nitrogen, phosphorus, TSS, and fecal coliform by vegetated filter strips (6.1, 1.2, 18.3m lengths) from runoff coming off of manure treated pasture.

70. Uusi-Kamppa, J. and Ylaranta, T. 1992. Reduction of sediment, phosphorus and nitrogen transport on vegetated buffer strips. *Agric. Sci. Finl*. 1:569-574.

Value: 2 for nitrogen-buffer data analysis. Type: Experimental, control-treatment. Location: Finland. The authors evaluated the effects of buffer strips at reducing solids and nutrients from crop fields. See sediment section for summary.

71. Valkama, E., Usva, K., Saarinen, M., and Uusi-Kamppa, J. 2018. A meta-analysis on nitrogen retention by buffer zones. *Journal of Environmental Quality*.

Value: Type: Meta-analysis. This paper presents a meta-analysis of nitrogen removal from surface runoff and groundwater. Previous studies have had variable conclusions as to the buffer width needed to effectively remove nitrogen, ranging from <10m to >50m. The authors assert that narrative reviews of primary literature lead to subjective determinations of buffer effectiveness. The meta-analyses performed by Zhang (2010) and Mayer (2007) are criticized for using traditional statistical methods and not estimating effect sizes. They state that the term meta-analysis should only be applied to evaluations that calculate effect size, use weighting, heterogeneity analysis, and models that account for “the distinct hierarchical structure of meta-analytic data.” “A pitfall in analyzing a number of independent studies lies in their methodological diversity. In addition, the study specific sampling error variances are almost never identical across studies, violating the underlying assumptions of traditional statistical analysis.”

For surface runoff, the overall buffer effect was a 33% reduction in NO3−N (95% CI = −48 to −17%, n =25) and a 57% reduction in total N (95% CI = −68 to −43%, n = 16). For groundwater, the overall buffer effect was a 70% reduction in nitrate (95% CI = −78 to −62%, n = 38). For surface runoff, the effect did not differ between reductions reports as concentrations or loads, or between natural vs. artificial runoff. The experimental design also had no effect upon groundwater results.

% Nitrogen removed increased linearly as the initial amount in surface or groundwater increased (yet note that a higher % removed from greater loads still generally results in greater amount of nitrogen lost from buffers relative to buffers receiving little nitrogen). “No buffer zone impact was found for the fields used for grass production, probably due to their initially low levels of pollution; however, double N retention was observed for fields used for cereal production and feedlots, which also had higher levels of pollution (Fig. 3a). In contrast, buffer zones improved groundwater quality to the same extent regardless of the source of pollution (Fig. 3a); moreover, concerning the same source of pollution, the groundwater quality clearly benefited more from buffer zones than the surface runoff.”

“Regardless of the soil texture, the N retention capacity of the buffer zone was similar for the surface runoff and for the groundwater (Supplemental Table S4), but again, the latter benefited more, as shown for loam soils (Fig. 3b). The effects of the buffer zones on the N retention for surface runoff or groundwater were similar for all the continents and climates (Fig. 3c and 3d).” The authors state that the effect of soils was difficult to evaluate; therefore, one should not conclude that soil texture has no effect. Individual studies have clearly shown that more permeable subsurface layers tend to have lower groundwater N reductions. This therefore implies that soils that can readily infiltrate runoff yet have slow rates of lateral movement are those that will have greater N reductions.

Vegetation type does not appear to influence N removal. Treed buffers were associated with a greater nitrate reduction in groundwater but not in surface water. However, the difference was not significant. For both groundwater and surface water, buffers with grass or grassed with trees were associated with the same nitrogen reduction.

Buffer zone age had no apparent effect upon nitrogen removal in groundwater but decreased with increasing age of buffer for surface runoff. Slope did not appear to have an effect on N removal from surface runoff and the slope data for groundwater was too limited to fully evaluate its effect. **The meta-regressions showed that buffer width had no effect upon N removal in ground or surface water**. It was noted that N removal per unit width of a buffer appears to be inversely related to the changes in the amount of subsurface water, and that this may confound the relationship between buffer width and N removal. In other words, this seems to imply that when there is a subsurface saturated uniformly through time, with water moving slowly through the buffer, the per meter N removal is higher and therefore buffer width does result in more N removal.

Removal of N from surface runoff is relatively ineffective (especially when considering that infiltration is often falsely equated to removal). For surface runoff, vegetative uptake can be important, but varies seasonally. Nitrate can also be removed from surface runoff by physical retention, microbial immobilization, and denitrification under saturated conditions. Removal from groundwater is much more effective and is mostly due to denitrification, and to a much lesser extent, by vegetative uptake. When nitrate loading to groundwater is high, nitrous oxide (a greenhouse gas) is a significant product of denitrification.

The authors concluded that buffer zones for nitrogen removal are more important for cropland and feedlots than for areas with permanent vegetation (e.g. pasture and rangeland) since N loads from the latter are typically low.

72. Vidon, P.G.F., and A.R. Hill. 2004. Landscape controls on nitrate removal in stream riparian zones. Water Resour. Res. 40:W03201

Value: 0 for nitrogen-buffer data analysis because it was an observational study, but value is 3 for the level of detail in describing landscape controls on nitrate removal. Location: Ontario, Canada. Type: Observational. This study examined landscape-scale controls on nitrate removal in riparian zones. Hydrology has a strong influence over denitrification levels and vegetative uptake. Sites that had a shallow confining layer (glacial till) overlain by sandy loam or loamy sand had removal rates >90% in the first 15m of the riparian zone. At some sites, 0 to 20% of the riparian zone width was required to achieve this reduction. At sites that had more permeable sand and cobble sediments, 25 to >176m was required to achieve 90% nitrate removal. At one site only 60% of nitrate was removed by the 25m buffer width. Nitrate inputs to riparian areas increased with increasing depth of permeable upland sediments, increasing riparian buffer slope, and increasing upland slope length. Some sites had low nitrate removal capacity, because although they had a shallow confining layer, nitrate inputs were low when the water table was high and groundwater/nitrate inputs were low during summer and fall. Depth of groundwater influences the carbon supply needed for denitrification. As hydraulic conductivity of soils decreases, denitrification capacity increases. Sites with seeps in the riparian area allow nitrate to bypass the zone of denitrification within the soil. When the depth of permeable sediments in the uplands was <2m, the hydrologic connection between uplands and riparian areas was impermanent because of limited water volume storage capacity. The article presents a graphic that summarizes the variability among hydrologic conditions that promote or inhibit nitrate removal, with the major drivers being the depth of upland and riparian permeable sediment, soil slope, and soil texture. The authors suggest that this conceptual model is probably applicable to other areas with glacial till and outwash (such as the Puget Sound Basin or northern portion of eastern Washington. On fine-textured soils that with low infiltration rates, nitrate removal may be limited if precipitation tends to result in overland flow even if the soils have a substantial potential for denitrification. The authors state that it may be possible to classify relative nitrate removal potential at the landscape scale (not site

scale) based on soil maps, topographic maps and surficial geology maps. Site scale determinations would require a filed investigation of soils, geology, and hydrology.

73. Webber, D.F., Mickelson, S.K., Ahmed, S.I., and Russell, J.R. 2010. Livestock grazing and vegetative filter strip buffer effects on runoff sediment, nitrate, and phosphorus losses. Journal of Soil and Water Conservation 65, no. 1: 34-41.

Value: 0 for data analysis since infiltration of runoff containing dissolved nitrogen does not equate to removal. Type: Experimental, control-treatment. Location: Iowa. This study examined the effects of filter strips on sediment and nutrients in runoff from livestock pasture. See sediment section for summary.

74. Weller, D.E., Correll, D.L., and Jordan, T.E. 1994. Denitrification in riparian forests receiving agricultural discharges. In: *Global Wetlands: Old World and New*. Ed: Mitsch, W.J. Elsevier. Amsterdam. pp 117-131.

Value: 0 for buffer-nitrogen data analysis, 2 for watershed process info. Location: Maryland. Type: Observational. This study examined nitrous oxide emitted from soils in cropland and an adjacent riparian forest. Nitrous oxide emitted from soil and in groundwater accounted for less than 1% of the groundwater nitrogen that was not captured by trees. The study did not examine nitrogen gas emission but should have since this is the primary denitrification product. The authors state that it is important to check groundwater flow paths and account for dilution before attributing changes in nitrate concentrations to removal processes. Plant uptake of nitrogen from groundwater can be highly variable, ranging from 15 to 100% in the studies reviewed. Quantifying nitrogen storage in soil is problematic due to spatial variability in N and soil properties; small errors in measurements can lead to very large uncertainty. Denitrification rates are highly spatially and temporally variable. Poorly drained riparian forests frequently have high denitrification rates.

75. Wigington, P.J., Jr., Griffith, S.M, Field, J.A., et al. 2003. Nitrate removal effectiveness of a riparian buffer along a small agricultural stream in western Oregon. *Journal of Environmental Quality*. 32: 162-170.*

Value: 0 for meta-analysis. Abstract: "The Willamette Valley of Oregon has extensive areas of poorly drained, commercial grass seed lands. Little is known about the ability of riparian areas in these settings to reduce nitrate in water draining from grass seed fields. We established two study sites with similar soils and hydrology but contrasting riparian vegetation along an intermittent stream that drains perennial ryegrass (Lolium perenne L.) fields in the Willamette Valley of western Oregon. We installed a series of nested piezometers along three transects at each site to examine NO3-N in shallow ground water in grass seed fields and riparian areas. Results showed that a noncultivated riparian zone comprised of grasses and herbaceous vegetation significantly reduced NO3-N concentrations of shallow ground water moving from grass seed fields. Darcy's law-based estimates of shallow ground water flow through riparian zone A/E horizons revealed that

this water flowpath could account for only a very small percentage of the streamflow. Even though there is great potential for NO3-N to be reduced as water moves through the non-cultivated riparian zone with grass-herbaceous vegetation, the potential was not fully realized because only a small proportion of the stream flow interacts with riparian zone soils. Consequently, effective NO3-N water quality management in poorly drained landscapes similar to the study watershed is primarily dependent on implementation of sound agricultural practices within grass seed fields and is less influenced by riparian zone vegetation. Wise fertilizer application rates and timing are key management tools to reduce export of NO3-N in stream waters.

76. Witt, E.L., Barton, C.D., Stringer, J.W., Kolka, R.K., and Cherry, M.A. 2016. Influence of variable streamside management zone configurations on water quality after forest harvest. Journal of Forestry, Volume 114, Number 1. pp. 41-51(11).

Value: 1 for meta-analysis. Type: Experimental, control-treatment. Location: Kentucky. Witt et al. (2016) evaluated three riparian treatments (T1, T2, and T3) that varied in width, canopy retention within the SMZ, and BMP utilization with replication in two watersheds each. See Sediment section for summary

77. Young, E.O. and Briggs, R.D. 2007. Nitrogen dynamics among cropland and riparian buffers: soil-landscape influences. Journal of Environmental Quality. 36: 801-814.*

Abstract: Nitrate (NO3-) leaching to ground water poses water quality concerns in some settings. Riparian buffers have been advocated to reduce excess ground water NO3- concentrations. We characterized inorganic N in soil solution and shallow ground water for 16 paired cropland-riparian plots from 2003 to 2005. The sites were located at two private dairy farms in Central New York on silt and gravelly silt loam soils (Aeric Endoaqualfs, Fluvaquentic Endoaquepts, Fluvaquentic Eutrudepts, Glossaquic Hapludalfs, and Glossic Hapludalfs). It was hypothesized that cropland N inputs and soil-landscape variability would jointly affect NO3- leaching and transformations in ground water. Results showed that well and moderately well drained fields had consistently higher ground water NO3- compared to more imperfectly drained fields receiving comparable N inputs. Average 50-cm depth soil solution NO3- and ground water dissolved oxygen (DO) explained 64% of average cropland ground water NO3- variability. Cropland ground water with an average DO of <3 mg L-1 tended to have <4 mg L-1 of NO3- with a water table depth (WTD) of 1 m. Water table depth and DO explain 83% of ground water NO3- variability among buffers. More poorly drained buffers had low ground water NO3- and DO, a shallow WTD, and higher ground water ammonium and soil organic matter. Chloride patterns indicated that dilution was minor in most buffers, suggesting that denitrification losses were important. Soil-landscape factors strongly influenced NO3- behavior and suggest the importance of accurately characterizing soil variability along cropland-riparian zones.

78. Young, E.O. and Briggs, R.D. 2005. Shallow ground water nitrate-N and ammonium-N in cropland and riparian buffers. Agriculture, Ecosystems and Environment. 109: 297-309.*

Abstract: The extent of nutrient reduction in shallow ground water flow between cropland and riparian buffers in the Northeast is not well established, yet there is an increasing need to quantify such reductions. A four-year project was initiated in 2002 to determine the relative effectiveness of riparian buffers on reducing nutrients in soil water and shallow ground water flow from adjacent cropland. The main objective of this study was to determine if shallow ground water nitrate nitrogen (NO3–N) and ammonium nitrogen (NH4–N) concentrations differed among cropland (hay or corn), restored riparian buffers (grass and Salix-grass), and established forested riparian buffers. Sixteen paired ground water monitoring wells were established in cropland and riparian buffers at two agricultural research sites during July 2002 and July 2003. Samples of ground water, tile drainage water, and stream water were collected approximately monthly over the 2003 field season and analyzed for NO3–N and NH4–N concentration. Average NO3–N concentration across sites was significantly lower in buffers for each sampling. Average NH4–N concentration was consistently higher beneath buffers and decreased markedly over the sampling period. Soil drainage, as indexed by depth to water table, was significantly correlated with NO3–N concentrations among cropland and buffer wells at individual sites. We hypothesize that this reflects the relationship between soil drainage and its direct impact on both NO3–N leaching and denitrification potentials across the landscape. Forested buffers had the lowest average NO3–N, highest NH4–N, and the highest water table. Cropland soils with appreciable NO3–N in ground water adjoining riparian buffers on outwash deposits were ineffective at reducing NO3–N. Consistent NO3–N reductions occurred between cropland and buffers where ground water flowed from moderately well and well drained cropland to poorly drained riparian buffer soils.

79. Young, R.A., Huntrods, T., and Anderson, W. 1980. Effectiveness of vegetated buffer strips in controlling pollution from feedlot runoff. *Journal of Environmental Quality*. 9: 483-487.

Value: 0 for data analysis since infiltration of runoff containing dissolved nitrogen does not equate to removal. Type: Experimental, before/after (i.e. up/down of filters). Location: Minnesota. This study evaluated the effectiveness of vegetated plots at reducing bacteria, suspended solids, and nutrients in feedlot runoff. See sediment section for summary.

80. Younos, T.M., Mendez, A., Collins, E.R., and Ross, B.B. 1998. Effects of a dairy loafing lot-buffer strip on stream water quality. *Journal of the American Water Resources Association*. 34: 1061-1069.

Value: 0 for data analysis since infiltration of runoff containing dissolved nitrogen does not equate to removal. Type: Experimental, before-after. Location: Virginia. The study evaluated the effectiveness of a filter strip at reducing sediment and nutrients from dairy loafing lot runoff. See sediment section for summary.

81. Zhang, X., Liu, X., Zhang, M., and Dahlgren, R. A. 2010. A review of vegetated buffers and a meta-analysis of their mitigation efficacy in reducing nonpoint source pollution. *Journal of Environmental Quality*. Vol. 39: 76-84.

Value: 0 for data analysis because the study treated infiltration of runoff containing dissolved nitrogen as removal and intermingled this with study data reporting actual removal (denitrification); it also appears to have intermingled concentration reductions with mass reductions. This paper includes a meta-analysis of nitrogen reductions in buffers. See summary in sediment section.

Pathogens

1. Abraham, J.D., I. Fosu, D. Agyapong, K.N. Hope, and J. Abraham. 2016. Quality assessment of River Offin along a canopy cover gradient. *Journal of Water Resource and Protection* 8: 337-344.

   Value: 0 for pathogen-buffer data analysis, 0 for other purposes. Location: Ghana. Type: Observational. In this study, river water samples were collected at different points along three different reaches of a river. One reach had a closed forest canopy, one reach flowed through a village area and had a lack of tree canopy, and the third reach flowed through a cocoa farm and had a semi-closed overstory canopy. In addition to total coliforms, multiple chemical attributes were analyzed. Fecal coliform levels were high in all three reaches, but highest in the agricultural reach. The study concludes that farming close to the river is likely induces elevated turbidity and accounts for the greatest fecal coliform levels being observed in the agricultural reach.

2. Atwill, E.R., Hou, L., Karle, B.M., Harter, T., Tate, K.W., and Dahlgren, R.A. 2002. Transport of *Cryptosporidium parvum* Oocysts through vegetated buffer strips and estimated filtration efficiency. *Applied and Environmental Microbiology*. 68: 5517-5527.

   Value: 1 for pathogen-data analysis because these were soil box trials (alters infiltration), 2 for other purposes. Location: California. Type: Experimental. This study evaluates the effectiveness of vegetated buffer strips at removing C. parvum from surface and subsurface flow. C. parvum is a waterborne pathogen associated with livestock waste. Three soil types and slopes were used- Hanford fine sandy loam, Argonaut loam, and Capay silty clay loam on 5, 10, or 20% slopes. Two rainfall intensities (1.5cm/h and 4.0cm/hr) were simulated using a peristaltic pump and rainfall emitter. Approx. 3 x 10^7 oocysts were applied to each plot. Increasing soil bulk density strongly decreased oocyst removal rates in surface runoff. The sandy loam soil generally had lower removal than the other soils. For the silty clay and loam soils, removal was generally greater at a 10% slope than at a 5 or 20% slope; however, this pattern broke down at higher soil bulk densities and was not observed for the sandy loam soil. Removal of oocysts was influenced by infiltration rate, which in turn was influenced by the rainfall intensity. In other words, for a given soil texture, removal of waterborne zoonotic organisms increases with increasing soil porosity. “Alternatively, the risk of waterborne transmission of *C. parvum* from entire livestock production systems (feedlot, cow to calf, dairy, etc.) at large distances from source water supplies, such as ≥30 m, should be quite minimal if the filtration efficiency of the intervening buffer has been properly maintained (e.g., adequate soil porosity and vegetative cover) and if the preferential flow paths and large macropores have been kept to a minimum (e.g., few rills, gullies, and complexes of small mammal burrows)." Removal rates for surface runoff were >99.9% for all variations of soil type, slope, rainfall amount.

3. Chaubey, I., Edwards, D.R., Daniel, T.C., Moore Jr. P.A., and Nichols, D.J. 1994. Effectiveness of vegetative filter strips in retaining surface-applied swine manure constituents. *Transactions of the American Society of Agricultural Engineers*. 37: 845-850.

   Value: 0 for pathogen-buffer data analysis due to lack of comparability/unresolved question about accuracy of data presented. Location: Arkansas. The authors investigated the efficacy of filter strips in attenuating nitrogen, phosphorus, suspended solids, and fecal coliform in runoff containing liquid swine manure. See summary in the sediment section.

4. Coyne, M.S., Gilfillen, R.A., Rhodes, R.W., and Blevins, R.L. 1995. Soil and fecal coliform trapping by grass filter strips during simulated rain. *Journal of Soil and Water Conservation*. 50: 405-408.

   Value: 0 for pathogen-buffer data analysis, due to a couple problems with the methods. Type: Experimental. Location: Kentucky. This study simulated the effectiveness of a grass filter strip at removing sediment and fecal bacteria from poultry waste applied to a field. See sediment section for summary.

5. Coyne, M.S., Gilfillen, R.A., Villalba, A., et al. 1998. Fecal bacteria trapping by grass filter strips during simulated rain. *Journal of Soil and Water Conservation*. 53: 140-145.

   Value: 2 of 3 for pathogen-buffer data analysis. Location: Kentucky. Type: Experimental. Abstract: Most fecal wastes produced by the poultry industry in Kentucky will be applied to agricultural land. Grass filter strips have been documented to protect public waterways from soil erosion. We used a rain simulator to investigate their potential to trap fecal bacteria in surface runoff from poultry manure-amended cropland. We incorporated 16.5 Mg ha−1 of poultry manure into each of four chisel-tilled plots and measured the trapping efficiency of 4.5 and 9.0 m grass filters for runoff sediment and fecal indicator bacteria. Sediment concentrations were reduced an average of 96% by 4.5 m filter strips and 98% by 9.0 m filter strips. Average fecal coliform trapping efficiency was 75% in 4.5 m filter strips and 91% in 9.0 m filter strips. Average fecal streptococci trapping efficiency was 68% in 4.5 m filter strips and 74% in 9.0 m filter strips. Flow-weighted fecal coliform concentrations in filter strip runoff were still 1000 times higher than the standard for primary contact water used in Kentucky (200 fecal coliforms per 100 mL). Grass filter strips long enough to minimize sediment loss will trap most of the fecal bacteria in surface runoff but will not reduce fecal contamination of runoff to sufficiently meet existing water quality standards.

6. Doyle, R.C., Wolf, D.C., and Bezdicek, D.F. 1975. Effectiveness of Forest Buffer Strips in Improving the Water Quality of Manure Polluted Runoff. In *Managing Livestock Wastes Proceedings of the 3rd International Symposium on Livestock Wastes* ASAE, St. Joseph, MI pp. 299-302.

   Value: 2 of 3 for pathogen-buffer data analysis. Location: Maryland. Type: Experimental. This study examined the effectiveness of a buffer at removing nitrogen, phosphorus, fecal coliform (FC), and fecal streptococcus (FS) from runoff containing dairy manure. Soil- Chester gravelly silt loam. Data was collected for four consecutive rain events following the first manure application and three consecutive rain events following the second manure application. Only data for the 0.0 m station is presented for the first four rain events. The reductions in N and P for each buffer distance are reported as concentrations and are thus not very useful because of rainfall dilution, but here they are (averaged for the 3 rain events): 3.8m: N- 94.7%; P- 99.8%. 7.6m: N-95.7%; P-99.6%. 15.2m: N-97.3%; P-99.7%. 30.5m: N-97.9%; P-99.7%. The reductions for FC and FS a following the second manure application (averaged for the three rain events) are as follows. 3.8m: FC- 98%; FS- 99.7%. 7.6m: FC- 39.6%; FS- 99.8%; 15.2m: FC- 100%; FS- 99.9; 30.5m: FC- 94.7%; FS- 99.8%.

7. Entry, J.A., Hubbard, R.K., Thies, J.E., and Fuhrmann, J.J. 2000a. The influence of vegetation in riparian filterstrips on coliform bacteria: 1. Movement and survival in water. *Journal of Environmental Quality*. 29: 1206-1214.

   Entry: 0 for pathogen-buffer data analysis, 2 for general removal info. Location: Georgia. Type: Experimental. This study examined the effectiveness of a buffer at removing fecal coliform (FC) from runoff containing swine wastewater. Soil- Tifton loamy sand in uplands, Alapaha loamy sand in riparian forest. Infiltrating water moves as shallow subsurface flow to waterways due to a shallow restrictive soil layer. 1.5 to 2.0% slopes. Three vegetation treatments: 20m warm-season grass + 10m slash pine forest; 10m warm-season grass + 20m slash pine forest; 10m warm-season grass + 20m maidencane (a wetland plant). 4m wide by 30m long plots. Wastewater (2570L) per trial was applied at the top of the plots using a tank and piping system. During wet months, wastewater was applied slowly, and during other months it was applied as quickly as the tank would drain. The distance that the runoff traveled varied somewhat by season and vegetation type. **The data for the surface runoff is not presented**, only data for the lysimeters. Fecal coliform concentrations in surface flow did not decline with increasing distance in any buffer regardless of vegetation type or season. Bacteria in groundwater decreased by 2 to 3 log orders of magnitude through the filter strips. The authors recommend a 20 to 30m buffer between animal confinement areas and watercourses.

8. Entry, J.A., Hubbard, R.K., Thies, J.E., and Fuhrmann, J.J. 2000b. The influence of vegetation in riparian filterstrips on coliform bacteria: 1. Survival in soils. *Journal of Environmental Quality*. 29: 1215-1224.

   Value: 0 for buffer-pathogen data analysis. Location: Georgia. This is part 2 of a study on the transport of bacteria from swine wastewater that addresses bacteria survival in soils. Decreasing soil moisture coupled with increasing temperature resulted in greater bacteria mortality. Physical and chemical adsorption to soil results in bacteria entrainment, which is influenced by soil texture and porosity. States that pathogen survival in soil may vary from 4 to 160 days. The risk of surface and groundwater contamination can be reduced by applying livestock waste to fields when the soil is expected to be dry for the following 2 to 4 weeks.

9. Fajardo, J.J., Bauder, J.W., and Cash, S.D. 2001. Managing nitrate and bacteria in runoff from livestock confinement areas with vegetative filter strips. *Journal of Soil and Water Conservation*. 56: 185-191.

   Value: 1 for buffer-pathogen data analysis because an extreme runoff volume was used. Abstract: A documented source of nitrate-nitrogen contamination of surface water is livestock waste and storage facilities. A vegetative filter strip (VFS) is effective in reducing some nutrients, sediment, and suspended solid in surface runoff from feedlots; however, results are variable in controlling water-soluble nutrients and bacteria in runoff. This study assessed the role of tall fescue (Festuca arundinacea Schreb.) as a VFS in reducing contaminants from stored animal wastes. The study evaluated the extent to which livestock manure stockpiles potentially contribute to nitrate-nitrogen (NO3-N) and coliform bacteria contamination of surface water resources. The experiment was conducted on Amsterdam silt loam (fine-silty, mixed, superactive Typic Haploboroll) soil. Tall fescue and bare soil fallow) strips were established on a 4% slope. Treatments consisted of manure applications in the upland position for the strips. For comparisons, vegetated and bare control (non-treated) strips without manure in the upland position were also studied. Manure was applied annually (approximately 2 t fresh weight per strip). Runoff was achieved by applying water at the head of the treatments and forcing the applied water to pass through the manure stockpiles and into the VFS and fallow strips. Runoff water samples were collected and analyzed for NO3-N and coliform. Concentration of NO3-−N in surface runoff from VFS with manure stockpiles in the headland was reduced up to 97% in 1997 and 99% in 1998 where a VFS was present. Coliform populations in runoff were reduced significantly by VFS in two runoff events, a 64% reduction in July 1937, and an 87% reduction in August 1998. However, the coliform counts in runoff, even from VFS treatments not receiving manure, remained substantially elevated. Dilution and residence time of water passing through the VFS appeared to be the most significant factors affecting reductions in NO3-N and bacteria in runoff.

   The authors note that they had to use large amounts of simulated runoff to force water to reach the end of the plots and that such runoff would be unlikely under natural rainfall.

10. Harmel, R.D., Wagner, K.L., Martin, E. Gentry, T.J., Karthikeyan, R., Dozier, M., and Coufal, C. 2012. Impact of poultry litter application and land use on *E. coli* runoff from small agricultural watersheds. *Biological Engineering Transactions* 691): 3-16.

    Value: 0 for buffer-pathogen data analysis, 3 for watershed process info. Location: Texas. Type: Experimental, control/treatment. This study compares differing poultry litter application rates and land use on *E. coli* in runoff. Poultry liter application had little effect on *E. coli* concentrations in runoff. That being said, the timing of litter applications is important as runoff generating precipitation that occurs soon after application increases the risk of surface water pollution. E. coli concentrations were high (median = 2,000cfu per 100mL) in runoff from native prairie without grazing or litter application occurred, presumably due to wildlife. Bacteria concentrations in runoff increased from cultivated cropland to hayed pasture to native prairie to mixed land use to grazed pasture. The one weakness of this study is that it examined bacteria concentrations instead of loading; just because a concentration is higher in the runoff from one field than another doesn't mean that it is contributing more bacteria. For example, BMPs could reduce runoff volume by 99% without having any effect upon the bacteria concentration in the runoff.

11. Harmel, R.D., Karthikeyan, R., Gentry, T., and Srinivasan, R. 2010. Effects of agricultural management, land use, and watershed scale on *E. coli* concentrations in runoff and streamflow. *Transactions of the ASABE*. Volume 53(6): 1833-1841.

    Value: 0 for buffer-pathogen data analysis, 2 for transport process info. Location: Texas. Type: Observational. This study evaluated variability in *E. coli* levels across multiple spatial scales- field runoff to small watershed to river basin scales. Dairy compost applied to cultivated land, pasture, and mixed-use land did not significantly increase *E. coli* levels in field runoff. This is expected because properly composted manure contains very little *E. coli* Grazed sites had higher *E. coli* levels in field runoff than cultivated sites, although there were sources other than livestock on the pastureland. At the field scale, high levels of bacteria were observed from time to time whether or not there were identified anthropogenic sources, presumably due to wildlife. *E. coli* concentrations decreased with increasing spatial scale.

12. Hay, V., Pittroff, W, Tooman, E.E. and Meyer, D. 2006. Effectiveness of vegetative filter strips in attenuating nutrient and sediment runoff from irrigated pastures. *Journal of Agricultural Science.* 144: 349-360.

    Value: 0 for buffer-pathogen data analysis because insufficient data is presented. Location: California. Type: Experimental, control-treatment. This study examines the effectiveness of filter strips at removing TSS, P, N, and fecal coliforms from flood irrigated pasture. Soils: fine-loamy, mixed, thermic, Mollic Haploxeralfs of the Auburn-Las Posas-Argonaut Rocky Loam association. Pasture vegetation was 40% strawberry/clover and 60% orchardgrass and perennial ryegrass. Plot slope ranged from 6.3 to 9.9% with an average of 9.81%. Filter strip length was 8.3m (6:1 pasture to buffer ratio) for VFS-1 and 17.1m (3:1 buffer area ratio) for VFS-2. Grazing rates were 32 animal units per hectare (stocking rate of 160 animal units/ hectare/day). There was no significant difference in fecal coliform in runoff among the control and treatment plots of two different lengths. N and P were also not reduced. The article does not actually report the fecal coliform concentrations for the control and treatments but does show a graph. Estimated averages (for the 3 irrigation events) are 1.25 x 10^8 'count per plot' for the control; 1.0x10^8 for VFS-1, and 1.25x10^8 for VFS-2. The vegetated filter strips did not consistently reduce runoff volume even though the amount of water used was half of the amount used under normal flood irrigation operations. The authors state that "slope, relatively high runoff volumes and some channeled flows were probably responsible for the limited effectiveness of VFS in the present study."

Quote from text: "US ACE requires vegetated buffers of at least 7.62–15.24 m under the US national permit program, Part 330 – Section C.19 (US ACE 2000). Recent revisions to the US Clean Water Act require a 30.48 m setback for manure application to any down-gradient surface waters. As a compliance alternative, the farms classified as Concentrated Animal Feeding Operations may substitute the 30.48 m setback with a 10.67 m wide vegetated buffer where applications of manure, litter or process wastewater are prohibited (US EPA 2003). In light of the present data, such policies do not appear to be flexible enough as the effectiveness of VFS in meeting the desired objectives seems to depend to a considerable degree on site-specific conditions. It is suggested that recommendations for use and subsequent size of VFS should be based on more detailed experimental research and modelling studies, considering factors such as slope, inflow volume and vegetation mass."

13. Lim, T.T., Edwards, D.R., Workman, S.R., Larson, B.T., and Dunn, L. 1998. Vegetated filter strip removal of cattle manure constituents in runoff. *Transactions of the American Society of Agricultural Engineers*. 41: 1375-1381.

    Value: 1 of 3 for buffer-pathogen analysis because bacteria data results are suspect. Type: Experimental, before-after treatment. Location: Kentucky. The authors studied the influence of vegetated filter strip (VFS) length on the reductions (concentrations and mass) in the transport of nitrogen, phosphorus, suspended and total solids, and fecal coliform from plots treated with cattle manure. See sediment section for summary.

14. Mankins, K.R., Barnes, P.L., Harner, J.P., Kalita, P.K. and Boyer, J.E. 2006. Field evaluation of vegetative filter effectiveness and runoff quality from unstocked feedlots. *Journal of Soil and Water Conservation*. 61: 209-217.

    Value: 0 for buffer-bacteria data analysis because the study results are not comparable to other study data since it was conducted on feedlot runoff management systems having a runoff collection and distribution system. Location: Kansas. Type: Observational.

    Abstract: "Smaller beef cattle feedlots—less than 1,000 head—are often used for only a part of each year, but little is known about the pollution potential caused by feedlot residual manure when cattle are not present or about the effectiveness of vegetative filter strips under these conditions. This study quantified beef cattle feedlot runoff quality, particularly during unstocked conditions, evaluated reductions of fecal bacteria and nutrients in vegetative filter strips treating feedlot runoff, and assessed the relative importance of site characteristics on observed reductions. Established vegetative filter strips on four commercial feedlots located across central and eastern Kansas were instrumented with automated samplers at vegetative filter strip inlets and outlets, and 22 feedlot runoff events were analyzed for reductions in fecal coliform, Escherichia coli, fecal streptococci, total nitrogen and total phosphorus. Events when few or no cattle were present averaged one-sixth the total nitrogen (20 mg L−1), one-seventh the total phosphorus (6 mg L−1), and one-fortieth the fecal coliforms (2.1 × 104 cfu 100 mL−1) of events with cattle present. Measured concentration reductions from all events and vegetative filter strips averaged 77 percent (fecal coliforms), 83 percent (E. coli), 83 percent (fecal streptococci), 66 percent (total nitrogen), and 66 percent (total phosphorus). Vegetative filter strips allowed no discharges for 92 and 93 percent of feedlot runoff events at the sites with the ratio of vegetative filter strip: drainage area greater than 0.5. Constituent reductions were positively correlated to vegetative filter strip: drainage area ratio and negatively correlated to event rainfall depth. This study provides general support for the use of vegetative filter strip: drainage area ratio as a design guideline."

Site A: Shellabarger fine sandy loam, well-drained, vegetated with brome grass; two sections- one 15m wide with 1% slope, the other 9m wide with 0.5% slope. Site B: Crete silt loam, somewhat poorly drained, brome grass vegetation; filter strip widened from 6m (0.4% slope) in the first 52m of length to 29m (1.4% slope) over the remaining 375m. Site C: Newtonia silt loam, well drained, vegetated with fescue; 46m wide (2% slope) separated into three 15m sections by 15cm high dikes. Site D: Wells loam, well-drained, vegetated with brome; 37m wide (0.6%) slope. Most rainfall events were less than 20mm depth, and most of those did not generate runoff. Only about half of the events generating runoff had flows that resulted in filter strip outflow. Reductions for fecal coliform were as follows: Site A 60.5% ± 59.1; Site B 94.0% ± 11.8; Site C 71.1% ± 24.4; Site D 96.7% ± 6.5.

Reductions for *E. coli* were as follows: Site A 67.5% ± 48.2; Site B 94.5% ± 10.8; Site C 77.0% ± 45.1; Site D 96.0% ± 7.8.

15. Moore, J.A., Grismer, M.E., Crane, S.R., and Miner, J.R. 1982. Evaluating dairy waste management systems' influence on fecal coliform concentration in runoff. *Station Bulletin 658*. Agricultural Experiment Station. Oregon State University. Corvallis, OR

    Value: 0 for buffer-pathogen data analysis, 1 for bacteria transport process info. Location: Oregon. Type: Modelling. This is a rather lengthy examination of processes affecting bacteria transport and removal from livestock wastes. A review of prior research led the authors to suggest that buffers are effective at reducing concentrations of bacteria in runoff when concentrations are greater than 10^5 organisms per 100mL, but further reductions depend on "season, soil infiltration rates, and other factors that need further investigation." They cite Young et al (1980) as presenting an equation for bacteria removal which indicates that a 36m buffer is needed to reduce bacteria down to 1,000 organisms per 100mL but note that the maximum buffer width in the study was 27m, so such extrapolation is questionable. The authors present a model for transport of bacteria from dairy manure for the Tillamook Bay area in Oregon. The results indicate that storage methods, getting water to infiltrate soils, buffer zones, and rate/timing of manure applications are critical to preventing water pollution.

16. Schellinger, G.R. and Clausen, J.C. 1992. Vegetative filter treatment of dairy barnyard runoff in cold regions. *Journal of Environmental Quality*. 21: 40-45*

    Value: 0 for buffer-pathogen data analysis because the study results are not comparable - the study involved an engineered runoff management system. Location: Vermont. Abstract:

A vegetative filter strip was installed to treat barnyard runoff from an active dairy farm in Vermont. Runoff from a concrete surfaced barnyard flowed through a detention pond, then onto a vegetative filter strip measuring 22.9 m by 7.6 m with a 2% slope. The water input and surface and subsurface outputs for the strip were continuously monitored from December 1984 through May 1986. Of the total barnyard runoff entering the strip, 65% left as surface runoff and 27% was measured as subsurface outflow. The average hydraulic loading rate was 14.7 cm wk^{-1} and the average overland flow detention time was 15 min. The filter strip did not significantly ($P < 0.05$) reduce solids, P, N and bacteria concentrations in the surface output. Over the period of study, the mass retention was 33% total suspended solids, 12% total P and 18% total Kjeldahl N. Mass retention was highest during the growing season and was poorest during snowmelt periods. It was concluded that poor filter strip performance was due to an excessive hydraulic loading rate resulting in an inadequate detention time for proper treatment. A preferential flow path from the level lip spreader to the subsurface drain tiles may have contributed to the poor subsurface treatment performance.

17. Stoddard, C.S., Coyne, M.S., and Grove, J.H. 1998. Fecal bacteria survival and infiltration through a shallow agricultural soil: timing and tillage effects. *Plant and Soil Sciences Faculty Publications.* 9.

    Value: 0 for buffer-pathogen data analysis, 1 for info on effects of ag practices on bacteria transport. Location: Kentucky. Type: experimental, control-treatment. This is a study of how manure application on tilled and non-tilled soils affected bacteria infiltration into the soil profile. The agronomic benefits (increased yield) of spring manure application and *E. coli* transport problem occurred for both tillage systems. Fecal coliform levels rose in shallow subsurface water whenever sufficient rainfall occurred to cause water percolation through soil profile, regardless of the timing of manure application or tillage treatment. Tilled fields often have fewer preferential flow paths than no-till fields and therefore it was expected that they would have lower bacteria concentrations in leachate; however, average bacteria concentrations in leachate from tilled fields tended to be as great as or greater than concentrations in leachate from no-till. Nevertheless, the effect of tillage was not consistent.

18. Sullivan T.J, Snyder, K.U., Mackey, S., Moore, D.L., Sullivan, J.M., and Sullivan, L.C. 2006. Evaluation of the effects of edge-of-field- grass and shrub filter strips on fecal coliform bacteria transport in an agricultural setting. *Results of Phase II of the Tillamook Buffer strip Effectiveness Project. Final Report.* Prepared for the Tillamook Estuaries Partnership, Garibaldi, OR. E & S Environmental Chemistry. Corvallis, OR.

    Value: 2 of 3 for buffer-pathogen data analysis. Location: western Oregon. Type: Experimental, control-treatment. This study examined the effectiveness of vegetated filter strips at removing fecal coliform bacteria (FCB) from runoff flowing from manure-treated pasture at two sites during seven storm events of varying precipitation amounts (3.3 to 20.4cm) and precipitation intensities (maximum 1hr intensities ranged from 0.18 to 1.30cm/hr). Filter strips at the primary experimental site were 0, 1, 3, 8, 15, or 25m in width. Soils at the primary site Quillayute silt loams had more sand and were better draining than the siltier soils at the secondary site. Filter strip vegetation at the primary site consisted of mixed pasture grasses along with native shrubs and sedges. Cells were constructed to either have an even or corrugated soil surface and gentle (3.8%), moderate (7.0%), or steep slopes (12%- applied to a single cell only). The soil of the simulated pasture treatment area had been "loosened" two years prior to the experiment and may have therefore had greater infiltration rates than pasture with livestock induced soil compaction. At the secondary site, filter strips were 0, 3, 5, or 8m wide (slope noted as moderate but not quantified) and were vegetated with pasture grasses. Livestock grazing occurred on the field immediately prior to the experiment but were excluded during it. 35 gallons of manure was applied just uphill of the filter strip at a rate of 0.1 gal per ft^2 in a 3m wide strip across the 35ft width of the treatment cell. Control cells at both sites had no manure application.

Primary site: The median FCB concentration from the 0m cell (with 3.8% slope) was 16,500 cfu/100mL. On both gentle and moderate sloped cells, >99% of precipitation infiltrated the soil on the treatment site rather than generating runoff. Narrower vegetated strips (1 and 3m widths) had higher FCB concentrations than wider strips, but the differences were not statistically significant. Median cfu/100mL concentrations for the gentle slope buffers were: 0m- 16,500; 1m- 10; 3m- 29; 8m- 0; 15- 2; 25- 0; 8m control- 9. Median cfu/100mL concentrations for the moderate slope buffers were: 0m- 620; 1m- 0; 3m- 7; 8m- 0; 15- 0; 25- 3; 8m control- 9. Median cfu/100mL concentration for the steep slope buffer was: 8m-1. Volume-weighted average concentrations are also reported for the study. In general, the presence of any width filter strip resulted in median FCB reductions that exceeded 99%. On gentle slopes, the 3m width buffers had the greatest percentage (29%) of samples that did not achieve a 99% FCB reduction while the 25m buffer had the lowest (6%- same as the control). On moderate slopes, the 3m width buffers had the greatest percentage (46%) of samples that did not achieve a 99% FCB reduction while the 8m buffer had the lowest (11%-control was 5%). There was no difference in FCB reductions between smooth and corrugated soil surfaces.

Secondary Site: Data from the secondary site was more limited but suggested that the narrower (1 and 3m width) vegetated strips were less effective than wider strips. Median cfu/100mL concentrations for the moderate slope buffers were: 0m- 10,600; 1m- 113; 3m-74; 8m- 22; 8m control- 32. Volume-weighted average concentrations are also reported for the study. The 1m width buffers had the greatest percentage (50%) of samples that did not achieve a 99% FCB reduction, the 3m buffer had 25% of samples not achieving a 99% reduction, the 8m had 17%, and the control had 30%.

There was some evidence that FCB reductions were lower on the secondary site that had a soil of finer texture and was less "loosened". This suggests that buffers need to be wider on soils having lower infiltration rates. The authors suggest that setting filter strip widths without considering soil attributes have a higher risk of being over- or under-sized. The main weakness of this study is that it examined FCB concentrations rather than loads, since concentrations can decrease due to precipitation dilution alone. In this regard, since 99% of the precipitation typically infiltrated the treatment areas, FCB concentrations in runoff from the buffers may have been influenced by the background levels of FCB on each of the buffers (e.g., voles, moles, gulls etc. and coliform soil bacteria were cited as potential background sources). This, however, does not negate the finding that precipitation infiltration is the key to achieving FCB reductions.

19. Tate, K.W., Atwill, E.R., Bartolome, J.W., and Nader, G. 2006. Significant *Escherichia coli* attenuation by vegetative buffers on annual grasslands. *Journal of Environmental Quality*. 35: 795-805.

    Value 0 for buffer-pathogen data analysis, 2 for transport process info: the study quantified how much bacteria was in the manure and how much remained after the buffer, but not how much entered the buffer, so actual reductions are unknown. Location: California. Type: Experimental, control-treatment. This study focuses on the effectiveness of vegetated buffers at removing E. coli from runoff derived from grasslands under natural rainfall. Soils-Sobrante-Timbuctoo gravelly loam complex. Study site vegetation- annual grasses and forbs. 48 runoff plots were employed, divided into three blocks based on slope - 5, 20, and 35%. Buffer lengths were either 0.1, 1.1, or 2.1m in length. Three residual dry matter treatments (225, 560, 900, and 4500kg/ha- the latter represented non-grazed conditions) were randomly implemented on the treatment blocks. For each block, three of the four replicate plots (same slope and residual dry matter) received livestock manure treatments. The two trial periods were 2002-2003 and 2003-2004. Specific methods were used to equalize and enumerate the bacteria counts applied to each plot. In the former trial period, the *E. coli* loading rate was 1.27×10^{10} cfu/plot and 53 days elapsed between placement of the manure and the last of 11 storms (205mm total precip). In the latter trial period, the bacteria loading rate was 2.88×10^{10} cfu/plot and 79 days elapsed between placement of the manure and the last of 16 storms (349mm total precip). E. coli levels in buffer runoff decreased buffer width increased and increased as plots slope increased. *E. coli* levels decreased with increasing residual dry matter up to 900kg/ha, however, the levels were the highest with the non-grazed control having 4500kg/ha residual dry matter. The effect of buffer width was partially dependent on total plot runoff- for the 1.1 and 2.1m buffers, *E. coli* discharge increased, and reductions decreased as runoff volume increased; for the 0.1m buffer the opposite trends occurred, albeit the trends were weak. The study did not determine how much E. coli entered the buffers (only how much was in the manure and how much left the buffers), so it could only say that >90% of the E. coli in the manure either remained on the treatment area or was filtered by vegetative litter and soil surface organic matter, and/or infiltrated into the soil. The evidence suggests that narrower buffers may be effective where storm intensities are low, soil infiltration capacity is high, and soil saturation is rare.

    One weakness of this study is that there was only a single manure application for an entire rainfall season, and this occurred at the beginning of season; this method seems unrealistic for grazing lands since livestock are going to deposit manure on a daily basis. Another weakness is that the sample hold times ranged from 4 to 72hours, whereas the standard practices call for either a 6 or 24hr hold time; the authors undertook a detailed procedure to adjust *E. coli* concentrations based on variable hold times, which seems like a sketchy thing to do. A third weakness is that actual bacteria reductions were not estimated because the amount of bacteria entering the buffers was no quantified. These three weaknesses severely limit the utility of this study.

20. Tate, K.W., Pereira, M.D.G.C., and Atwill, E.R. 2004. Efficacy of vegetated buffer strips for retaining *Cryptosporidium parvum*. *Journal of Environmental Quality*. 33: 2243-2251.

    Value: 1 for buffer-pathogen data analysis (2 for transport process info) due to study methods- used soil boxes (alters infiltration) and applied water at a rate greater than a 100yr event in the Sierra Nevada foothills. Location: California. Type: Experimental, control-treatment. This study employed soil boxes at different slope angles to examine removal of *Cryptosporidium parvum* oocysts from simulated runoff. Soils were Ahwahnee sandy loam (soil hydrologic group B). The soil boxes were 1.0m in length. The initial number of oocysts was 2 x 10^8. Water was applied at a rate of 53mm/hr for 2 hours- greater than a 100yr event in this location. Oocyst removal ranged from 1.5 x 10^6 (99.3%) to 23.9 x 10^6 (88%). Mean rates of overland flow increased with increasing soil slope, but mean concentrations of oocysts did not. At 5% slope, substantial subsurface transport of oocysts occurred, while at 12 and 20% slopes, the majority of transport was via overland flow. Soil macroporosity may have been reduced due to the soil repacking into boxes. Based on these results, the authors estimate that a grass buffer equal or greater than 5m on this well-draining soil would be required to "adequately reduce" the transport of *C. parvum* from a 100 head cattle herd on California annual grasslands.

21. Trask, J.R., Kalita, P., Kuhlenschmidt, M.S., Smith, R.D., and Funk, T.L. 2004. Overland and near-surface transport of *Cryptosporidium parvum* from vegetated and non-vegetated surfaces. *Journal of Environmental Quality*. 33: 984-993.

    Value: 1 for pathogen-data analysis because these were soil box trials (which alters infiltration), 2 for other purposes. Location: Illinois. Type: Experimental, control-treatment. This study examines transport of *Cryptosporidium parvum* in surface and near surface runoff transport using soil boxes and simulated rainfall. Three slopes (1.5, 3.0, and 4.5%) and two rainfall intensities (25.4 and 63.5mm/hr for 44min- 1 and 10 yr. storms in this study location) were used. Soil was a well-drained silt-loam (Catlin series). The soil box was 3.6m in length. A *C. parvum* fecal slurry containing 1 x 10^7 oocysts was applied in a band at the upper end of the box only before the first rainfall trial for a given sloped box. The second rainfall simulation occurred 7 to 10 days after the first and the third 7 to 10 days after the second. Under low intensity rainfall, surface runoff for the vegetated boxes was 16.3, 23.6, and 20.8% for the 1.5, 3.0, and 4.5% slopes, respectively. Under high intensity rainfall, surface runoff for the vegetated boxes was 59.6, 64.0, and 76.7% for the 1.5, 3.0, and 4.5% slopes, respectively. For the low intensity rainfall, surface runoff reductions of oocysts for the vegetated box were 98.4, 99.2, and 99.4% for the 1.5, 3.0, and 4.5% slopes, respectively. For the high intensity rainfall, surface runoff reductions of oocysts for the vegetated box were 98.6, 99.2, and 73% for the 1.5, 3.0, and 4.5% slopes, respectively. For surface and subsurface flows combined for the vegetated boxes, reductions were above 97% for all slopes and rainfall intensities, except 4.5% slope under high rainfall intensity, which had a combined reduction of 68%. An increase in % reductions at greater slopes under low intensity rainfall (but to a much lesser degree on the vegetated boxes) may be caused by dilution or oocyst adsorption to sediment, since both surface runoff volume and suspended sediment increased with increasing slope. Steeper slopes and high rainfall intensity lead to the most transport. Soil infiltration is a key factor in reducing oocysts in runoff.

22. Tyrrel, S.F. and Quinton, J.N. 2003. Overland flow transport of pathogens from agricultural land receiving faecal wastes. *Journal of Applied Microbiology*. 94: 87S-93S.

    Value: 0 for buffer-pathogen data analysis, 2 for transport process info. Type: review article. This article reviews research on the transport of pathogens in agricultural surface runoff. The most important factor influencing pathogen survival in stored manure is temperature; ammonia, high pH, dessication, and competition also increase pathogen mortality. Survival of pathogens in soil is also driven by temperature, but is also influenced by factors including moisture level, pH, organic matter content, and sunlight. Research indicates that levels of most pathogen generally decline to non-detectable levels after 3 months. Plot-scale experiments suggest that surface applied animal waste leads to 10 times greater pathogen transport compared to waste that is incorporated into the soil.

23. Wagner, K.L, Redmon, L.A. Gentry, T.J., and Harmel, R.D. 2012. Assessment of cattle grazing effects on *E. coli* runoff. *Transactions of the ASABE*. Vol. 55 (6): 2111-2122.

    Location: eastern Texas. Type: Observational, control/treatment. Value: 0 for meta-analysis. This study examined *E. coli* in runoff from grazed and non-grazed pastures. It does not examine buffer effectiveness. The study involved multiple soil series, all of which had a clay texture and are in soil hydrologic group D. Soil slopes ranged from 0.2 to 3.8%. Runoff from non-grazed pastures exceeded 394cfu/100mL (the Texas single sample maximum criterion for *E. coli*) 88 to 100% of the time. Median background levels in runoff were 3,500 to 5,000 cfu/100mL. The key take home message is that background levels of *E. coli* should be acknowledged and estimated.

24. Walker, S.E., Mostaghimi, S., Dillaha, T.A., and Woeste, F.E. 1990. Modeling animal waste management practices: impacts on bacteria levels in runoff from agricultural lands. *Transactions of the American Society of Agricultural Engineers*. 33: 807-817.

    Value: 0 for meta-analysis. Type: modelling. Location: model based on site conditions on the coastal plain of Virginia. This paper uses modelling to identify the most effective BMPs for controlling fecal bacteria transport in agricultural runoff. Model inputs include rainfall and temperature variations, and simulated the effects of waste storage, filter strips, and incorporation of manure into soils. The model scenario was for an 1153-hectare watershed with shallow silt loam soils and five dairies having a total of 150 head of cattle. The model indicated that with a sole BMP of a 30m buffer with a 3% slope in all areas where manure was applied would result in a 75% maximum bacteria reduction. By themselves, buffers were not effective at reducing bacteria to levels that achieved the water quality goal (200 fecal coliforms per 100mL). Increasing the buffer width did not achieve additional reductions. The model indicated that long-term manure storage and soil incorporation were equally effective, however, the latter was more expensive. The model indicated that wither incorporation or long-term manure storage would achieve the WQ goal, but it was not clear if these scenarios also included the 30m buffer. Overall, the results suggest that buffers coupled with manure storage and soil incorporation where appropriate can effectively reduce fecal coliform transport to surface waters.

25. Young, R.A., Huntrods, T., and Anderson, W. 1980. Effectiveness of vegetated buffer strips in controlling pollution from feedlot runoff. *Journal of Environmental Quality*. 9: 483-487.

    Value: 1 for buffer-pathogen data analysis because it examines feedlot conditions, which may not be directly comparable to runoff from pasture, range, or cropland. Type: Experimental, before/after (i.e., up/down of filters). Location: Minnesota. This study evaluated the effectiveness of vegetated plots at reducing bacteria, suspended solids, and nutrients in feedlot runoff. See sediment section for summary.

Phosphorus

1. **Abu-Zreig, M.R., Rudra, P., Whiteley, H.R., Lalonde, M.N., and Kaushik, N.K. 2003. Phosphorus removal in vegetated filter strips. *Journal of Environmental Quality*. 32: 613-619**.
   Value: 3 for buffer-phosphorus data analysis. Location: Ontario, Canada. Type: Experimental, control-treatment. This is a study of total and dissolved phosphorus removal from artificial surface runoff using filter strips having one of three different vegetation covers. Soils were silt loams 38% sand, 54% silt, 8% clay. Vegetation cover A was perennial ryegrass, B was legume/fescue, C bare soil, and D native grass. Filter strip lengths were 2, 5, 10 and 15m. The strips with native vegetation had 5% slopes, whereas the others had 2.3% slopes. The artificial runoff averaged 4000mg/L of TSS, 2.37mg/L of total P, and 0.15 mg/L dissolved P. "A typical test run was divided into five different phases: a wetting phase, an unsaturated phase (Q1A), and three consecutive saturated phases (Q1B, Q.65, and Q.3) with flow rates of 1.0, 1.0, 1.0, 0.65, and 0.3 L s^{-1}, respectively." Most water infiltrated the filters during the initial wetting phase. Approximately 94% of the P was in particulate form. P removal was significantly lower and more variable than sediment removal on these same plots, as described in Abu-Zreig et al. (2002). The lower removal rates for P was attributed to a portion of P being dissolved and due to P tending to be adsorbed to the silt and clay particles. "In a simulation study, Abu-Zreig (2001) found that the sediment trapping efficiency in a 3-m-long filter for sand (d = 0.2 mm), silt (d = 0.01 mm), and clay (d = 0.002 mm) particles was about 90, 60, and 2%, respectively."

The 2, 5, 10, and 15m filter strips reduced phosphorus in surface runoff by 32, 54, 67, and 79%, respectively. Note that infiltration was equated with removal in this study, but in reality, infiltration of P does not necessarily mean that it has been immobilized. The authors state that dilution may have affected removal more so on longer filter strips than on the shorter ones. The native vegetation filter strips had greater removal rates even though their slope was greater; this was attributed to a higher % cover and a greater litter layer on these strips in comparison to the two other vegetation covers. The native vegetation strips also had lower surface flow velocities and greater % runoff infiltration. **The power equation developed for the study suggests that filter strips greater than 20m would be required to "remove" at least 90% of P.**

2. Bingham, S.C., Westerman, P.W., and Overcash, M.R. 1980. Effect of grass buffer zone length in reducing the pollution from land application areas. *Trans. ASAE* 23: 330-336.

   Value: 0 for buffer-nitrogen data analysis due to experimental methodology (land application, distribution system, use of area ratios, reporting in concentrations rather than mass). Location: North Carolina. Type: Experimental, control-treatment. See summary in nitrogen section.

3. **Borin, M., Vianello, M., Morari, F., and Zanin, G. 2005. Effectiveness of buffer strips in removing pollutants in runoff from a cultivated field in north-east Italy. *Agriculture, Ecosystems and Environment.* 105: 101-114.**

   Value: 3 for meta-analysis. Location: NE Italy. Terrain is flat, with a shallow water table (1-3m deep). Mean annual temperature is approx. 12^{o}C and precip averages 32.7 inches (but precip during study was 28.2in, 14% lower). Fields in this area average 1.4 acres. Crops include corn, soybeans, sugar beets and winter wheat. The authors evaluate the effectiveness of a **6m wide buffer** at reducing suspended solids, nitrogen and phosphorus exports from crop fields. Hillslope dimensions were 35m long at 1.8% slope. The buffer was composed of two rows of alternating trees and shrubs (1.5 and 4.5m from the ditch) planted 8 years prior and fescue grass sown throughout the buffer. Soils were loamy, with sand increasing to 50-60% at 1.4m depth. Soil infiltration rates ranged from 2.8 x 10-3 cm s-1 to 2.7 x10-4 cm s-1 in compacted areas; hydraulic conductivity averaged 1.2 x 10-3 cm s-1. Fertilizer application rates ranged from 16 to 150 kg/ha for nitrogen and 0 to 20kg/ha for phosphorus, depending on the crop rotation (winter wheat, maize, and soybean).

   Buffer strips reduced runoff volumes by an average of 80%. No significant difference in export concentrations was found for phosphate (annual median ranged from 0.04 to 0.19mg/L). Total P concentrations in runoff (annual median ranged from 0.56 to 1.28mg/L) were significantly less with the buffer strip. **However, in terms of total mass losses, the buffer reduced losses by 81% for total P (0.6 vs. 3.2kg/ha) and 83% for phosphate.**

Relatively few run-off events were responsible for a large proportion of the total pollutant loads.

4. **Chaubey, I., Edwards, D.R., Daniel, T.C., Moore Jr. P.A., and Nichols, D.J. 1994. Effectiveness of vegetative filter strips in retaining surface-applied swine manure constituents. *Transactions of the American Society of Agricultural Engineers.* 37: 845-850.**

   Value: 2 for meta-analysis. Location: Arkansas. The authors investigated the efficacy of filter strips in attenuating nitrogen, phosphorus, suspended solids, and fecal coliform in runoff containing liquid swine manure. See summary in the sediment section.

5. **Chaubey, I., Edwards, D.R., Daniel, T.C., Moore Jr. P.A., and Nichols, D.J. 1995. Effectiveness of vegetative filter strips in controlling losses of surface-applied poultry litter constituents. *Transactions of the American Society of Agricultural Engineers.* 38: 1687-1692.**

   Value: 2 for meta-analysis. Location: Arkansas. The authors investigated the efficacy of filter strips in attenuating nitrogen, phosphorus, and suspended solids in runoff containing poultry litter. See summary in the sediment section.

6. Clausen, J.C., Guillard, K., Sigmund, C.M., and Dors, K. M. 2000. Water quality changes from riparian buffer restoration in Connecticut. *Journal of Environmental Quality*. 29: 1751-1761.

   Value: 2 for meta-analysis. Location: Connecticut. The authors investigated how TSS, nitrogen, and phosphorus changed when half of a 35 by 250m plot of corn was converted to fescue grass along a first order stream. See the summary in sediment section.

7. **Daniels, R.B. and Gilliam, J.W. 1996. Sediment and chemical load reduction by grass and riparian filters. *Soil Science Society of America Journal*. 60: 246-251.**

   Value: 2 for meta-analysis. Location: North Carolina Piedmont. The study evaluated the effectiveness of grassed and forested buffers at removing sediment and nutrients from agricultural runoff at two sites. See summary provided in the sediment section.

8. **Dillaha, T.A., Reneau, R.B., Mostaghimi, S., and Lee, D. 1989. Vegetative filter strips for agricultural nonpoint source pollution control. *Transactions of the American Society of Agricultural Engineers*. 32: 513-519.***

   Value: 2 for meta-analysis. Type: Experimental, before-after. Location: SW Virginia. Abstract: "A rainfall simulator was used to evaluate the effective-ness of vegetative filter strips (VFS) for the removal of sediment, nitrogen (N), and phosphorus (P) from cropland runoff. Simulated rainfall was applied to nine experimental field plots on an eroded

Groseclose silt loam soil (clayey, mixed, mesic Typic Hapludalt) with a 5.5 by 18.3 m bare cropland source area and either a 0, 4.6, or 9.1 m VFS located at the lower end of each plot. Fertilizers were applied to the plots at rates of 222 kg/ha of liquid N and 112 kg/ha of P2O5 and K2O. Water samples were collected from the base of each plot and analyzed for sediment and nutrient content. One set of plots was constructed to encourage concentrated rather than shallow uniform flow. The 9.1 and 4.6 m VFS with shallow uniform flow removed an average of 84 and 70% of the incoming suspended solids mass, 79 and 61% of the incoming P mass, and 73 and 54% of the incoming N mass, respectively. Soluble nutrients in the filter effluent were sometimes greater than the incoming soluble nutrient load, presumably due to lower removal efficiencies for soluble nutrients and the release of nutrients previously trapped in the filters. Concentrations of soluble inorganic N and P in filter strip effluent were sufficient to cause eutrophic plant growth in aquatic ecosystems. Observation of existing VFS showed that on-farm VFS were not likely to be as effective as experimental VFS because of problems with flow concentrations."

From: Dosskey 2002, citing this paper regarding sediment: 11% slope plot, 6 events, 4.6m length had 86% reduction, 9.1m plot had 98% reduction; 16% plot (concentrated flow), 6 events, 4.6m plot had 53% removal, 9.1m plot had 70% removal.

Removal rates appear to be strongly correlated with infiltration.

9. **Dillaha, T.A., Sherrad, J.H., Lee, D., Mostaghimi, S., and Shanholtz, V.O. 1988. Evaluation of vegetative filter strips as best management practices for feed lots. *Journal of Water Pollution Control Federation*. 60: 1231-1238.**

Value: 2 for meta-analysis. Type: Experimental, control-treatment. Location: SW Virginia. The effectiveness of reducing sediment and nutrients in runoff from a simulated feedlot was evaluated. The authors note that storms of high intensity often result in a majority of the pollutant transport even though such storms comprise a small amount of the total annual precipitation received at a location. Soils were clayey, mixed, mesic, Typic, Hapludult (silt loam). Simulated feedlots were 5.5 by 18.3m long and were grouped into a set of 3, and there were multiple sets. Each feedlot plot within a set had either no vegetated filter strip (VFS), a 4.6m VFS, and a 9.1m VFS. Discharge from the plot with no VFS was assumed to be equal to the input to the VFS of the other two plots in the set. Set 1 had a slope of 11% with cross slope <1%, Set 2 a slope of 16% with cross slope <1%, and set 3 a slope 5% plus a cross slope of 4% in order to evaluate the effectiveness of the VFS on concentrated flow. Vegetation was in the VFS was Orchard grass cut to 10cm. The simulated feedlots were cleared of weeds and residue, tilled, and then compacted. Dairy manure was applied uniformly and then compac67ted at a rate of 7500/kg/ha wet weight during the first run and 15,000 kg/ha on the second run which were the estimated feedlot accumulation after 1 and 2 weeks. Manure nutrient content was 0.65% N, 0.15% ammonia, 0.1% Phosphorus, and a 17.1% solids content (equates to approx. 80g P and 490g of N for first run and twice as much for second run). Simulated rainfall at a rate of 50mm/hr was applied to approximate a 2 to 5 yr recurrence interval, 1hr storm duration in Virginia. The 9.1m 11%

slope filter with uniform flow reduced total suspended sediments by 94% and the 4.6m filter with 11% slope reduced it by 87%. The 9.1m 16% slope filter with uniform flow reduced total suspended sediments by 87% and the 4.6m filter with 16% slope reduced it by 74%. The first few meters of the VFS accounted for most of the load reduction; doubling the VFS length increased load reduction by an additional 10%. Sediment reductions decreased in subsequent runs as sediment accumulated in the vegetated plot. In the plot with the 4% cross-slope, sediment reductions were 31% for the 4.6m VFS and 58% for the 9.1m VFS; since these plots had the same slope as the first set of plots, the reduced sediment rapping efficiency can be attributed to experimental inducement of concentrated flow. Plots with concentrated flow had a greater loss of sediment despite a loading that was 3 times less than the plots with uniform flow. Phosphorus reductions were: 80% for the uniform flow 9.1 m 11% slope plot; 63% for the uniform flow 4.6m 11% slope plot; 57% for the uniform flow 9.1m 16% slope plot; 52% for the uniform flow 4.6m slope plot; 19% for the concentrated flow 9.1m 11% slope plot; and 2% for the concentrated flow 4.6m 11% slope plot. For phosphate, there were inconsistent results, with the 9.1m plots with uniform flow reducing losses by 30% and -51%. Plots with concentrated flow were not effective. In many cases, phosphate in the effluent was higher than the influent, indicating mobilization of phosphate previously stored in the VFS. The 4.6m uniform flow plots reduced total nitrogen by an average of 67%, while the 9.1m uniform flow plots reduced it by an average of 74%. Sediment bound total Kjeldahl nitrogen (TKN) accounted for 77 to 80% of the nitrogen in effluent from the VFS. The filters were much less effective at removing soluble N than sediment bound N and subsequent runs resulted in mobilization of previously trapped soluble N. The highest load reduction for any plot was 17%. The 9.1m concentrated flow VFS reduced nitrogen by 9% and the 4.6m VFS had no net reduction. The lack of nutrient reductions is likely due to the low infiltration rates- the amount of water runoff reduced by the VFS ranged from -6 to 25%, with four of the 6 plots having runoff reductions below 10%. The authors stress that if concentrated flow into a VFS is not minimized, they are unlikely to be effective at removing pollutants from runoff.

10. Dodd, R.J., Sharply, A.N., and Berry, L.G. 2018. Organic phosphorus can make an important contribution to phosphorus loss form riparian buffers. *Agric. Environ. Lett*. 3: 180002.

    Value: 0 for buffer-P data analysis, 2 for watershed process info. Location: Arkansas. Type: Observational. Retention of dissolved phosphorus by a 30m forested buffer was investigated. The source of P was pasture treated with poultry liter and swine manure. "Three possible mechanisms for the release of P from VBS have been suggested (Roberts et al., 2012): (i) decreased P sorption capacity due to saturation of P sorption sites, (ii) desorption of P from soil surfaces or dissolution of precipitated P, and (iii) biological cycling through the plant and microbial pools." There were three different sites. Field 1 had Noark very cherty silt loam soils with 2 to 20% slopes and was grazed at 0.5 animal units per ha. Field 5a had Razort silt loams with 0.2 to 1.0% slopes and was hayed and grazed at 0.3 animal units per ha. Field 12 was Spadra loam with 0.5 to 2% slopes and was hayed and grazed at 0.3 animal units per ha. *"All three fields received poultry litter once every 2 yr in March from 2004 to 2012 (4.5 Mg ha-1 yr-1; approximately 50 kg P and 120 kg N ha-1 yr-1).*

Fields 1 and 12 currently receive only swine manure. In 2014, Field 1 received a total of 47 kg P ha-1 and 94 kg N ha-1 and Field 12 received 65 kg P ha-1 and 128 kg N ha-1. In 2015, Field 1 received a total of 7.3 kg P ha-1 and 32 kg N ha-1 and Field 12 received 35 kg P ha-1 and 146 kg N ha-1. While no swine manure has been applied to Field 5a, diammonium phosphate fertilizer was applied annually since 2012 at 11 kg P and 25 kg N ha-1. On Fields 1 and 12, receiving swine manure, a required application buffer of 30 m from the field edge is in place. Field 1 has a steep topography and drains into an ephemeral stream located within the riparian zone and connected to Big Creek. Fields 5a and 12 have slopes of <2%. These fields border Big Creek and are prone to flooding during large storm events. Field 1 is continuously grazed by cattle, whereas grass is cut for silage in Fields 5a and 12." Transects ran from the fertilized pasture zone (FPZ), through a 30m vegetated buffer zone (VBS) and then a 30m forested riparian zone (FRZ). Soil samples were collected in October, January, April, and July. Water extractable soil P (WEP)- total, inorganic, and organic) was analyzed. WEP is a measure of how much dissolved P is released from soils into surface runoff. "This study demonstrates that the significant decrease in soil test P concentrations in FRZ soils compared with regularly fertilized FPZ does not necessarily translate to a reduction in the total amount of P, which can be released to runoff due to the increase in WEPo. Furthermore, while DPS [degree of P saturation], of which soil test P is a component, was a good predictor of WEPi release, additional factors relating to biological cycling need to be considered when trying to account for the potential release of organic P." Take home message: buffers and source control (e.g. applying P at agronomic rates) are needed to manage P in runoff since P can accumulate in buffers and transform into organic forms that a degree of P saturation test cannot detect.

11. Dodds, W.K. and Oakes, R.M. 2006. Controls on nutrients across a prairie stream watershed: land use and riparian cover effects. *Environmental Management*. 37: 634-646.

    Value: 0 for buffer-nitrogen data analysis, 3 for watershed process info. Location: Kansas. Type: Observational. This study examined land use at multiple spatial scales relative to instream concentrations of total phosphorus, total nitrogen and nitrate. See nitrogen section for summary.

12. **Dosskey, M.G.G., Hoagland, K.D., and Brandle, J.R. 2007. Change in filter strip performance over ten years. *Journal of Soil and Water Conservation*. 62: 21-32.**

    Location: Nebraska. The study sought to determine if the age of buffer strip establishment has an influence upon its ability to remove pollutants from agricultural runoff. See summary in sediment section.

13. **Doyle, R.C., Wolf, D.C., and Bezdicek, D.F. 1975. Effectiveness of Forest Buffer Strips in Improving the Water Quality of Manure Polluted Runoff. In *Managing Livestock Wastes Proceedings of the 3rd International Symposium on Livestock Wastes ASAE*, St. Joseph, MI pp. 299-302.**

Location: Maryland. Type: Experimental. This study examined the effectiveness of a buffer at removing nitrogen, phosphorus, fecal coliform (FC), and fecal streptococcus (FS) from runoff containing dairy manure. See summary in pathogens section.

14. **Eghball, B., Gilley, J.E., Kramer, L.A., and Moorman, T.B. 2000. Narrow grass hedge effects on phosphorus and nitrogen in runoff following manure and fertilizer application. *Journal of Soil and Water Conservation*. 55: 172-176.**

    Value: 2 for surface flow buffer-nitrogen data analysis due to methods- simulated rainfall. Location: Iowa. Type: experimental. This study examined removal of nutrients in surface runoff by a narrow grass hedge bordering a corn field where feedlot manure and fertilizer application occurred. See nitrogen section for summary.

15. Fillion, M., Brisson, J., Guidi, W., and Labrecque, M. 2011. Increasing phosphorus removal in willow and poplar vegetation filters using arbuscular mycorrhizal fungi. Ecological Engineering Vol. 37, Iss. 2 pages 199-205.*

    Abstract: "Fast growing woody species are increasingly used in vegetation filters for wastewater treatment. Their efficiency in phosphorus (P) removal notably depends on plant uptake and storage in aboveground tissues. In this study, Populus NM5 (P. nigra × P. maximowiczii), Salix miyabeana (SX64) and Salix viminalis (5027) were planted in pots to evaluate the influence of colonization by arbuscular mycorrhizal fungi (AMF) Glomus intraradices on P uptake using two different P concentrations in irrigation water. Based on analysis of the foliar and woody components, our results show that the two treatments (inoculation with G. intaradices and P-irrigation) interact differently with total P content. Foliar P content is principally enhanced by the P-irrigation concentration, whereas the mycorrhizal colonization increases stem P content. In the presence of G. intraradices, both S. miyabeana and S. viminalis showed a 33% increase in stem P content. The latter finding is mainly due to an increase in biomass production, without modification of the P concentration, indicating that AMF associations affect P use efficiency. Thus, using arbuscular mycorrhizal fungi for phytoremediation strategies may increase biomass productivity and hence improve pollutant uptake."

16. Gburek, W.J. and Sharpley, A.N. 1998. Hydraulic controls on phosphorus loss from upland agricultural watersheds. *Journal of Environmental Quality*. 27: 267-277.

    Value: 0 for phosphorus-buffer data analysis, 3 for watershed process information. Location: Pennsylvania. Type: Observational. This study investigated the spatial variability of phosphorus sources within small agricultural watersheds. Phosphorus export from agricultural uplands is a product of the interaction between soils, crops, and land management practices with runoff, erosion, and channel dynamics (i.e. source and transport processes). In some areas, flow through porous subsurface soils/sediments or through soils atop an impervious layer can be a significant source of dissolved P delivery to surface waters. Dissolved and Total P exports were analyzed in two small upland watersheds (slopes ranged from 1 to 20% in one and 3 to 17% in the other; soils were channery silt loams in both). Most dissolved P was exported during storm events. Variable source areas of runoff occur due to spatial and temporal variation in depth to groundwater and saturated soils that prevent infiltration. The evidence suggested that most storm runoff was derived from near channel areas, and in these watersheds most of that runoff was produced within 30m of the channel. **The authors suggest reducing or eliminating P fertilizer application in near stream areas that tend to produce runoff, as well as applying P at agronomic rate in areas farther from the stream to avoid dissolved P transport in soils where preferential subsurface flow occurs.**

17. Georgakakos, C.B., Morris, C.K., and Walter, M.T. 2018. Challenges and opportunities with on-farm research: total and soluble reactive stream phosphorus before and after implementation of a cattle-exclusion, riparian buffer. *Frontiers in Environmental Science*. Vol. 6, Article 71.

    Value: 0 for buffer-data analysis due to uncontrolled hydrology (i.e. tile drain inflows) and legacy P. Location: New York. Type: Observational- before/after. This study changes in Total and soluble reactive phosphorus in relation to the implementation of riparian exclusion fencing on first and second order streams within a dairy farm. Fertilized corn and hay fields were up-gradient of the dairy pastureland. The livestock exclusion buffer was 14m wide. Settling ponds used for capturing dairy runoff were renovated during the study due to identification of a tile drain serving as a significant source of P to stream channels, however, it was not the focus of this study. After livestock exclusion, total P and total suspended solids concentrations were significantly lower, although soluble reactive P was not. The effect of the buffer on total P and TSS appeared to be higher during low flow periods and lower during wet periods. The lack of response in SRP to buffer installation may have been due to soils serving as a legacy source of P from historic land management practices. Variable source areas of runoff and associated concentrated flow also delivered SRP through the buffer to stream channels during wet periods. This indicates that buffers should be expanded to include areas where soil saturation occurs under normal precipitation conditions.

18. Gilley, J.E., Sindelar, A.J., and Woodbury, B.L. 2016. Removal of cattle manure constituents in runoff from no-till cropland as affected by setback distance. *Biological Systems Engineering: Papers and Publications.* 489.

    Value: 0 for buffer-phosphorus data analysis, because the reductions data are not presented in a useable format. Location: Nebraska. Type: Experimental. This study evaluated the removal of nutrients from manure applied to no-till cropland for multiple filter strip widths with runoff generated by simulated rainfall. See nitrogen section for summary.

19. Hay, V., Pittroff, W., Tooman, E.E., and Meyer, D. 2006. Effectiveness of vegetative filter strips in attenuating nutrient and sediment runoff from irrigated pastures. *The Journal of Agricultural Science*. 144: 349-360.

    Value: 0 for buffer-phosphorus data analysis because insufficient data is presented. Location: California. Type: Experimental, control-treatment. This study examines the effectiveness of filter strips at removing TSS, P, N, and fecal coliforms from flood irrigated pasture. See pathogens section for summary.

20. Heathwaite, A.L., Griffiths, P., and Parkinson, R.J. 1998. Nitrogen and phosphorus in runoff from grassland with buffer strips following application of fertilizers and manures. *Soil Use and Management*. 14: 142-148.*

    See nitrogen section for abstract.

21. Houlahan, J.E. and Findlay, C.S. 2004. Estimating the 'critical' distance at which adjacent land-use degrades wetland water and sediment quality. *Landscape Ecology*. 19: 677-690. Value: 0 for buffer-nitrogen data analysis. Location: Ontario, Canada. This study used modelling to evaluate the relationship between land use and nutrient concentrations in wetland water and sediment. See nitrogen section for summary.

22. Kelly, J.M., Kovar, K.L., Sokolowsky, R., and Moorman, T.B. 2007. Phosphorus uptake during four years by different vegetative cover types in a riparian buffer. *Nutrient Cycling in Agroecosystems*. 78: 239-251.

    Value: 0 for buffer-P data analysis. Location: Iowa. Type: Observational. This study compared phosphorus uptake rates among different types of vegetation in riparian buffers in order to address their ability to reduce P pollution from agricultural fields. The vegetation types tested were: 5-7m strip of smooth brome grass; 5m wide switchgrass; 5m wide alfalfa-smooth brome; 15m wide (4 rows) hybrid cottonwood. Soils were silt loams. After 4 years, both cottonwood biomass and P content in tissue was an order of magnitude greater than the other vegetation cover types. Differences in mycorrhizal species and higher root surface area are noted as potential reasons for greater biomass and P uptake in the cottonwoods. The authors assert that if removal of P is a goal, then periodic removal of buffer vegetation is necessary as P levels tended to increase in soil surface layers due to litter fall and reach an equilibrium with plant biomass production over time. The authors suggest harvesting vegetation annually for herbaceous species and 7 to 10 yrs for cottonwoods. Based on simplifying assumptions, it was estimated that harvesting over a 4 yr period could remove P at the following rates: 20kg/ha for alfalfa, 19 kg/ha for switchgrass, 62kg/ha for cottonwood; authors also provide an estimate of 62 kg/ha P harvestable for smooth brome, but this seems to contradict their earlier statements that cottonwood accumulated much more P than smooth brome. Authors note prior research finding that P associated with colloids (clay) moves freely through macropores while dissolved P disperses into micropores where it is retained.

23. Kozlowski, D.F., Hall, R.K., Swanson, S.R. and Heggem, D.T. 2016 Linking management and riparian physical functions to water quality and aquatic habitat. *Journal of Water Resource and Protection*, 8. pp. 797-815.

Value: 0 for buffer-nitrogen data analysis. Type: Observational, before-after. Location: Nevada. This paper provides a retrospective before/after comparison of wetland/riparian assessments (1994 vs. 2006) and water quality data (before/after 1994) for a watershed (Maggie Creek) in which prescriptive livestock management was implemented in 1994. See summary in sediment section.

24. Kronvang, B., Laubel, A., Larsen, S.E., Andersen, H.E., and Djurhuus, J. 2005. Buffer zones as sink for sediment and phosphorus between the field and stream: Danish field experiences. *Water Science and Technology*. 51(3-4): 55-62.

Value: 0 for meta-analysis. Type: Observational, chronosequence. Location: Denmark. The authors surveyed sediment deposition and retention of phosphorus in 140 field slope units throughout Denmark. See sediment section for summary.

25. Kuusemets, V., Mander, Ü., Lõhmus, K., and Ivask, M. 2001. Nitrogen and phosphorus variation in shallow groundwater and assimilation in plants in complex riparian buffer zones. Water Science and Technology. Vol. 44 No. 11-12. pp 615-622.

Value: 3 for groundwater buffer-nitrogen data analysis. Location: Estonia. This study examined nitrogen and phosphorus removal from shallow groundwater through buffers at two different sites. See nitrogen section for summary.

26. Lee, K-H., Isenhart, T.M., and Schultz, R.C. 2003. Sediment and nutrient removal in an established multi-species riparian buffer. *Journal of Soil and Water Conservation*. 58: 1-8.

Value: 2 for meta-analysis. Type: Experimental, control-treatment. Location: Iowa. The authors investigated sediment and nutrient removal in buffers of different widths and vegetation composition. See sediment section for summary.

27. Lee, K-H., Isenhart, T.M., Schultz, R.C., and Mickelson, S.K. 2000. Multispecies riparian buffers trap sediment and nutrients during rainfall simulations. *Journal of Environmental Quality*. 29: 1200-1205.*

Value: 2 for meta-analysis. Type: Experimental, control-treatment. Location: Iowa. See sediment section for abstract.

28. Lee, K-H. 1999. Effectiveness of a multi-species riparian buffer system for sediment and nutrient removal. Retrospective Theses and Dissertations. 12148. IA State University. Ames, IA. https://lib.dr.iastate.edu/rtd/12148

Value: 2 for meta-analysis. Type: Experimental, control-treatment. Location: Iowa. The author investigated sediment and nutrient removal in buffers of different widths and vegetation composition. See sediment section for summary.

29. Lim, T.T., Edwards, D.R., Workman, S.R., Larson, B.T., and Dunn, L. 1998. Vegetated filter strip removal of cattle manure constituents in runoff. *Transactions of the American Society of Agricultural Engineers*. 41: 1375-1381.

    Value: 2 for meta-analysis. Type: Experimental, before-after treatment. Location: Kentucky. The authors studied the influence of vegetated filter strip (VFS) length on the reductions (concentrations and mass) in the transport of nitrogen, phosphorus, suspended and total solids, and fecal coliform from plots treated with cattle manure. See sediment section for summary.

30. Lowrance, R. and Sheridan, J.M. 2005. Surface runoff water quality in a managed three zone riparian buffer. *Journal of Environmental Quality*. 34: 1851-1859.

    Value: 2 for buffer-nitrogen data analysis due to some comparability issues. Type: Observational. Location: Georgia. This study evaluates the performance of a three-zone riparian buffer at removing N and P from cropland runoff. See nitrogen section for summary.

31. Lowrance, R., Williams, R.G., Inamdar, I. P., Bosch, D.D., and Sheridan, J.M. 2001. Evaluation of coastal plain conservation buffers using the riparian ecosystem management model. JAWRA Vol. 37, No. 6.

    Value: 0 for buffer-nitrogen data analysis. Location: Georgia. Type: model. This study employed a USDA riparian model to evaluate nutrient removal rates (under 2 different loading scenarios) for 14 different NRCS buffer configurations (4.6m to 51.8m widths) based on site conditions at an experimental farm in Georgia. See nitrogen section for summary.

32. Lowrance, R., Hubbard, R.K., and Williams, R.G. 2000. Effects of a managed three zone riparian buffer system on shallow groundwater quality in the southeastern Coastal Plain. *Journal of Soil and Water Conservation*. 55: 212-220.*

    See nitrogen section for summary.

33. Lowrance, R., Todd, R., Fail Jr., J., Hendrickson, Jr., O., Leonard, R., and Asmussen, L. 1984. Riparian forests as nutrient filters in agricultural watersheds. *BioScience*. 34: 374-377.

    Value: 0 for buffer-nitrogen data analysis. Location: Georgia coastal plain. Type: In this study, the role of riparian buffers in an estimated nitrogen and phosphorus budget was examined for a small agricultural watershed. See nitrogen section for summary.

34. Magette, W.L., Brinsfield, R.B., Palmer, R.E., and Wood, J.D. 1989. Nutrient and sediment removal by vegetated filter strips. *Transactions of the American Society of Agricultural Engineers*. 32: 663-667.

Type: Experimental, control-treatment. Location: mid-Atlantic Coastal Plain- Maryland. The authors evaluated sediment and nutrient retention by vegetated filters strips under simulated rainfall. See sediment section for summary.

35. Mander, Ü., Kuusemets, V., Lõhums, K., Mauring, T. 1997. Efficiency and dimensioning of riparian buffer zones in agricultural catchments. Ecological Engineering. 8: 299-324.

Value: 0 for meta-analysis. Location: Estonia. The authors perform a meta-analysis of nutrient retention in riparian zones and also present an efficiency assessment for nutrient retention for sites in Estonia and the U.S. See summary in nitrogen section.

36. Mankin, K.R., Barnes, P.L., Harner, J.P., et al. 2006. Field evaluation of vegetative filter effectiveness and runoff quality from unstocked feedlots. *Journal of Soil and Water Conservation*. 61: 209-217.

Value: 0 for buffer-phosphorus data analysis because the study results are not comparable to other study data since it was conducted on feedlot runoff management systems having a runoff collection and distribution system. Location: Kansas. Type: Observational. See Pathogens section for abstract.

37. Mbonimpa, E.G., Yuan, Y., Mehaffey, M.H., Jackson, M.A. 2012. SWAT model application to assess the impact of intensive corn-farming on runoff, sediments and phosphorus loss from an agricultural watershed in Wisconsin. *J. of Water Resource and Protection*, 4. pp. 423-431.

Value: 0 for meta-analysis. Type: Observational, case study. Location: Wisconsin. The SWAT model was used to evaluate the use of BMPs (including conservation tillage, fertilizer management, and vegetative buffers) in an agricultural watershed (66% cropland, 13% wetlands, 12% forest and grassland, 6% urban, 3% water) for reducing sediment and total P losses from cropland. See sediment section for summary.

38. McKergow, L.A., Weaver, D.M., Prosser, I.M., Grayson, R., and Reed, A.E.G. 2003. Before and after riparian management: sediment and nutrient exports from a small agricultural catchment, western Australia. *Journal of Hydrology*. 270: 253-272.

Value: 0 for meta-analysis. Type: Observational, Chronosequence. Location: western Australia. This study evaluated changes in sediment and nutrients delivered to a stream as a result of riparian livestock fencing. See sediment section for summary.

39. Neilen, A.D., Chen, C.R., Parker, B.M., Faggotter, S.J., and Burford, M.A. 2017. Differences in nitrate and phosphorus export between wooded and grassed riparian zones from farmland to receiving waterways under varying rainfall conditions. *Science of the Total Environment*, 598. pp. 188-197.

Value: 0 for buffer-nitrogen data analysis, 2 for nutrient transport process info. Location: Australia. Type: Observational. This study examined variation in nitrate and phosphorus exports through grassed vs. wooded riparian buffers and under differing amounts of rainfall. See nitrogen section for summary.

40. **Newbold, J.D., Herbert, S., Sweeney, B.W, Kiry, P. and Alberts, S.J. 2010. Water quality functions of a 15-year-old riparian forest buffer system. *JAWRA* 46:2:299-310**.

    Value: 2 for meta-analysis. Type: Experimental, treatment-control. Location: Pennsylvania. The study evaluated the long-term effectiveness of a three-zone buffer at removing suspended solids, nitrogen and phosphorus from runoff. See sediment section for summary.

41. Omernik, J.M., Abernathy, A.R., and Male, L.M. 1981. Stream nutrient levels and proximity of agricultural and forest land to streams: some relationships. *Journal of Soil and Water Conservation*. 36: 227-231.*

    See nitrogen section for summary.

42. Parsons, J.E., Daniels, R.B., Gilliam, J.W., and Dillaha, T.A. 1994. Reduction in sediment and chemical load agricultural field runoff by vegetative filter strips. *UNC-WRRI-94-286.* University of North Carolina. Raleigh, NC.

    Value: 0 because data not presented in a complete or readily useable format. Type: Experimental, treatment-control. Location: Coastal Plain and Piedmont, North Carolina. The authors investigated the performance of grass filters followed by riparian buffers at reducing sediment and nutrients from crop fields after natural rainfall events. See summary in sediment section.

43. Patty, L., B. Real, and J.J. Gril. 1997. The use of grassed buffer strips to remove pesticides, nitrate and soluble phosphorus compounds from runoff water. Pesticide Sci.49:243-251.

    Value: 3 for toxics/buffer analysis. Location: France. Type: Experimental, control-treatment, before-after. See summary in toxics section.

44. Reed, T. and Carpenter, S.R. 2002. Comparisons of P-yield, riparian buffer strips, and land cover in six agricultural watersheds. *Ecosystems.* 5: 568-577.*

    Abstract: "Riparian buffer strips may protect streams from phosphorus (P) pollution. We compared 2 years of daily P-yield (μg/m^2/day) from six southeast Wisconsin watersheds with contrasting riparian buffer attributes. Of the variables measured, mean daily P-yield was most closely correlated with the variability in riparian patch size. Variability in P-yield was most closely correlated with characteristics of the riparian buffer, such as percent wetland land cover, riparian continuity, and stream sinuosity. During the most extreme events, mean P-yield was negatively correlated with the percentage of wetland land cover in the upland watershed. Correlations suggest that riparian continuity may influence P-loading in these watersheds. Our results corroborate the importance of continuity and uniformity of riparian buffers as moderators of P flow from upland agricultural lands into streams."

45. **Rosa, D.J., Clausen, J.C., and Kuzovkina, Y. 2017. Water quality changes in a short-rotation woody crop riparian buffer. *Biomass and Bioenergy*, 107. 370-375.**

    Value: 0 for meta-analysis due to seeming inaccuracies in the data. Type: Experimental, treatment-control. Location: Connecticut. The authors studied how suspended solids and nutrient concentrations were affected by short-rotation biomass crops of willows used as riparian buffers. See summary in sediment section.

46. Schellinger, G.R. and Clausen, J.C. 1992. Vegetative filter treatment of dairy barnyard runoff in cold regions. *Journal of Environmental Quality*. 21: 40-45*

    Value: 0 for buffer-pathogen data analysis because the study results are not comparable-the study involved an engineered runoff management system. Location: Vermont. See summary in pathogens section.

47. **Schmitt, T.J., Dosskey, M.G.G., and Hoagland, K.D. 1999. Filter strip performance and processes for different vegetation widths and contaminants. *Journal of Environmental Quality*. 28: 1479-1489.**

    Value: 2 for meta-analysis. Type: Experimental, before-after. Location: Nebraska. The effectiveness of different filter strip designs at removing permethrin, atrazine, alachlor, nitrate, and phosphorus was evaluated. See summary in toxics section.

48. Schoonover, J.E., Williard, K.W.J., Zaczek, J.J., et al. 2005. Nutrient attenuation in agricultural surface runoff by riparian buffer zones in southern Illinois, USA. *Agroforestry Systems*. 64: 169-180.*

    Value: 0 for phosphorus-buffer data analysis because infiltration of runoff containing dissolved nitrogen in does not equate to dissolved P removal. See abstract in nitrogen section.

49. **Smith, C.M. 1989. Riparian pasture retirement effects on sediment, phosphorus and nitrogen in channellised surface run-off from pastures. *N. Z. J. Mar. Freshwater Res*. 23:139-146.**

    Value: 2 for meta-analysis. Type: Observational, before-after. Location: New Zealand. An examination of changes in suspended solids and nutrients in channelized flow before and after livestock exclusion from riparian strips. See sediment section for summary.

50. Snyder, N.J., Mostaghimi, S., Berry, D.F., Reneau, R.B., Hong, S., McClellean, P.W., and Smith, E.P. 1998. Impact of riparian forest buffers on agricultural nonpoint source pollution. *Journal of the American Water Resources Association*. 34: 385-395.

Value: 2 for groundwater buffer-phosphorus data analysis, study results reported as concentrations, but dilution and evapotranspiration were unaccounted for. Location: Virginia. Type: Observational. See nitrogen section for summary.

51. Srivastava, P., Edwards, D.R., Daniel, T.C., Moore Jr., P.A., and Costello, T.A. 1996. Performance of vegetative filter strips with varying pollutant source and filter strip lengths. *Transactions of the American Society of Agricultural Engineers*. 39: 2231-2239.

    Value: 0 for nitrogen-buffer data analysis because only surface runoff was examined, and infiltration of dissolved nitrogen does not equate to removal. Location: Arkansas. Type: Experimental, control-treatment. See nitrogen section for summary.

52. **Uusi-Kamppa, J. and Ylaranta, T. 1992. Reduction of sediment, phosphorus and nitrogen transport on vegetated buffer strips. *Agric. Sci. Finl.* 1:569-574.**

    Value: 1 for meta-analysis, due to experimental design- buffer vegetation was dormant during part of the study. Type: Experimental, control-treatment. Location: Finland. The authors evaluated the effects of buffer strips at reducing solids and nutrients from crop fields. See sediment section for summary.

53. Webber, D.F., Mickelson, S.K., Ahmed, S.I., and Russell, J.R. 2010. Livestock grazing and vegetative filter strip buffer effects on runoff sediment, nitrate, and phosphorus losses. Journal of Soil and Water Conservation 65, no. 1: 34-41.

    Value: 2 for meta-analysis. Type: Experimental, control-treatment. Location: Iowa. This study examined the effects of filter strips on sediment and nutrients in runoff from livestock pasture. See sediment section for summary.

54. Young, R.A., Huntrods, T., and Anderson, W. 1980. Effectiveness of vegetated buffer strips in controlling pollution from feedlot runoff. *Journal of Environmental Quality*. 9: 483-487.

    Value: 0 for meta-analysis- incomparable due to feedlot runoff. Type: Experimental, before/after (i.e., up/down of filters). Location: Minnesota. This study evaluated the effectiveness of vegetated plots at reducing bacteria, suspended solids, and nutrients in feedlot runoff. See sediment section for summary.

55. Younos, T.M., Mendez, A., Collins, E.R., and Ross, B.B. 1998. Effects of a dairy loafing lot-buffer strip on stream water quality. *Journal of the American Water Resources Association*. 34: 1061-1069.

    Value: 0 for meta-analysis. Type: Experimental, before-after. Location: Virginia. The study evaluated the effectiveness of a filter strip at reducing sediment and nutrients from dairy loafing lot runoff. See sediment section for summary.

56. Weld, J.L., Sharpley, A.N., Beegle, D.B., and Gburek, W.J.2001. Identifying critical sources of phosphorus export from agricultural watersheds. *Nutrient Cycling in Agroecosystems*. 59: 29-38.

Value: 0 for buffer-P data analysis, 3 for watershed process info. Location: Pennsylvania. Type: Observational. This study is a continuation of Gburek et al (1998) and further supports the conclusions of that study. This study also evaluated a modified NRCS phosphorus index (PI) which ranks the susceptibility of individual fields to P losses based on soil P, hydrology, and land use. The PI identified near channel areas as critical sources of P loss. These areas tended to be sources of surface runoff and had high soil P levels. Thus, the modified PI indicated where improved management of fertilizer and manure applications should occur-within about 30m of the stream channels in the watersheds studied.

57. Zhang, X., Liu, X., Zhang, M., and Dahlgren, R. A. 2010. A review of vegetated buffers and a meta-analysis of their mitigation efficacy in reducing nonpoint source pollution. Journal of Environmental Quality. Vol. 39: 76-84.

This paper includes a meta-analysis of phosphorus reductions in buffers. See summary in sediment section.

58. Simard, R.R., Beauchemin, S., and Haygarth, P.M. 2000. Potential for preferential pathways of phosphorus transport. *J. Environ. Qual.* 29.

Abstract*:* "This paper briefly reviews the existing literature and uses evidence from three studies to demonstrate the occurrence of preferential pathways of P transport through soil. Studies conducted in the St. Lawrence lowlands, Canada, indicated that particulate P (PP-i.e., >0.45 µm) the main fraction of total P (TP) in tile-drainage water generated by storm events after periods of low rainfall. In the remainder of the year, the concentration of TP and P forms were related to soil texture, primary tillage intensity and frequency, and showed wide seasonal variations. For a study conducted in the UK under grassland, higher TP concentrations were found in near-surface runoff (0–30 cm) compared with concentrations measured in drainflow. Water passing through the artificial drainage system had a higher proportion of PP (43%) than water passing close to (<30 cm) or over the soil surface (31%). **Installation of tile drainage in a poorly draining soil reduces P transfer by improving the infiltration capacity, thereby reducing overland flow volume and allowing P to be retained/sorbed by the soil matrix**. Because of the absence of tillage, permanent grasslands accumulate P near the surface. We hypothesize that, if the soil P store is coincident with preferential flow pathways (either artificial mole drainage channels or natural macropores), permanent grassland will be vulnerable to transfer large amounts of P through subsurface pathways. Phosphorus transfer through preferential flow pathways may be particularly important after storm events that rapidly follow periods of drought and/or surface P inputs as inorganic fertilizer or manure."

Sediment/Suspended Solids

1. Arora, K., Mickelson, S.K., Baker, J.L., Tierney, D.P., and Peters, C.J. 1996. Herbicide retention by vegetative buffer strips from runoff under natural rainfall. Transactions of the American Society of Agricultural Engineers. 39: 2155-2162.

   Value: 1 for meta-analysis due to concentration rather than mass data. Type: Experimental, before-after. Location: Iowa. The authors investigated removal of herbicides and sediment from agricultural field runoff. Source area was a 0.41 ha corn field, 3% avg. slope, planted up-down slope to enhance runoff. The herbicides that were applied were atrazine (2.12kg/ha), metolachlor (2.80kg/ha), and cyanazine (3.36kg/ha). Six 1.25 by 20.1m filter strips were established downgradient of a mixing tank collecting the field runoff. Vegetation on the strips average 81% smooth bromegrass, 12% Kentucky bluegrass, 5% tall fescue, 2% other. Soil was silty clay loam with a uniform slope of approximately 2% throughout the study area. The buffer area ratio for the strips was 15:1, but runoff volume to three of the strips was doubled to simulate a 30:1 buffer area ratio. There was no statistical difference at the .10 level for sediment retention between the 15:1 and 30:1 filter strips. Data is not provided for all rain events parsed among the two buffer area ratio treatments, but for rain event #6, sediment retention ranged from 83.1 to 91.1% (avg. 87.6) for the 15:1 strips and 75.9 to 90.2% for the 30:1 strips. For all buffer area ratio treatments combined for 6 rain events: average water infiltration ranged from 9% to 97%; sediment mass retention ranged from 44 to 100% (overall average = 75%); atrazine mass retention ranged from 13 to 100% (overall average = 61%); metolachlor mass retention ranged from 22 to 100% (overall average = 63%); cyanazine mass retention ranged from 15 to 100% (overall average = 61%). There was no statistical difference between retention of herbicide for the 15:1 vs. the 30:1 area ratio treatment, and no difference in retention among the three herbicides. The wide range in herbicide retention was attributed to variable infiltration (sometimes all runoff infiltrated, sometimes not) of runoff which was related to storm variability. The proportion of herbicide adsorbed to sediment is expected to increase as the proportion of fine sediment particles in runoff increases. However, in this experiment, although the concentrations of herbicide in sediment were higher than in water, the mass of herbicide adsorbed to sediment retained in the buffer was low. Reductions in herbicide in the filter strip outflow was therefore attributable to infiltration of herbicide laden water. Since the sediment retention was relatively high, herbicides that adsorb to sediment more strongly than those used in this study would be expected to have greater retention under the same conditions.

2. Barfield, B.J, Blevins, R.L., Fogle, A.W., Madison, C.E., Inamdar, S., Carey, D.I., and Evangelou, V.P. Water quality impacts of natural filter strips in karst areas. *Trans. ASAE.* Vol. 41(2): 371-381.*

   Abstract: "Naturally occurring riparian filter strips are widely recommended as a technique for removing chemicals from flow prior to entering a stream. Data on their effectiveness is sparse as is information on the partitioning of chemicals trapped by various mechanisms in these strips. Studies were conducted on the effectiveness of natural riparian grass buffer strips in removing sediment, atrazine, nitrogen and phosphorus from surface runoff. The strips were located in a karst watershed. No-till and conventional-tillage erosion plots served as the sediment and chemical source area. Runoff from the plots was directed onto 4.57, 9.14, and 13.72 m filter strips where the inflow and outflow concentrations and flow rates were measured. Trapping percentages for sediment and chemicals typically ranged above 90%. An evaluation was made of the distribution of trapped chemicals among infiltrated mass and mass stored in the surface layer. The analysis showed that most of the chemicals were trapped by infiltration into the soil matrix and that trapping efficiency increased with filter strip length and with fraction of water infiltrated."

Data as reported in Helmers et al., 2005: slope was 9% for the silt loam soil; area ratios for the 4.57, 9.14, and 13.72 m filters were: 4.84:1, 2.42:1, 1:61:1; corresponding sediment reductions were 97, 99.9, and 99.7%, and infiltration % of 91.3, 97.0, and 94.3%.

3. Barton, D.R., Taylor, W.D., and Biette, R.M. 1985. Dimensions of riparian buffer strips required to maintain trout habitat in southern Ontario streams. *North American Journal of Fisheries Mgmt.* 5: 364-378.

   See summary of this reference in the temperature section; the reference is not particularly useful for evaluating buffers for sediment trapping.

4. **Borin, M., Vianello, M., Morari, F., and Zanin, G. 2005. Effectiveness of buffer strips in removing pollutants in runoff from a cultivated field in north-east Italy. *Agriculture, Ecosystems and Environment.* 105: 101-114.**

   Value: 0 for meta-analysis due to sediment sample method and reporting in concentrations rather than mass. Type: Experimental, before-after. Location: NE Italy. Terrain is flat, with a shallow water table (1-3m deep). Mean annual temperature is approx. 12^{o}C and precip averages 32.7 inches (but precip during study was 28.2in, 14% lower). Fields in this area average 1.4 acres. Crops include corn, soybeans, sugar beets and winter wheat. The authors evaluate the effectiveness of a 6m wide buffer at reducing suspended solids, nitrogen and phosphorus exports from crop fields. Hillslope dimensions were 35m long at 1.8% slope. The buffer was composed of two rows of alternating trees and shrubs (1.5 and 4.5m from the ditch) planted 8 years prior and fescue grass sown throughout the buffer. Soils were loamy (fulvic, calcaric Cambisol), with sand increasing to 50-60% at 1.4m depth. Soil infiltration rates ranged from 2.8 x 10^{-3} cm s^{-1} to 2.7 x10^{-4} cm s^{-1} in compacted areas; hydraulic conductivity averaged 1.2 x 10^{-3} cm s^{-1}. Fertilizer application rates ranged from 16 to 150 kg/ha for nitrogen and 0 to 20kg/ha for phosphorus, depending on the crop rotation (winter wheat, maize, and soybean).

   Buffer strips reduced runoff volumes by an average of 80%. Maximum TSS concentrations greater than 10,000mg/L occurred without a buffer strip, while concentrations with the buffer strip were nearly always below 1000mg/L. The buffer strip reduced TSS in runoff by 78%; however, this varied from 28% in the first year, 86% in the 2nd year, 83% in the 3rd year, and 57% in the fourth year (grass cover was substantially reduced in this drier year). Overall, the buffer strip reduced the TSS mass loss by 94% (0.4t/ha with buffer and 6.9t/ha without buffer).

5. **Chaubey, I., Edwards, D.R., Daniel, T.C., Moore Jr. P.A., and Nichols, D.J. 1994. Effectiveness of vegetative filter strips in retaining surface-applied swine manure constituents. *Transactions of the American Society of Agricultural Engineers*. 37: 845-850.**

   Value: 0 for meta-analysis, suspended solids were from manure, not sediment. Type: Experimental, before-after. Location: Arkansas. The authors investigated the efficacy of filter strips in attenuating nitrogen, phosphorus, suspended solids, and fecal coliform in runoff containing liquid swine manure. The soil was a fine-silty, mixed mesic, Typic Fragiudult (silt-loam) and was graded to a uniform 3% slope. Fescue grass was established (at 500kg/ha seeding rate) in each of three plots (1.5m x 24m) and measurements were made at 3, 6, 9, 12, 15, and 21m. The swine manure was uniformly applied at a rate of 81,500 L/ha to the upper 3m of each plot. Grass height was approximately 10cm when the manure was applied. Simulated rainfall at a rate of 50mm/hr, applied until runoff duration of one hour occurred. Flow-weighted, mean concentrations decreased over filter strip lengths for nitrate, ammonia, total Kjeldahl nitrogen (TKN), and phosphate, total phosphorus, and total suspended solids, chemical oxygen demand, and fecal coliforms, although these last four parameters did not decrease further after a distance of 3 m. Decreasing concentrations was expected due to dilution with simulated rainfall, which is why mass transport was also analyzed. Mass transport of nitrate increased with filter strip length and may have been due to the amount of nitrate pre-existing in the simulated rainfall, soil, or grass. Filter strip length had no effect on mass transport of fecal coliform. Decreases in mass transport with filter strip length occurred for all other parameters. Masses of ammonia, TKN, phosphate and total P did not become further reduced after a length of 9m. Mass transport of TSS did not lessen after a distance of 3m. Runoff infiltration, trapping by vegetation and debris, and/or adsorption to debris/vegetation was responsible for the decreases in pollutant concentrations. Buffer effectiveness for TSS removal did not vary between 3 and 21m and the average removal effectiveness was 61%.

   The buffer strip effectiveness for removal of ammonia, TKN, phosphate, and total P did not increase significantly beyond a distance of 9m, although the limited replication likely limited the power of the statistical test to detect differences.

Figure 15: Table from Chaubey et al. (1994) of effectiveness of VFS lengths

Table 8. Mean* effectiveness of VFS lengths

VFS length	Parameter			
	NH_3-N	TKN	PO_4-P	TP
(m)	(%)			
3	70.9c†	64.9b	65.4b	67.0b
6	82.9b	69.1b	71.3b	70.9b
9	96.4a	88.7a	88.7a	87.2ab
15	98.8a	86.2a	92.9a	91.1a
21	99.2a	87.3a	94.3a	92.4a

* Mean of three replications.

† Within-column means followed by the same letter are not significantly ($p < 0.05$) different by LSD test.

6. **Chaubey, I., Edwards, D.R., Daniel, T.C., Moore Jr. P.A., and Nichols, D.J. 1995. Effectiveness of vegetative filter strips in controlling losses of surface-applied poultry litter constituents. *Transactions of the American Society of Agricultural Engineers*. 38: 1687-1692**.

   Value: 0 for meta-analysis, suspended solids were from manure, not sediment. Type: Experimental, before-after. Location: Arkansas. The authors investigated the efficacy of filter strips in attenuating nitrogen, phosphorus, suspended solids, and fecal coliform in runoff containing poultry litter. The soil was a fine-silty, mixed mesic, Typic Fragiudult (silt-loam) and was graded to a uniform 3% slope. Fescue grass was established a year prior (at 500kg/ha seeding rate) in each of three plots (1.5m x 24.4m) and measurements were made at 3.1, 6.1, 9.2, 15.2, and 21.4m. The poultry litter was uniformly applied at a rate of 5Mg/ha to the upper 3.1m of each plot. The source area was considered to be small relative to the filter strip since an actual farm setting would typically have a longer slope length with litter application. Grass height was approximately 10cm when the manure was applied. Simulated rainfall at a rate of 50mm/hr, applied until runoff duration of one hour occurred. Filter strip length affected concentrations of all parameters except TSS, which did not significantly decrease after a length of 3.1m. Decreasing concentrations was expected due to dilution with simulated rainfall, which is why mass transport was also analyzed. Mass transport of nitrate increased rather than decreased with filter strip length, likely due to nitrate in the simulated rainfall and mobilization from the test plots. Mass transport of total Kjeldahl nitrogen (TKN), ammonia, and phosphate decreased up to a length of approximately 9.2m. Mass transport of total P did not further decrease after a distance of 6.1m. Mass transport of total suspended solids (TSS) did not decrease beyond 3.1m. Infiltration seemed to be the primary mechanism for N and P removal, since most P was dissolved in the form of phosphate and most N was dissolved in the form of organic uric acid. The average effectiveness for TSS removal was 34.5%, which did not vary between

3.1m and 21.4m. Removal effectiveness for TKN and TP did not increase significantly beyond 9.2m, while effectiveness for ammonia and phosphate did not increase significantly after 15.2m. However, the table below shows increased effectiveness at further distances for TKN and TP, suggesting that the low amount of replication limited the power of the statistical test at detecting differences.

Figure 16: Table from Chaubey et al. (1995) of Mean VFS length effectiveness

Table 7. Mean* VFS length effectiveness

Constituent	VFS Length (m)				
	3.1 (%)	6.1 (%)	9.2 (%)	15.2 (%)	21.4 (%)
TKN	39.2c†	53.5bc	66.6ab	75.7a	80.5a
NH_3-N	46.6c	69.8b	77.6b	94.1a	98.0a
TP	39.6c	58.4bc	74.0ab	86.8a	91.2a
PO_4-P	38.8d	55.1cd	70.5bc	84.9ab	89.5a

* Mean of three replications.

† Within-row means followed by the same letter are not significantly different by LSD test.

7. **Clausen, J.C., Guillard, K., Sigmund, C.M., and Dors, K. M. 2000. Water quality changes from riparian buffer restoration in Connecticut. *Journal of Environmental Quality*. 29: 1751-1761.**

- Value: 0 for meta-analysis, suspended solids, not suspended sediment.Type: Experimental, treatment-control. Location: Connecticut. The authors investigated how TSS, nitrogen, and phosphorus changed when half of a plot of corn was converted to fescue grass along a first order stream. The soil beyond 5m from the stream was a poorly drained coarse-loamy, mixed, active, mesic, Aquic Dystrudept with a 5% slope that developed from glacial till. The upper surface of the till was 45 to 60cm below the soil surface. Within 5m of the stream was wetland underlain by poorly to very poorly draining alluvium. For the study all woody vegetation as removed from a 5m floodplain area along the stream. During the 22-month calibration period the field had a crop rotation of corn, followed by winter rye as a fall/winter cover crop. The field was fertilized with 112kg/ha of ammonium nitrate during April/May, followed by 112kg/ha of urea in June. Manure was also applied in one summer when the ryegrass cover crop was seeded. After the calibration period, the lower 30m of the (60 x 125m) treatment field was seeded with fescue and woody vegetation regrowth (dogwood, alder, cottonwood, red maple) was permitted in the 5m floodplain area; reed canary grass was also present in the floodplain. For the control field (60 x 125m), the floodplain area was kept free of woody vegetation and vegetation consisted primarily of reed canary grass. Runoff plots were originally 2 x 1m, but additional plots were installed that were 2m wide by 6.3 to 14.6m long. The buffer reduced concentrations in overland flow by 70% for total Kjeldahl (TKN), 83% for nitrate, 25% for ammonia, 73% for total phosphorus, and 92% for TSS. Groundwater TKN and P concentrations generally increased as water flowed through the riparian area (122% increase for total P). Ammonia was relatively unchanged in groundwater and nitrate declined in certain areas of the buffer. TKN and ammonia concentrations in groundwater did not change significantly. During the treatment period, most of the nitrate decline (52 of the 70%) occurred within 2.5m of the stream and very little (2% of the 70%) decreased in the upper 30m of the buffer. Denitrification in groundwater is influenced by organic carbon, moisture content, aeration, pH, temperature, and the amount and forms of nitrogen. The greatest loss of nitrogen from the treatment field was through groundwater. Nitrate comprised 93 to 97% of the total N mass entering the buffer and 80% of the N exiting the buffer. An estimated 1% of the N load was denitrified; it was thought that denitrification was underestimated and that groundwater upwelling near the stream were the primary causes of the nitrate concentration decreases. Plant uptake of the N mass in the buffer ranged from 7 to 13%. Restoration of the buffer decreased nitrate in groundwater by 35%, with the absence of fertilization in the buffer area being partly responsible for the decline.

8. **Coyne, M.S., Gilfillen, R.A., Rhodes, R.W., and Blevins, R.L. 1995. Soil and fecal coliform trapping by grass filter strips during simulated rain. *Journal of Soil and Water Conservation*. 50: 405-408**.

   Value: 3 for meta-analysis, suspended solids were from manure, not sediment. Type: Experimental, before-after. Location: Kentucky. This study simulated the effectiveness of a grass filter strip at removing sediment and fecal bacteria from poultry waste applied to a field. The soil was a fine, mixed, mesic, Typic Paleudalf (silt loam) with an average slope of 9%. The erosion strip was 22.1m long and the grass filter strip was 9m long. Grass on the filter strip was mowed to a 4.0cm height. Poultry litter was applied at a rate of 16.5 Mg/ha (7 tons/acre) and was incorporated into the soil to a depth of 15cm. The litter contained 2.8% total nitrogen and 2.9% total P. Simulated rainfall was applied to the erosion plot at a rate of 6.4cm/hr (which approximated a 10yr storm event for the study area) for one hour after runoff began (a total of 132 and 140 minutes in the two replicate plots. It was noted that a longer period between litter application and rainfall as well as lower rainfall intensity would have led to decreased soil erosion and bacteria mobilization. Approximately 88% of the surface runoff infiltrated the soil of the filter strips. The sediment trapping efficiency for both replicate plots was 99%; authors noted that this may have been an overestimate since the simulated rainfall was not applied to the filter strip. The average trapping efficiency for bacteria was 58.5% (74 and 43% in the two plots, with the latter plot having a lower infiltration rate). Runoff from the filter strip had bacteria concentrations exceeding 200cfu/100mL (actual concentrations not reported). The study did not evaluate effectiveness at different distances along the filter strips. Some channelized flow occurred in the filter strip, which limited the trapping efficiency for bacteria. The authors noted that bacteria mortality was probably enhanced by covering the erosion strips with a tarp when air temperatures stayed above 27^{o}C. The study cites Albrecht and Barfield (1981) as finding that grass filter strip sediment trapping efficiency declined from >98% to 75% as sediment deposition increased and water infiltration decreased.

9. **Daniels, R.B. and Gilliam, J.W. 1996. Sediment and chemical load reduction by grass and riparian filters. *Soil Science Society of America Journal*. 60: 246-251.**

   Value: 3 for meta-analysis, suspended solids were from manure, not sediment. Type: Experimental, before-after. Location: North Carolina Piedmont. The study evaluated the effectiveness of grassed and forested buffers at removing sediment and nutrients from agricultural runoff at two sites. The authors state that riparian zones are less effective at removing phosphorus from runoff than they are at nitrogen or sediment removal; they cite Cooper and Gilliam study finding 50% removal of P from runoff on the Coastal Plain of North Carolina. The soils on the first site were primarily clayey, kaolinitic, thermic typic Kanhapludult (sandy to clay loam). The second site had clayey, kaolinitic, thermic, Typic Hapludults (silt loam to silty clay). Valley slopes ranged from 4 to 15% with first to second order ephemeral and intermittent streams present. Slope length at the first site ranged from 48 to 86m. Four plots were used on the first site. All four plots had fescue filter strips. Plots 1 (avg. slope 4.9%, max 10%) and 2 (avg. slope 2.1%, max 8.8%) had runoff subsequently entering a grassed waterway with 80 to 100% cover. Plot 3 (avg. slope 3.3%, max 7.7%) had runoff subsequently crossing a field lane and entering groundcover of weeds and vines, while Plot 4 (avg. slope 4.1%, max 6.8%) had runoff subsequently crossing a field lane and entering mixed hardwood and pine trees. The riparian area had weeds and small shrubs at the upslope edge, trees within a few meters of the channel, and complete coverage of the soil by tree litter. Runoff collectors were placed at distances of 3 and 6m into the grass filters. Distances of downslope collectors varied according to the topography, but all plots had 3 lines of samplers if topography allowed. For the second site, where concentrated flow was evaluated, many details are not provided. Collectors were placed at the field edge and down to the junction with a higher order channel. Two fields drained to two separate ephemeral channels with a narrow floodplain having hardwoods and sparse understory with 20-30% of area having bare soil. As the study doesn't really discuss riparian buffer effectiveness at this second site, this summary excludes it from here on, except to say that based on the findings the authors state that concentrated runoff flows from fields need to be dispersed into a buffer in order to reduce flow velocity and energy and thereby allow pollutant removal. Reading from graphs for load reductions: At Site 1, the sediment reductions were: Plot 1- approximately 58% for 3m and 60% for 6m distance; Plot 2- approx. 45% for 3m and 55% for 6m distance; Plot 3- approx. 22% for 5m and 60% for 13m; Plot 4- approx. 15% for 7m and 30% for 18m. At Site 1, the total phosphorus reductions were: Plot 1- approximately 70% for 6m distance; Plot 2- approx. 63% for 6m distance; Plot 3- approx. 40% for 5m and 50% reduction for 13m; Plot 4- approx. 33% for 7m and 63% for 18m. At Site 1, the phosphate reductions were: Plot 1- approximately 50% for 6m distance; Plot 2- approx. 40% for 6m distance; Plot 4- approx. 5% for 7m and 60% for 18m; Plot 3 had an unexplained increase in phosphate concentrations of 50% at 6m and 225% at 13m. At Site 1, the total Kjeldahl nitrogen reductions were: Plot 1- approximately 60% for 6m distance; Plot 2- approx. 65% for 6m distance; Plot 3- approx. 45% for 5m and 55% for 13m; Plot 4- approx. 15% for 7m and 45% for 18m. At Site 1, the ammonia reductions were: Plot 1-

approximately 45% for 6m distance; Plot 2- approx. 50% for 6m distance; Plot 3- approx. 50% (increase) for 5m and 30% (increase) for 13m (fertilizer was applied right before a storm in 1987) ; Plot 4- approx. 10% for 7m and 25% reduction for 18m. At Site 1, the nitrate reductions were: Plot 1- approximately 90% for 6m distance; Plot 2- approx. 45% for 6m distance; Plot 3- approx. 75% for 5m and 85% for 13m; Plot 4- approx. 55% for 7m and 60% for 18m.

10. **Dillaha, T.A., Reneau, R.B., Mostaghimi, S., and Lee, D. 1989. Vegetative filter strips for agricultural nonpoint source pollution control. *Transactions of the American Society of Agricultural Engineers*. 32: 513-519.***

    Value: 1 for meta-analysis, suspended solids, not suspended sediment. Location: SW Virginia. Abstract: A rainfall simulator was used to evaluate the effectiveness of vegetative filter strips (VFS) for the removal of sediment, nitrogen (N), and phosphorus (P) from cropland runoff. See abstract in the phosphorus section.

11. **Dillaha, T.A., Sherrad, J.H., Lee, D., Mostaghimi, S., Shanholtz, V.O. 1988. Evaluation of vegetative filter strips as best management practices for feed lots. *Journal of Water Pollution Control Federation*. 60: 1231-1238.**

    Value: 1 for meta-analysis, suspended solids, not suspended sediment Location: SW Virginia. The effectiveness of reducing sediment and nutrients in runoff from a simulated feedlot was evaluated. See summary in the phosphorus section.

12. **Dosskey, M.G.G., Helmers, M.J., Eisenhauer, D.E., Franti, T.G., and Hoagland, K.D. 2002. Assessment of concentrated flow through riparian buffers. *Journal of Soil and Water Conservation*. 57: 336-343.**

    Value: 0 for meta-analysis, due to apparent inaccuracies in the data. Type: Observational, descriptive. Location: Nebraska. The purpose of the study was to evaluate the effect of concentrated flow upon sediment transport in riparian buffers. The study areas consisted of four farms on which corn, soybeans, sorghum, and grain were grown. Slopes ranged from 1 to 4%, except for localized areas of fields with slopes up to 9%. Soils were silt loams and silty clay loams. Riparian buffer widths ranged from 5 to 61m, but the four farms averaged {35, 12, 10, 9} m. The vegetation in buffers was trees and grass, except on one farm where it was entirely grasses. Stream channels ranged from ephemeral to 3rd order perennial. Sediment trapping efficiency is greater where more runoff water infiltrates riparian buffer soils and is lesser where high sediment loads result in sediment accumulation that inundates herbaceous riparian vegetation. The ratio of buffer area per unit contributing area is called the buffer area ratio and several researchers have emphasized the importance of this ratio in determining the effectiveness of riparian buffers. Using a VFSMOD model indicates that buffer area ratios of 0.20 or greater result in the highest sediment trapping efficiency for buffers. This is a field-scale, mechanistic, single event model that is based on flow hydraulics and sediment transport and deposition processes. The model assumes that runoff is distributed across the entire buffer area. Ratios of 0.10 are estimated to have a sediment trapping efficiency roughly between 65 and 85%, while a ratio of 0.20 is estimated to result in an efficiency roughly between 85 to 95%. Field evaluation of the farms indicated that concentrated flow through buffers was common, as indicated by a comparison of the total gross buffer area and the total effective buffer area. The effective buffer areas on the four farms were 6, 12, 40, and 81% of the gross buffer areas. Based on gross buffer area, the sediment trapping efficiencies for the farms were 99%, 67%, 50%, and 41%. Based on effective buffer area (i.e., accounting for concentrated flow), the efficiencies were 43%, 15%, 23%, and 34%, respectively. Concentrated flow tended to initiate crop field swales; crop rows parallel to buffers and field berms seemed to facilitate runoff into swales. A table of prior experimental studies is provided showing the relationships between known buffer area ratios and sediment trapping efficiency for grass buffers. A review of the references cited in this publication shows that some of the numbers in the Dosskey table are oversimplified or incorrect; for example, the Parsons et al. (1994) study are stated as having grass buffer slopes of 1% in the Dosskey table, while in actuality they are reported by Parsons as being 0.7 to 1.4% at one site and 4.2 to 6.3% at the second site. Also, Dosskey says that forest buffer slopes were left out because the buffer area ratio could not be calculated, or the slopes were too steep. Forest buffer data from Parsons et al. (1994) were left out, but the area ratio could be calculated, and the riparian slopes were 0.7 to 0.8% on one site and 12.4 to 16.4% on the second site, which are within the range for the data (up to 16% slopes) reported in the Dosskey table.

Tillage and sediment accumulation at field edges has been observed to cause water to concentrate and flow along a berm until a low point is reached that allows the runoff to flow into a buffer, rather than entering the buffer as non-concentrated flow. Modification of buffer topography (for example, when spoils from stream channelization are deposited into buffer area) has also been observed to result in concentrated flow exiting a buffer and associated head cutting. “Sediment-trapping efficiency of riparian buffers based on gross buffer area may greatly overestimate actual performance.” The authors suggest several ways to improve buffer effectiveness: remove micro-topographical features that promote concentrated flow; orient row crops to inhibit flow into swales; refrain from uphill-downhill farming; implement level spreaders at field margins to disperse runoff into a buffer; in hilly areas, locate the riparian buffer edge along a specified contour instead of using a fixed distance from the stream.

13. **Dosskey, M.G.G., Hoagland, K.D., and Brandle, J.R. 2007. Change in filter strip performance over ten years. *Journal of Soil and Water Conservation*. 62: 21-32.**

Value: 3 for meta-analysis. Type: Experimental, before-after. Location: Nebraska. The study sought to determine if the age of buffer strip establishment has an influence upon its ability to remove pollutants from agricultural runoff. Soils and vegetation change through time after agricultural land is converted to a buffer strip. Soil structure and macroporosity increase. Organic matter accumulates within and upon the soil surface, which also affects the structure and function of soils. Changes in nutrient cycling also occur. Changes that increase infiltration rates promote sediment deposition and decrease loads of dissolved pollutants in surface runoff. Increasing vegetation density and litter leads to reduced surface flow velocities. Initial reductions in nutrients in buffer effluent may reverse if a buffer receives nutrients at a higher rate than it can be removed from runoff (e.g., denitrification) or assimilated into vegetation. Soils in the study area were fine, montmorilonitic, mesic, Typic, Argiudoll and graded from silty clay loam to sandy loam along the length of the crop field margin. Test plots (N = 40) were approximately 7m (the 7m border was grassed) downslope of a grain-sorghum-soybean rotation that employed contour cultivation (but during the study the crop plots were rotated between sorghum and naturally seeded smooth brome grass). Two test plot sizes were used: 3 x 7.5m and 3 x 15m. One random plot of each length in each block of plots was left in the existing grass while the vegetation on other randomly selected plots was killed with herbicide and planted to grass, grass and trees (grass was switchgrass and tall fescue, with other grass/herbs naturally establishing as well), or sorghum. On the tree and grass plots, the upper half was planted to switchgrass and tall fescue, while the downhill half was planted with rows of honeysuckle and currant, and fast-growing cottonwood and maple. The long plots had two rows of shrubs and two of trees, while the shorter plots had one row of each. Simulated rainfall was applied to the crop plots at a rate amounting to 2.54cm of water in 30 minutes (a 1yr return interval storm). To the 500 gal. water tank used for rainfall simulation was added 18.9kg sediment (12% sand, 30% clay, 3% organic matter), 287g ammonium nitrate, 5.7g superphosphate, and 28.2g potassium bromide. This resulted in simulated runoff containing 10,000mg/L sediment, 68mg/L total N, 36mg/L nitrate + Nitrite, 4723µg/L Total P, and 523µg/L total dissolved phosphorus. The effectiveness of the "old grass" and "crop" plots in retaining runoff varied over the course of the study. For total suspended solids (TSS) mass, the old grass effectiveness ranged from 95 to >99% and the crop effectiveness ranged from 79 to 95%. Bromide tracer mass reductions ranged from 64 to >99% for the old grass plots and 45 to 82% for the crop plots. The variation in tracer was thought to be due to variation in antecedent soil moisture among runoff events. Sediment loads appeared to be largely trapped in the 7m grass border between the crop plots and the test plots. Nitrate was increased in the test plot effluent in the first season (negative reduction) - this has also been reported in similar studies. At 0.2 years, the new grass and new forest plots performed worse than the old grass and crop plots possibly due to the lag in vegetation establishment. At 1.1 yrs, the new filters had greater sediment retention than the crop plot but was not different for other parameters. At this time, the new filters had lower retention than the old grass plots only for TSS and total P. At 2.1 yrs, there were no differences between the old grass and new plots for any parameter. After 8.1 yrs and 9.1yrs, there were also no significant differences between the new plots and old grass filters. At 9.1yrs, the new plots performed better than crop plots for TSS and total P masses and possibly for total N mass as well. Nitrate + Nitrite showed no evidence of change over time in any of the treatments. Overall, the new plots became as effective as the old grass plots by ten years and outperformed the crop plots, with most change occurring in the first 3 yrs, when infiltration rates increased the most. Performance of the new grass and new forest plots was not significantly different throughout the study.

14. **Gharabaghi, B., Rudra, R.P., and Goel, P.K. 2006. Effectiveness of vegetative filter strips in removal of sediments from overland flow. *Water Qual. Res. J. Canada.* Vol. 41, No 3. pp 275-282**.

    Value: 0 for meta-analysis, no replicate plots. Type: Experimental, before-after. Location: southern Ontario. The study evaluated the effects of differing vegetation, filter strip width, and flow rate upon sediment removal. Test plots used one of six different mixtures of grass/herbaceous plants. Plots were established at three different locations and plot lengths varied from 2.5 to 20m. There were no true replicates in the study. All plots were on hills with a uniform slope of approximately 5%. At one location, sediment removal efficiency by particle size was analyzed. It was found that the first 5m of a filter removes most of the sediment; for a 5m filter with an average unit flow rate of 1L/s, removal efficiencies ranged from 62% for the 0.5 to 2.9-micron particle size to 97% for the 68-to-151-micron particle size (1 micron = 1/1000 of a millimeter, silt is approx. 2 to 60 micron). Isobar graphs display the effectiveness of trapping different particles sizes based on flow path length and flow rate. 50% of sediments were removed within the first 2.5m on average. The authors concluded that filter width, grass type, flow rate, and sediment particle size distribution significantly affect the sediment removal effectiveness. They also assert that more than 95% of particles larger than 40 µm can be removed from runoff within the first 5m of a grassed filter.

15. **Gilley, J.E., Eghball, B., Kramer, L.A., and Moorman, T.B. 2000. Narrow grass hedge effects on runoff and soil loss. *Journal of Soil and Water Conservation*. 55: 190-196.**

    Value: 3 for meta-analysis. Type: Experimental, control-treatment. Location: Iowa. This study examined the effectiveness of grass hedges at reducing runoff and sediment from plots with corn residue. Soils were fine-silty, mixed, super active, mesic, Typic, Hapludolls developed from loess. Annual average precip is 816mm (32.6in). The average soil slope was 12% and ranged from 8 to 16%. 0.72m (2.4ft) strips of switchgrass were planted along the hillslope contours between strips of corn (16 rows each) in a 6-hectare (15 acre) watershed. The grass strips were at intervals of 15.5m. Six years after being established, concentrated flow through the grass strips was minimal, but sediment had accumulated into visible berms at the upslope edge of the strips. Simulated rainfall was applied at a rate of 64mm/hr and again at the same rate 24hrs later. This rate has a 10 yr recurrence interval for the study location and combined the two events have a recurrence interval of >25yrs. Nutrients were also applied to the plots and the results are described in Eghball (2000). Under tilled conditions, the grass hedges reduced soil loss by 57% and by 53% under no-till conditions (averaged across the two simulated rainfall events). For treatments where corn residue was removed, the grass hedges reduced soil loss by 63%. The combination of grass hedges with no-till cropping and residue left was shown to result in an order of magnitude less soil loss than conventional tillage with grass hedges. This strongly indicates that filter strips or buffers need to be implemented in conjunction with source control practices (e.g. tillage and residue management practices) and that looking at just the % reduction in sediment loads without considering the intensity of the land use activity is not appropriate because of the wide variation in sediment loads generated from different agricultural practices.

16. Griffen, E.R. and Smith, J.D. 2001. Analysis of vegetation controls on bank erosion rates, Clark Fork of the Columbia River, Deer Lodge Valley, Montana. U.S. Dept. of Interior, Geological Survey. WRIR 01-4115.

    Value: 0 for meta-analysis. Type: Observational. Location: Montana. This paper utilized aerial imagery to evaluate bank erosion rates relative to the density of woody vegetation in riparian areas. Erosion rates decreased with increasing woody vegetation density. The analysis indicated that areas with dense woody vegetation could reduce erosion rates on channel bends by a factor of at least six (from 1.27ft/yr down to <0.23ft/yr) relative to bends without woody vegetation. "Moderatey-spaced" shrubs could reduce erosion by roughly one-half (from 1.27ft/yr down to 0.58ft/yr). The bank materials are not described, besides noting that a large flood in 1908 left large silt deposits on banks in the study area.

17. Hay, V., Pittroff, W., Tooman, E.E., and Meyer, D. 2006. Effectiveness of vegetative filter strips in attenuating nutrient and sediment runoff from irrigated pastures. *The Journal of Agricultural Science*. 144: 349-360.*

    Location: California. Abstract: "Increasing concern about non-point source pollutants released from grazing livestock, a worldwide problem, motivated the present study on the effects of vegetative filter strips (VFS) for controlling pollutants (nutrients, micro-organisms and sediment loading) from grazed, irrigated pastures. Flood-irrigated pastures are an important source of forage for livestock during summer months in California, USA when the surrounding rangelands are dry and dormant. Significant amounts of runoff can be generated from these pastures during irrigation events.

    Nine plots on an irrigated pasture were assigned randomly to one of three treatments: Control (no VFS), Treatment VFS-1 (8·3×7 m, 0·0058 ha VFS) and Treatment VFS-2 (17·1×7 m, 0·012 ha VFS). In 2000, two grazing events (in April and June/July) occurred during the irrigation season prior to the experiment; further, the experimental plots were grazed between irrigations 2 and 3. Attenuation of runoff loads by VFS treatment was measured during four irrigation events (between 1 August and 3 October 2000) for total suspended solids (TSS), ortho-phosphate (Ortho-P), inorganic phosphate (Inorg-P), total phosphate (Total-P), organic phosphate (Org-P), polyphosphate (Poly-P), total Kjeldahl nitrogen (TKN), NH3, NO3 and presumptive faecal coliforms (FC).

    On average, approximately 0·43 of the applied water left the plots as runoff. Treatment effects approached significance for TSS and TKN and were significant ($P<0·05$) for Poly-P and NH3. Irrigation number effects were significant for all but TSS, NO3 and FC. The effects of VFS treatments were not consistent. Treatment VFS-2, although representing the largest buffer strip, did not always produce the lowest pollutant loads in runoff. Slope, relatively high runoff volumes and some channeled flow were probably responsible for the limited effectiveness of VFS in the present study. These results suggest that effectiveness of VFS for reducing sediment and nutrient transport from irrigated pastures may be questionable."

18. **Helmers, M.J., Eisenhauer, D.E., Dosskey, M.G.G., Franti, T.G., and Brothers, J.M. 2005. Flow pathways and sediment trapping in a field-scale vegetative filter. *Transactions of the American Society of Agricultural Engineers*. 48: 955-968.**

    Value: 0 for meta-analysis, suspended solids data. Location: Nebraska. The study was performed to evaluate variability in the flow of runoff through a vegetated filter strip and evaluate its influence upon sediment capture. The authors note that many experimental studies are performed on an area that is smaller (i.e. plot scale) than field scale, with buffer area ratios (BAR) below 20:1; however, they point out that a ratio greater than 20:1 is expected under most agricultural settings and the NRCS plans are typically based on a ratio of 30:1. They assert that plot-scale studies do not accurately capture the types of runoff flow conditions that occur at the field scale. The study area soil was a fine-silty, mixed, mesic, Pachic Haplustoll (silt-loam) with a 1% field slope. The 13 x 250m buffer was established in big bluestem, switchgrass, and Indiangrass six years prior. Grass in the buffer existed in clumps with bare soil in between, which is considered low to moderately low cover. Five experimental runoff events were performed using furrow irrigation and measurements were made for an additional rainfall event. Three irrigation events simulated typical irrigation, while the other two simulated runoff from a storm with a greater return period (apparently approximated a 1 hr, 10yr event). Sediment trapping efficiency ranged from 74 to 93%, with an average of 80%. Convergence of flow in one of the filters was indicated by runoff outflows at grid points that were greater than grid inflows for 4 of 6 events; some evidence of diverging flow was also observed. The data indicated that flow convergence and divergence within the filter strip had minimal effect upon sediment transport. This is believed to be the result of the majority of sediment being deposited in the upper part of the filter before flow convergence or divergence developed. Where flows converge in a field, the vegetation in the filter strip needs to be denser. Based on their observations, the authors assert that it's unlikely that shallow overland flow within a filter strip is entirely uniformly distributed, but that instead, micro-topography (e.g., at the centimeter scale) causes flow convergence and divergence.

19. Knight, K.W., Schultz, R.C., Mabry, C.M., and Isenhart, T.M. 2010. Ability of remnant riparian forests, with and without grass filters, to buffer concentrated surface runoff. *JAWRA*. Vol. 46, No. 2.

    Value: 0 for meta-analysis, suspended solids Type: Observational, descriptive. Location: Missouri. This study examined the frequency at which riparian forest remnants, with and without additional grass buffers, dispersed concentrated runoff flow paths. Slopes ranged from 0 to 25% for the three involved soil series. 100% of forest buffers with adjacent grass buffers dispersed flow, while 80% of forests buffers without adjacent grass buffers dispersed flows. Remnant forests that did not disperse concentrated flow were narrower than those that did (averaging 12.8m vs. 17.9m for non-breached forest only buffers). Grass + forest buffers averaged about 42m wide, grass filters adjacent to forest averaged about 20m wide, remnant forest buffers with no grass averaged about 18m wide, and non-effective forest remnant buffers (where concentrated flow paths had cut all the way through) averaged about 13m wide

20. Kozlowski, D.F., Hall, R.K., Swanson, S.R. and Heggem, D.T. 2016 Linking management and riparian physical functions to water quality and aquatic habitat. *Journal of Water Resource and Protection*, 8. pp. 797-815.

    Value: 0 for meta-analysis, no experimental design. Type: Observational, before-after. Location: Nevada. This paper provides a retrospective before/after comparison of wetland/riparian assessments (1994 vs. 2006) and water quality data (before/after 1994) for a watershed (Maggie Creek) in which prescriptive livestock management was implemented in 1994. The study used the BLM Riparian Proper Functioning Conditions assessment which is designed to look at indicators of the integrity of soil, vegetation and hydrology processes. Annual precipitation in the region ranges from approximately 11.2 to 32.7 inches, varying with elevation. Vegetation includes short and mountain big sagebrush, grasses (e.g. Idaho fescue), and some juniper and aspen in tributary headwaters areas. Hay and pastureland occur along streams, where willows are the predominant overstory vegetation. As a result of improved livestock management, the functional rating of Maggie Creek improved 13%, largely due to an increase in the age class diversity, composition, and abundance of riparian vegetation, and improved ability to dissipate flood flows, and improvement in hydrology resulting from increased beaver dam occurrence. Total suspended sediment data suggested that concentrations at higher flows decreased after improved livestock management. The authors state that nitrogen levels continued to increase, but at a lower rate after management changes (although this is questionable based on the scatter). DO was observed to increase both pre and post management change at the upper station but showed a slight decreasing trend at the lower station (data not provided). It was concluded that orthophosphate was on a decreasing trend after the management change (data not provided). Among the changes in habitat: 138% increase in riparian vegetation acreage among the prescribed grazing pastures; stream width to depth ratios decreased in all target Lahontan cutthroat trout reaches; the average number of deep pools with cover increased.

21. Kronvang, B., Audet, J., Baattrup-Pederson, A., Jensen, H.S., and Larsen, S.E. 2012. Phosphorus load to surface water from bank erosion in a Danish lowland river basin. Journal of Environmental Quality. 41: 304-313.

    Value: 0 for meta-analysis, no experimental design. Location: Denmark; Type: Observational. This is a study of bank erosion and associated phosphorus loading to lowland streams. Buffer strips ≤2m wide did not have significantly higher erosion rates than buffer strips ≥10m wide. Bank erosion rates were not statistically different among stream orders. Bank erosion was not statistically different between straightened and naturally meandering channels. Bank erosion rates were 25 to 40% greater for channels with buffers dominated by grass and herb vs. buffers dominated by trees and shrubs. Bank erosion was found to deliver 21 to 62% of nonpoint P in the watershed, most of which appeared to be bioavailable P.

22. Kronvang, B., Laubel, A., Larsen, S.E., Andersen, H.E., and Djurhuus, J. 2005. Buffer zones as sink for sediment and phosphorus between the field and stream: Danish field experiences. *Water Science and Technology*. 51(3-4): 55-62.

    Value: 0 for meta-analysis, no experimental design. Type: Observational, correlative. Location: Denmark. The authors surveyed sediment deposition and retention of phosphorus in 140 field slope units throughout Denmark. Soils were predominantly Alfisols and Spodosols with textures ranging from sand to loam. The slope of the units ranged from 2 to 20%. Buffer zones ranged from 0.6 to 125m wide (median = 8.3m). More than 50% of slope units had no rill erosion. A logistic regression model was developed to evaluate the probability of sediment delivery to streams. Units with no rills had a less than 5% probability of delivering sediment to streams at all buffer widths. Units with small rills had a 25%

probability of sediment delivery at 0m buffer width, approx. 15% probability at 20m width, approx. 10% probability at 40m width, and approx. 5% probability at 60m width. Units with large rills had a 65% probability of sediment delivery at 0m, approx. 50% probability at 20m, approx. 25% probability at 60m, and approx. 10% probability at 100m. Less than half of the total P loss to freshwaters was sediment-bound P. Buffers are less effective at controlling dissolved P losses; in erosive areas, incorporating manure into soils at an appropriate time of year would help reduce dissolved P delivery to waterbodies.

23. Lakel III, W.A. Aust, W.M., Bolding, M.C., Dolloff, A., Keyser, P., and Feldt, R. 2010. Sediment trapping by streamside management zones of various widths after forest harvest and site preparation. *Forest Science*. 56(6).

    Value: 0 for meta-analysis. Type: Experimental, Before-after. Location: North-central Virginia. The authors examined the effects upon erosion of three different buffer widths along intermittent streams with or without tree thinning. Average annual rainfall during the study was 1,020mm. Side slopes ranged from 10 to 65% (average = 25%). Soils were variable and consisted of various Inceptisols and Ultisols with loam, silt loam, or clay loam with coarse rock fragments textures. Treatments- T1: 7.6m width, no thinning; T2: 15.2m width, no thinning; T3: 15.2m width, 30-50% basal area thinning; T4: 30.4 m width, no thinning. Outside the streamside management zones (SMZs), sites were clearcut, burned, and hand-planted with loblolly pine. Misinterpretation of SMZ borders resulted in altered replications, leading to analysis as an incomplete randomized block design. Erosion pins and sediment traps were used to measure erosion. SMZs were 1.9, 6.3, and 11.8% of the watersheds for the respective 7.6, 15.2, and 30.4m SMZs. Decks, roads, skid trails and fire lines were 1.5% of the watershed areas on average but resulted in 16.5% of the erosion (with bulldozer fire lines being the major source). Harvesting and burning covered an average of 76% of the watershed areas and 80% of the predicted erosion. The amount of sediment trapped within the SMZ treatments was not significantly different, but 38 times increase in sediment deposited occurred between pre and post-harvest. The results suggested that bare soil areas near the SMZs (i.e., fire lines) contribute a disproportionate amount of sediment to SMZs; the fire lines were between harvest areas and SMZs and contributed 12 times more sediment per unit area than harvest areas. In 3 of the 24 subwatersheds, sediment in concentrated flow bypassed the SMZ regardless of width and was attributed to insufficient runoff control structures on steeper slopes/erosive soils along roads and fire lines. Sediment traps results indicated that 97% of sediment was captured within harvest areas or SMZs. The study concludes that the current policy of 15.2m wide SMZs with or without thinning provides adequate sediment capture for the region, but that wider zones may be needed when soil disturbance is greater, when other pollutants are of concern, BMP non-adherence is more frequent, or for other land management goals. The authors suggest that the timber harvesting practices are a less erosive activity than agriculture, which may therefore require wider SMZs.

24. Langendoen, E.J., Lowrance, R.R., and Simon, A. 2009. Assessing the impact of riparian processes on streambank stability. Ecohydrology. 2, 360-369.*

Abstract: "The series of biennial United States (US) National Water Quality Inventory surveys shows no reduction in the percentage of degraded miles of streams since the early 1990s despite an exponential increase in river restoration projects to improve water quality, enhance in-stream habitat and manage the riparian zone. This may suggest that many river restoration projects fail to achieve their objectives. This is partly due to a lack of understanding of the dynamics of the degraded riverine system and its interaction with the riparian zone. These projects could, therefore, benefit from using proven models of stream and riparian processes to guide restoration design and to evaluate indicators of ecological integrity. The US Department of Agriculture has developed two such models: the channel evolution computer model CONCEPTS and the riparian ecosystem model REMM. These models have been integrated to evaluate the impact of edge-of-field and riparian conservation measures on stream morphology and water quality. Vegetative riparian conservation measures are commonly used to stabilize failing streambanks. The shear strength of bank soils is greatly affected by the degree of saturation of the soils and root reinforcement provided by riparian vegetation. The integrated model was used to study the effectiveness of woody and herbaceous riparian buffers in controlling streambank erosion of an incised stream in northern Mississippi. Comparison of model results with observations showed that pore-water pressures are accurately predicted in the upper part of the streambank, away from the groundwater table. Simulated pore-water pressures deviate from those observed lower in the streambank near the phreatic surface. These discrepancies are mainly caused by differences in the simulated location of the phreatic surface and simulated evapotranspiration in case of the woody buffer. The modelling exercise further showed that a coarse rooting system, e.g., as provided by trees, significantly reduced bank erosion rates for this deeply incised stream."

25. **Lee, K-H., Isenhart, T.M., and Schultz, R.C. 2003. Sediment and nutrient removal in an established multi-species riparian buffer. *Journal of Soil and Water Conservation*. 58: 1-8.**

Value: 3 for meta-analysis. Type: Experimental, control-treatment. Location: Iowa. The authors investigated sediment and nutrient removal in buffers of different widths and vegetation composition. Plots had either no buffer, a 7.1 switchgrass buffer, or a 16.3m buffer composed of 7.1m switchgrass and 9.2m mixed woody plants. Soils under the buffer was fine-loamy, mixed, mesic, cumulic, Haplaquoll with a 5% average slope. The upslope crop field source area (corn-soybean rotation) had fine-loamy, mixed, mesic, typic Hapludoll soils with an 8% average slope. The size of the crop source areas (4.1 by 22.1m) were equal to the standard erosion plots used to develop the Universal Soil Loss Equation. Measurements were taken after natural rainfall events. Annual precip. was 738mm in 1997 (12% below normal) and 872mm (4% above normal) in 1998. Sediment from the control plot was 25% sand, 64% silt, and 11% clay. The 7.1m grass buffer removed and average of >92% of the sediment mass. The 16.3m mixed buffer removed an average of >97% of the sediment mass, with most being trapped in the grassed portion. More than 90% of the sediment leaving the buffered plots was <0.05mm. Three times less sediment was conveyed through the grass-woody buffer than the grass buffer, and the grass buffer had 13 times less sediment conveyed than the control. The high sediment retention rate may be due to the density and litter production of the switchgrass. The 7.1m grass buffer reduced total nitrogen, nitrate, total P, and phosphate by an average of 80.3, 62.4, 78.0, and 57.5% respectively. The 16.3m grass-woody buffer reduced total nitrogen, nitrate, total P, and phosphate by an average of 93.9, 84.9, 91.3, and 79.8% respectively.

26. **Lee, K-H., Isenhart, T.M., Schultz, R.C., Mickelson, S.K. 2000. Multispecies riparian buffers trap sediment and nutrients during rainfall simulations. *Journal of Environmental Quality*. 29: 1200-1205.***

    Value: 3 for meta-analysis. Type: Experimental, control-treatment. Location: Iowa (?) Abstract: "A study was conducted to evaluate the ability of a multispecies riparian buffer (MRB) to remove sediment, nitrogen, and phosphorus from cropland runoff. Simulated rainfall was applied to 4.1- by 22.1-m bare cropland source areas paired with either no buffer, a 7.1-m-wide switchgrass (Panicum virgatum L. cv. Cave-n-Rock) buffer, or a 16.3-m-wide switchgrass-woody plant buffer (upslope 7.1m switchgrass zone, downslope 9.2m woody plant zone). Each treatment plot combination had three replicates. The switchgrass buffer trapped 70% of the incoming sediment, while the switchgrass-woody buffer trapped more than 92%. In general, these buffers retained 93% of sand and silt particles and 52% of clay particles. During a 2-h rainfall simulation at 25 mm h^{-1}, the switchgrass buffer removed 64, 61, 72, and 44% of the incoming total N, NO_3−N, total P, and PO_4-P, respectively. The switchgrass-woody buffer removed 80, 92, 93, and 85% of the incoming total N, NO_3−N, total P, and PO_4-P, respectively. During a 1-h rainfall simulation at 69 mm h^{-1}, the switchgrass buffer removed 50, 41, 46, and 28% of the incoming total N, NO_3−N, total P, and PO_4-P, respectively. The switchgrass-woody plant buffer removed 73, 68, 81, and 35% of the incoming total N, NO_3−N, total P, and PO_4-P, respectively. The switchgrass buffer was effective in trapping coarse sediment and sediment-bound nutrients. But the additional buffer width with high infiltration capacity provided by the deep-rooted woody plant zone was effective in trapping the clay and soluble nutrients. This is probably the same study area as in Lee et al. (2003)."

27. **Lee, K-H, Isenhart, T.M., Schultz, C, and Mickelson, S.K. 1999. Nutrient and sediment removal by switchgrass and cool-season grass filter strips in Central Iowa, USA. *Agroforestry Systems* 44: 121-132.**

    Value: 3 for meta-analysis. Same study as study #1 in Lee (1999)

28. **Lee, K-H. 1999. Effectiveness of a multi-species riparian buffer system for sediment and nutrient removal. *Retrospective Theses and Dissertations*. 12148. IA State University. Ames, IA.**

    Value: 3 for meta-analysis. Location: Iowa. The author investigated sediment and nutrient removal in buffers of different widths and vegetation composition. This appears to be the same data used in Lee et al. (2003) and Lee et al. (2000). Infiltration rates are one of the most important processes affecting the effectiveness of buffers. Infiltration reduces the ability of runoff to transport sediment and reduces the mass of clay particles and dissolved nutrients in surface runoff. At the time of this publication, the NRCS in Iowa had riparian forest buffer standards comprised of an inner zone with shrubs/trees extending a minimum of 10.7m followed by an outer grassed zone (native, warm season grass recommended) extending an additional 6.1 to 36.6m. Limited experimental data is available about the effectiveness of this standard.

96.8% of the landscape had slopes ≤9%. Soils were formed in glacial till of alluvium derived from till. Cites Wilson (1967) as concluding that interactions among filter width, initial sediment concentration, runoff rate, soil slope, grass height, grass density, and degree of submergence were the drivers of sediment removal in buffers. Cites Haan et al. (1994) as concluding that sediment and nutrients are removed in three main ways: deposition of bedload and adsorbed nutrients, typically in the upper edge of a buffer or in ponded areas upslope of the buffer edge; trapping of suspended solids in organic surface litter; infiltration of water carrying clay and soluble nutrients into the soil profile, which also reduces surface runoff volume and therefore sediment transport. Sediment removal effectiveness depends on sediment size, slope, length, channelization, and density of vegetation. Removal of sediment or particulate bound N and P is greater than the dissolved fraction. Buffers with dense, deep-rooted vegetation and high soil porosity maximize N and P retention.

Study 1- Type: Experimental, treatment, no control: The author investigated sediment and nutrient removal effectiveness for warm-season and cool-season grass filter strips using simulated rainfall and runoff. The average soil slope was 3%. Filter strips of 3m (buffer area ratio 40:1) and 6m (buffer area ratio 20:1) were used. Simulated rainfall rate was 5.1 cm/hr. Approx. 100kg of soil sieved through a 2mm screen was added to the runoff tank. K_3PO_4 was added to make a solution of 2mg P per L. Three 500mL samples of run-on solution was collected each integrated over 15minutes and up to nine integrated 500mL samples of runoff was collected, each integrated over 5 minutes.

The 6m wide filters removed an average of 77% sediment and the 3m strips averaged 66% sediment removal. The 3 and 6m switchgrass filters removed an average of 69% and 78% sediment, respectively. The 3 and 6m cool-season grasses removed an average of 62% and 75%, respectively. The higher removal for switchgrass was attributed to a more uniform distribution (cool season grass actually had greater stem density) and more surface litter (nearly 4x greater for the switchgrass). The author concluded that filter width should be adjusted based on contributing area and vegetation type. For nutrients: the 6m strip removed 46% of total N, 42% nitrate, and 52% total P, and 43% phosphate; the 3m strip removed 28% of total N, 25% nitrate, 37% total P, and 34% of phosphate. Switchgrass (warm-season) had significantly higher removal rates than cool-season grasses for total N, nitrate, total P, and phosphate. The average infiltration volume was 37% for the 6m filters and 23% for the 3m filters.

Study 2: Same as Lee et al. 2000. Type: Experimental, control-treatment. Soils in the filter were a fine-loamy, mixed, mesic, cumulic, Haplaquoll with a 5% average slope. Soils in the crop field were a fine-loamy, mixed, mesic, typic, Hapludoll with 8% average slope. Simulated rainfall was applied to 4.1- by 22.1-m bare cropland source areas paired with either no buffer, a 7.1-m-wide switchgrass (Panicum virgatum L. cv. Cave-n-Rock) buffer, or a 16.3-m-wide switchgrass-woody plant buffer (upslope 7.1m switchgrass zone, downslope 9.2m woody plant zone). Before the experiment, the soybean crop and residue was removed; no fertilizer was applied to the plot during the experiment. First rainfall simulation intensity = 2.5cm/hr for 2hrs. Second rainfall simulation intensity = 6.9cm/hr for 1hr. The grass only buffer removed >82% of sand, >71% silt, >15% clay (70% overall) mass. The grass-woody buffer removed >98% sand, >93% silt, and >52% clay mass. Rainfall intensity did not alter the sediment reductions. Overall, the grass only buffer removed 70% of sediment at both rainfall intensities; the grass-woody buffer removed 94% of sediment at the low intensity and 92% at the higher intensity. For the low intensity rainfall: switchgrass removed 64.3% total N, 61.1% nitrate, 67.6% total P, and 43.7% phosphate mass; grass-woody buffer removed 89.7% total N, 87.8% nitrate, 93.1% total P, 85.3% phosphate mass. For higher intensity rainfall: switchgrass removed 49.7% total N, 40.5% nitrate, 46.2% total P, and 27.6% phosphate mass; grass-woody buffer removed 72.8% total N, 67.5% nitrate, 80.7% total P, 34.7% phosphate mass. The results suggest that maximizing infiltration capacity of buffers will increase retention of clay and P.

Study 3: same as Lee et al. 2003 (see that entry for summary). States that 95% of sediment removed from grass buffer instead of >92% as stated in Lee et al. (2003). The sediment from the control plots was 25% sand, 64% silt, 11% clay.

Riparian buffers should be employed in concert with other BMPs such as conservation tillage, contour plowing, strip cropping, prescribed grazing, and nutrient/fertilizer management.

29. **Lim, T.T., Edwards, D.R., Workman, S.R., Larson, B.T., and Dunn, L. 1998. Vegetated filter strip removal of cattle manure constituents in runoff. *Transactions of the American Society of Agricultural Engineers*. 41: 1375-1381**.

Value: 0 for meta-analysis, suspended solids were from manure, not sediment. Type: Experimental, before-after treatment. Location: Kentucky. The authors studied the influence of vegetated filter strip (VFS) length on the reductions (concentrations and mass) in the transport of nitrogen, phosphorus, suspended and total solids, and fecal coliform from plots treated with cattle manure. Soil was fine, mixed, mesic Typic Paleudalf (silt loam). Three 30.5 by 2.4m experimental plots were established with 100% cover of tall fescue had a 3% linear slope. “Near-worst-case” conditions were simulated for the experiment. 7.8 kg of fresh cattle manure was applied to the upper 12.2 m of each plot (60kg N per hectare rate), equivalent to nine (450kg) animal units/ha for one-week grazing duration (this is high rate, rather than typical rate was intended to facilitate the measurement of filter performance). Simulated rainfall applied at a rate of 100mm/hr (>100yr return interval). Runoff samples were collected at {2, 4, 8, 18, 39, 45, 60} minutes after initiation of runoff at distances of {0, 6.1, 12.2 and 18.3} meters along the plots. Almost all of the P was in the form of soluble phosphate. No fecal coliform was detected after a distance of 6.1m and the reductions were thought to be associated with high infiltration rates. The 6.1m distance had the following mean mass reductions: 78.0% TKN, 74.5% PO_4-P, 76.1% TP, 70.0% TSS, 23.6% total solids. The 12.2m distance had the following mean mass reductions: 89.5% TKN, 87.8% PO4-P, 90.1% TP, 89.5% TSS, 40.8% total solids. The 18.3m distance had the following mean mass reductions: 95.3% TKN, 93.0% PO4-P, 93.6% TP, 97.6% TSS, 69.8% total solids. Insignificant removal of nitrate and ammonia was attributed to the lack of these chemicals in the manure. Cites the following steady-state equation developed by Overcash et al. (1981) for modeling reductions in mass transport within filter strips:

Equation 1: Steady-state Equation for Modeling Reductions within Filter Strips from Lim et al. (1998)

$$p_M = \left[1 - (1 + K)\, e^{\left(\frac{1}{1-D}\right) \ln \left(\frac{1}{1+K}\right)}\right] \qquad (5)$$

where

p_C = reduction (as proportion of incoming value) in concentration of pollutant entering the VFS

p_M = reduction (as proportion of incoming value) in mass transport of pollutant entering the VFS

D = ratio of infiltration to total rainfall

K = ratio of VFS to pollutant source length

30. Liu, X, Zhang, X., and Zhang, M. 2008. Major factors influencing the efficacy of vegetated buffers on sediment trapping: a review and analysis. *J. Environ. Qual.* 37: 1667-1674.

    Type: Meta-analysis. Location: N/A. The authors present a meta-analysis of the effectiveness of vegetated buffers (grassed waterways, filter strips, riparian buffers) at removing sediment from agricultural runoff. Sediment retention in vegetated buffers is controlled by rainfall intensity, runoff flow rate, soil type, soil slope, the ratio of source area to buffer area, buffer width, and runoff depth relative to vegetation height. "The Natural Resources Conservation Service (NRCS) sets standards for buffer width based on universal soil loss equation (USLE) R factor values (rainfall amount and intensity). The recommendations are that the ratio of the filter strip area to the source area be greater than 1:70 in regions with USLE R factor values between 0 and 35, 1:60 in regions with R factor values between 35 and 175, and 1:50 in regions with R factor values more than 175." Page 50 of NRCS RUSLE manual (Renard, 1999) shows that eastern WA ag areas have R values less than 35, while western WA ag areas have R values between 35 and 175.

    Note: the analysis in this paper mixed sediment and suspended solids data; suspended solids is often not limited to sediment, but may include organic material (Young, 1980), which typically has a greater buoyancy than sediment, and therefore has a lower removal rate in a buffer than does sediment. This discrepancy probably accounts for some of the observed variation in buffer effectiveness among studies.

    The median sediment removal effectiveness for the examined vegetated buffer studies was 87%. Using the buffer width equation presented in the study, the minimum predicted buffer width corresponding to an 87% sediment removal effectiveness is 9.2m (approximately 30ft); this is irrespective of differences in slope, soils, vegetation, etc. The minimum predicted width to achieve 95% removal is 17m. A 24m width is predicted to have 100% removal. Estimated another way, the median width for buffers achieving a removal rate of 95% or better in the examined studies is also 9.2m (30ft) (based on the minimum width at a given slope that achieved 95% or higher removal in a given study). Using the equation provided in the study, the soil slope that corresponds to a removal effectiveness of 87% is 5.3%. The authors state that sediment removal increases as slope increases up to 9%, and then declines again; the explanation of lower sediment removal at low slopes is that the low hydraulic gradient prevents formation of a runoff path that allows water to trap sediment. This assertion is not supported by any citations and does not seem to make sense. For example, if there was a dam (negative slope) on one side of the buffer then 100% of the sediment would be trapped. A more likely explanation is that sediment retention is dependent on more than the slope of the buffer alone; it likely depends on the slope of the contributing area as well (e.g., whether the source area + buffer has a concave, convex, or uniform slope pattern). As such, the analysis of slope vs. effectiveness in this paper has no utility.

Stepwise regression indicated that buffer width and slope were found to result in the strongest correlation with sediment removal. Regression equation for estimating sediment removal based on buffer width and slope:

Equation 2: Regression equation from Lui et al. (2008)

$$Y_{sediment} = 53.77 + 1.58X_{width} + 5.67X_{slope} - 0.314X_{slope^2}$$

Table of computed values, with an example target effectiveness of 90% (dark green is where % removal target is first achieved for a given slope (note: assuming the hyperbolic relationship as presented in the paper, which is rather un-supported:

Table 36: From Lui et al. (2008) Showing Computed Values with Example Target Effectiveness

	slope											
width (m)	0.50%	1%	2%	4%	6%	8%	10%	12%	14%	16%	18%	20%
3	61	64	69	76	81	84	84	81	76	69	59	46
6	66	69	73	81	86	89	89	86	81	74	64	51
9	71	73	78	86	91	93	93	91	86	78	68	56
12	75	78	83	90	95	98	98	96	91	83	73	61
15	80	83	88	95	100	103	103	100	95	88	78	65
18	85	88	92	100	105	107	108	105	100	93	83	70
21	90	92	97	105	110	112	112	110	105	97	97	75
24	94	97	102	109	114	117	117	115	110	102	102	79
27	99	102	107	114	119	122	122	119	114	107	107	84
30	104	107	111	119	124	126	126	124	119	112	112	89
33	109	111	116	124	129	131	131	129	124	116	116	94

31. Lowrance, R., Williams, R.G., Inamdar, I. P., Bosch, D.D., and Sheridan, J.M. 2001. Evaluation of coastal plain conservation buffers using the riparian ecosystem management model. *JAWRA* Vol. 37, No. 6.

    Value: 0 for meta-analysis. Location: Georgia. Type: model. This study employed a USDA riparian model to evaluate nutrient removal rates (under 2 different loading scenarios) for 14 different NRCS buffer configurations (4.6m to 51.8m widths) based on site conditions at an experimental farm in Georgia. See nitrogen section for further analysis.

32. **Lynch, J.A. and Corbett, E.S. 1990. Evaluation of best management practices for controlling nonpoint pollution from silvicultural operations. *JAWRA* Vol. 26 No. 1.**

    Value: 0 for sediment-buffer data analysis as the data is not comparable. Type: Experimental, control-treatment. Location: Pennsylvania. The study evaluated the efficacy of forest harvesting BMPs at preventing nitrate, temperature, suspended sediments, and turbidity in streams. Three study watersheds- LR1 (303 acres), LR2 (106 acres) and LR3 (257 acres). Mean slopes in the watershed were between 12 and 17%, with maximum slopes near 50%. Soils of lower slopes were primarily well-drained silt loams and stony loams with high water holding capacity. Middle and upper slopes have well-drained stony and cobbly loams with high water holding capacity. Ridgetop- cobbly and sandy loams. Average soil depth is 66 inches. Prior to harvesting timber was even aged 80yr mixture of oak, hickory, maple. LR1 was control watershed with no harvest. LR3 has clearcut treatment of 110 acres. Stream water quality changes were based on analysis of 3 yrs of pre-treatment data followed by 11 yrs of post-treatment data. BMPs in the clearcut watershed included: 100ft buffer on all perennial streams, but with selective harvest of trees that could have an effect on the channel if they were to fall; no skidding over perennial streams, except on culverts or bridges; removal of culverts and installation of water bars/drainage features, and grading to pre-logging conditions on roads and skid trails; no logging during excessively wet periods. Greater peaks in turbidity were observed after logging. Growing, dormant and annual SSC in the first year after harvest were 5.5, 6.1, and 5.9mg/L. For the same year in the control watershed levels were 2.1, 0.4, and 1.7mg/L. In post-harvest year two, SSC in LR3 was 18.6, 4.6, and 9.3mg/L; in the control watershed it was 8.8, 2.7, and 5.1mg/L. Increase in LR3 were attributed to wind throw related soil disturbance near an intermittent channel that was not buffered. Maximum water temperature after harvest increased by up to 4.0^{o}F (April), with max in July increasing by 2.9^{o}F and 2.2^{o}F in August. A significant increase in nitrate occurred for five years post-harvest.

33. **Lynch, J.A., Corbett, E.S., and Mussallem, K. 1985. Best management practices for controlling nonpoint-source pollution on forested watersheds. *Journal of Soil and Water Conservation*. 40: 164-167**.

    Value: 0 for sediment-buffer data analysis as the data is not comparable. Type: Experimental, control-treatment. Location: Pennsylvania. Same watersheds and BMPs, and treatments for LR1 and LR3 as described Lynch et al. 1990. LR2 watershed seems to have been entirely clearcut and with herbicide treatment and without the BMPs as LR3. The LR2 treatment was intended to represent worst-case scenario in terms of NPS Annual average suspended sediment concentrations for LR1, LR2, LR3 were 1.7, 10.4, and 5.9 mg/L in first year post-harvest and 8.8, 51.3, and 18.6mg/L in the second year. In LR2, the average monthly max stream temperature increase was 4.4^{o}C, temps were above 21^{o}C every day during summer, and the max was 31.7^{o}C. The average nitrate concentration post-harvest was approx. seven times greater in LR2 post treatment than LR3, which was nearly five times greater than LR1. LR3 had nitrate almost eight times higher after harvest, while the control has nitrate about 3 times higher than pre-harvest.

34. **Magette, W.L., Brinsfield, R.B., Palmer, R.E., and Wood, J.D. 1989. Nutrient and sediment removal by vegetated filter strips. *Transactions of the American Society of Agricultural Engineers*. 32: 663-667.**

    Value: 1 for sediment-buffer data analysis-suspended solids data Type: Experimental, control-treatment. Location: mid-Atlantic Coastal Plain- Maryland. The authors evaluated sediment and nutrient retention by vegetated filters strips under simulated rainfall. Soil type was siliceous, fine-loamy, mesic typic Hapludult. Sources areas were 5.5m wide, 22m long. Filter strips were either 4.6 or 9.2m long with fescue grass cover. Soil slope not reported. Three sets, each one with a 9.2m, 4.6m and no filter plots. Liquid nitrogen as 305 urea-ammonium-nitrate and chicken litter were used in separate tests. The first applied liquid N at 112kg N/ha. No P was applied in test 1 since it was already high in the soil. In the second test, chicken litter was applied at 4ton/ac which was the lowest rate that could be applied with uncalibrated manure spreaders; the litter contained 252kg N/ha and 114kg P/ha. For both tests a series of simulated rainfall occurred- 1hr dry soil test at 48.25mm, 24hrs later a 1/2hr wet soil test at 24.13mm, after ½ hr a very wet soil test at 24.13mm. Some data was excluded due to test problems. Study was intended to simulate a “worst case scenario”. Results here are for different rainfall tests and plots averaged together. For the liquid nitrogen application: the 9.2m filter strips reduced the total suspended solids mass loss from by an average of 27%, Total N mass loss by 49%, and increased total P mass loss by 103%; the 4.6m plot reduced TSS by 51%, increased total N by 115%, and increased total P by 121%. For the poultry litter, the 9.2m plot reduced TSS by 23%, total N by 80%, and total P by 57%; for the 4.6m plot TSS was reduced by 44%, total N increased by 115%, and total P decreased by 68%. Increase above 100% were due to “flushing” of accumulated nutrients. The study concluded that: filter strips result in highly variable nutrient reductions; filter strips more effectively remove suspended solids than nutrients; as more runoff events occur, filter strip performance in reducing TSS and nutrients appears to decline; performance generally decreases as the ratio of un-vegetated source area to vegetated filter increases.

35. Mahoney, D. and Erman, D.C. 1984. An index of stored fine sediment in gravel bedded streams. *JAWRA*. Vol. 20, No 3.

    Value: 0 for sediment-buffer data analysis. Type: Observational, Correlational (?). Location: northern California. The authors present an index for evaluating the amount of fine sediment deposited in streams. The amount of fine sediment in stream channels was greater in watersheds with logging that had either no riparian buffers or buffers less than 30m than it was in watersheds without logging.

36. Mbonimpa, E.G., Yuan, Y., Mehaffey, M.H., and Jackson, M.A. 2012. SWAT model application to assess the impact of intensive corn-farming on runoff, sediments and phosphorus loss from an agricultural watershed in Wisconsin. *J. of Water Resource and Protection*, 4. pp. 423-431.

Value: 0 for sediment-buffer data analysis- modeled data. Type: Observational, case study. Location: Wisconsin. The SWAT model was used to evaluate the use of BMPs (including conservation tillage, fertilizer management, and vegetative buffers) in an agricultural watershed (66% cropland, 13% wetlands, 12% forest and grassland, 6% urban, 3% water) for reducing sediment and total P losses from cropland. The simulation was performed assuming farmers would skip a soybean rotation in favor of continuous corn cropping when corn prices were high. The model results indicated that buffers 15 to 30m wide would reduce sediment losses by 51 to 70% (37 to 56% at the watershed outlet) and total P losses by 41 to 63%. SWAT assumes that all sediment and nutrients are trapped by buffers that are greater than 30m. Total P losses increased 4% when generic conservation tillage was modeled, 24% increase under reduced tillage, and 35% increase under conventional tillage. "Application of proper fertilization rates, conservation tillage and vegetative strips were shown as effective BMPs to mitigate sediment and TP loss increase when corn-soybean rotation and alfalfa farmlands were progressively converted to continuous corn for biofuel generation." Residue left by conservation tillage or not till can result in reduced yields on poorly drained soils

37. McKergow, L.A., Weaver, D.M., Prosser, I.M. Grayson, R., and Reed, A.E.G. 2003. Before and after riparian management: sediment and nutrient exports from a small agricultural catchment, western Australia. *Journal of Hydrology*. 270: 253-272.

Value: 1, for general process info, but does not provide useable quantitative info. Type: Observational, Chronosequence. Location: western Australia. This study evaluated changes in sediment and nutrients delivered to a stream as a result of riparian livestock fencing. Watershed area was 5.9km^2. Topography: low rolling hills, with one major granite outcrop, elevation 20 to 180m above sea level. Soils were shallow sands covering laterite, gravels, and clay on valley slopes and deep sand on valley bottoms; soils had low P retention ability. Climate: cool, wet winters and dry, warm to hot summers with 803mm average annual precip. Some farms periodically received potash and/or lime fertilizer. Six years of data collected before riparian management, four after. Riparian fencing (and tree planting) was placed along 1.6km of stream on one farm (the downstream most where the monitoring site was located), but the other three had no riparian fencing. Cattle were replaced by sheep on one upstream farm in the after fencing period. The riparian buffer width is not provided. Streambanks were trampled with sparse vegetation prior to fencing. Event mean concentrations of suspended sediment decreased by 94%, with the median dropping from 54.9mg/L to 7.3mg/L. The annual sediment load decreased from 153kg/ha/yr to 9kg/ha/yr. There was no detectable change in TP, an increase in filterable reactive P of 67%, and a decrease in TN by 37% (numbers are event mean concentrations). TN annual exports decreased from approx. 3.6kg/ha/yr to approx. 0.8kg/ha/yr. "The FRP:TP ratio may have increased because the sediment concentrations have decreased, reducing the availability of sorption sites for leached soluble phosphorus." "Total nitrogen concentration and export

reductions are most likely due to a combination of a reduction in the amount of cattle urine and faeces entering the stream, increased trapping of particulate nitrogen in surface runoff and in-stream nutrient uptake."

38. Mickelson, S.K., Baker, J.L., and Ahmed, S.I. 2003. Vegetative filter strips for reducing atrazine and sediment runoff transport. *Journal of Soil and Water Conservation*. 58: 359-367.*

    Type: Experimental, Before-after (?). Location: Iowa (?) Abstract: "A rainfall simulation study was performed on twelve vegetative filter strips (VFS), six 1.5 × 4.6 m (5 × 15 ft) long, and six 1.5 × 9.1 m (5 × 30 ft) long, to determine: (1) the effects of vegetative filter strips on atrazine and sediment transport in runoff inflow with an average of 7,650 mg L^{-1} sediment (WS) and no-sediment (NS), and (2) the effects of vegetative filter strips length (4.6 and 9.1 m) (15 and 30 ft), and thus area ratio (with constant width), on atrazine and sediment transport. Herbicide runoff losses were simulated by adding a dilute atrazine solution as inflow (with sediment and without sediment) to the upper end of the vegetative filter strips. The with-sediment treatment was used to represent conventional tillage, while the without-sediment treatment represented no-tillage. Atrazine, and bromide (Br) as a hydrologic tracer, were dissolved in the inflow to the vegetative filter strips at a concentration of approximately 1 and 23 mg L-1, respectively. The results showed that for the with-sediment inflow treatment, the 87% reduction in sediment transport for the 9.1 m (30 ft) vegetative filter strips was significantly ($P = 0.05$) greater than the 71% reduction for the 4.6 m (15 ft) vegetative filter strips. There was no significant difference in atrazine transport between the with-sediment and without-sediment treatments, but the 80% reduction in atrazine transport for the 9.1m (30 ft) vegetative filter strips was significantly greater than the 31% reduction for the 4.6 m (15 ft) vegetative filter strips. Infiltration of inflow was a dominant factor in reducing atrazine transport with vegetative filter strips, and the Br data showed that a higher proportion of inflow infiltrated than did rainfall."

39. **Mihara, M. 2006. The effect of natural weed buffers on soil and nitrogen losses in Japan. *Catena*. 65: 265-271.**

    Value: 3 for sediment-buffer data analysis. Type: Experimental. Location: Japan. Abstract: "In Japan, heavy rains from June to October cause severe erosion in the agricultural fields. Natural weed buffers may help conserve the soil and water. We measured the mass balances of the water, soil and nitrogen components in a plot of 159 m^2 (7.2 m wide and 22.1 m long). Plant growth in the plot was dominated by the weeds Humulus scandens Merrill [hops] and Poa annua L [annual meadow grass]. We also evaluated the ability of the natural weed buffer to reduce soil and nitrogen losses. Measurements of the mass balances of the water, soil and nitrogen components showed that 93.1% of the total water received by the plot was lost through percolation. The weed buffer captured 99.6% of the soil introduced into the plot. The plot stored 80.0% of the total nitrogen input, while 13.4% percolated through the soil and 1.8% flowed off the plot from the surface. Only 0.1% of the nitrogen was taken up by plants. Because 99.6% of the soil and 80.0% of the nitrogen components were captured, we concluded that the natural weed buffer was very effective in minimizing soil and nitrogen losses. As Japanese farmers grow older and more agricultural fields in the semi-mountainous regions of Japan fall into disuse, the natural weeds that grow on those fields may become efficient tools for conserving the soil and water in these regions."

40. **Muñoz-Carpena, R.J., Parsons, J.E., and Gilliam, J.W. 1999. Modeling hydrology and sediment transport in vegetative filter strips. *Journal of Hydrology*. 214: 111-129**.

    Value: 3 for sediment-buffer data analysis. Type: Experimental, control-treatment. The authors discuss development and testing of a model (VFSMOD) for hydrology and sediment transport for vegetated filter strips. A field experiment was part of the model development. Soil was clayey, kaolinite, thermic, Typic Hapludult with silt-loam surface horizon. Slopes on plots were 5-7%. Two plots were 4.3m long (9:1 buffer area ratio) and two were 8.5m long (4.5:1 buffer area ratio), both with fescue, bluegrass, Bermuda grass cover. Two riparian plots, lengths 4.3 and 8.5m (area ratios of 27:1 and 13.5:1) with slopes of 18-20% with trees and bush were also used. 27 rainfall events had data recorded, but only a subset of nine cases from the experiment are reported. For these nine cases, the 4.25m grass buffer reduced sediment mass by an average of 85% (N = 5), the 8.5m buffer reduced sediment mass by an average of 93% (N =2), the 4.25m riparian plot reduced sediment by 91% (N=1), and the 8.5m riparian buffer reduced sediment by 77% (N=1). Note: may not be appropriate to use these results since they are only a subset of the data. A sensitivity analysis indicated that sediment transport was sensitive to initial soil water content, vertical saturated hydraulic conductivity, particle class (size, fall velocity, sediment density) and grass spacing.

41. **Newbold, J.D., Herbert, S., Sweeney, B.W, Kiry, P. and Alberts, S.J. 2010. Water quality functions of a 15-year-old riparian forest buffer system. *JAWRA* 46:2:299-310.**

    Value: 1 for sediment-buffer data analysis- suspended solids data. Type: Experimental, treatment-control. Location: Pennsylvania. The study evaluated the long-term effectiveness of a three-zone buffer at removing suspended solids, nitrogen and phosphorus from runoff. A paired watershed approach was used. Soil slopes range from 5 to 10%. Soils were mainly Typic Hapludults in uplands and Aquic Fragiudults with seasonally high-water tables (within 0.5 to 1.5m of surface). Saprolite or weathered rock is generally within 5-7m of surface. The watershed with the riparian forest buffer system (RFBS) was 14.9 hectares; zone 1 had 10m of woody vegetation along the 1st order stream, zone 2 had 18-20m wide strip of reforested hardwoods, zone 3 had a 6-10m wide grass filter containing a level spreader (buffer area ratio of 18:1). Nitrogen fertilizer application ranged from a max of 75kg/ha in 1991 to 42kg/ha in 2006. The control watershed was 34.4 hectares, mostly planted with hay, corn, and soybeans and with a first order stream; a sparsely forest/brush zone was within 50 to 200m of the stream. A third reforested 14.5-hectare watershed was also monitored; mature forest was within 30m of the stream, all cropland (26% of watershed) was planted to hardwoods, and 24% of the watershed (upper elevations) remained mostly in pasture. Annual precip ranged from 0.84 to 1.73m/yr. Nitrate initially increased in the RFBS stream to a peak in 2002, then declined thereafter through 2007 when monitoring ceased; streamwater concentrations were significantly less than upslope groundwater concentrations. Nitrate also increased in the control stream between 1995 and 2000 but could not entirely account for the increase in the RFBS stream. Overall, the RFBS was estimated to reduce nitrate inputs to the stream by 26% for the 10 yr post-treatment period. Soluble reactive phosphorus (SRP) was approximately 67% of the total P. Decreases in groundwater SRP had no impact on streamwater P. The RFBS was estimated to have removed 43% of sediment (with zone 3 accounting for approx. 32%). It was noted that overland flow was first intercepted by contour strips and grassed waterways before entering the buffer, which may have significantly reduced sediment loads prior to reaching the buffer- this is a difference from other research on buffers that does not include additional BMPs in the study and reported higher sediment reductions for buffers. Nitrate concentrations through the RFBS increased and ammonia concentrations did not significantly change. SRP in overland flow increased through the RFBS, but particulate P concentrations decreased by 22%, resulting in no net effect upon P in overland flow. Again, unmeasured upslope reductions in P removal may have occurred.

42. Nigel, R, Chokmani, K., Novoa, J., Rousseau, Al. N., Dufour, P. 2013. Recommendations for riparian buffer widths based on field surveys of erosion processes on steep cultivated slopes. *Canadian Water Resources Journal*, 38:4. 263-279.

    Value: 0 for sediment-buffer data analysis- no field data. Type: Observational, case-study. Location: Quebec, Canada. The authors surveyed and classified erosional features on cropland and developed recommendations on how slope should be accounted for in riparian buffer delineations; digital terrain analysis, remote sensing surveys, and field surveys were performed. The study cites Montgomery (2007) as showing that soil erosion on conventionally tilled fields is on average one to two orders of magnitude greater than long-term geological erosion, erosion under native vegetation, and rates of soil formation. Cite Gagnon and Gangbazo (2007) as finding that buffer width to address soil erosion depends on soil type, topography, and hydrology (among other factors) and that optimal widths for capturing sediment from uniform shallow flow vary from 7.5 to 114m. Four factors influence erosion- rainfall, soil type, topography, and land cover and practices. On an individual parcel, topography is the only factor that influences spatial variability in erosion. Slopes 0-2% have readily controllable erosion. Slopes 2-8% have low erosion rates that can be readily controlled by crop selection. Slopes 8-13% have moderate erosion that is more extensive and more costly to control. Slopes 13-20% have moderate erosion that is controllable through more "investment, technical knowledge, and maintenance." Slopes 20-30% have high rates of erosion that are the most difficult and expensive to control. Erosion on slopes greater than 30% is technically or financially impossible to control. "Erosion features are highly correlated with the rate of change of slope." Erosion features on slopes greater than 8% were found to be "hydrologically and sedimentologically connected to watercourses", while the opposite was found where slopes were less than 8%. Sediment delivery to streams occurred where slopes were steeper occurred despite riparian buffer strips of 1 to 3m. The authors suggest a system of BMPs to reduce erosion including reduced tillage or direct seeding; cross-slope cropping; cover crops; grassed waterways in swales; putting slopes >8% into buffer (and leaving 1-2m vegetated at the upslope end of the buffer so that runoff is slowed before encountering the steeper slope); installing drainage systems at the upper end of the buffer to infiltrate runoff. Modelling is suggested for delineating buffer width where near-stream slopes are <8%.

43. Parsons, J.E., Daniels, R.B., Gilliam, J.W., and Dillaha, T.A. 1994. Reduction in sediment and chemical load agricultural field runoff by vegetative filter strips. *UNC-WRRI-94-286.* University of North Carolina. Raleigh, NC.

Value: 0 because data not presented in a complete or readily useable format. Type: Experimental, treatment-control. Location: Coastal Plain and Piedmont, North Carolina. The authors investigated the performance of grass filters followed by riparian buffers at reducing sediment and nutrients from crop fields after natural rainfall events.

Piedmont site had linear slope averaging 3.6% in crop fields, greater slopes in the grass filter strips, and much greater slopes in the riparian filters. Coastal Plain (CP) site had "gentle linear to concave head slope" with crop fields having average slope of 1.9%, grass filters <1.5%, and riparian filters <1%. Crop fields at both sites were 27.4m wide and 36.6m long. Level spreaders were used between the upslope grass filters and downslope riparian buffers.

Table 37: From Parsons et al. (1994) Showing Average Slope of Cultivated and Filter Plots at the Piedmont and Coastal Plain Sites

Table 1: Average Slope of Cultivated and Filter Plots at the Piedmont and Coastal Plain Sites

Plots	% Slope	
	Piedmont	Coastal Plain
Cultivated Plot	3.6	1.9
Grass Filter (Length in m)		
4.2 (Set 1)	6.3	0.8
4.2 (Set 2)	4.2	1.4
8.4 (Set 1)	5.2	0.7
8.4 (Set 2)	4.8	1.1
Riparian Filters (Length in m)		
4.2	12.4	0.8
8.4	16.4	0.7

Crops were corn and soybean rotations in rows parallel to the slope. Grass filter vegetation was sparse crab grass at 90% cover in year 1 but was aerated renovated and seeded to fescue at the end of year 1 (100% cover). Grass filters were 4.3 and 8.5m at both sites. Riparian buffers at Piedmont (PD) site had mixed hardwood and pine, with dense vine and sapling understory. Riparian buffers at Coastal Plain had dog fennel in 4.2m buffer and fescue in the 8.4m buffer. Sediment deposition was measured by topographic survey converted to volume. Nutrient changes were soil samples (upper 5cm). Sediment and nutrient loads were calculated from samples collected every 30 seconds during storm events. See Appendix for rainfall data. Initial results were influenced by the sparse density of vegetation in the grass filters. Authors state that the two sets of grass filter plots were treated as replicates but were not true replicates: no replicates for the riparian buffers. Sediment and nutrient concentrations are reported for selected storm events, which is not helpful for summarizing load reductions. One would have to go through the appendices and combine the data to calculate effectiveness for select storms based on the data provided. Cites Dillaha et al. (1989) as finding that filter strips in hilly areas are ineffective at removing sediment due to concentrated runoff flows.

44. **Robinson, C.A., Ghaffarzadeh, M., and Cruse, R.M. 1996. Vegetative filter strip effects on sediment concentration in cropland runoff. *Journal of Soil and Water Conservation*. 51: 227-230.**

Value: 0 for sediment-buffer data analysis- suspended solids, not suspended sediment data. Type: Experimental. Location: Iowa. The study evaluated the effects of different vegetated filter strip (VFS) lengths on sediment reductions under natural rainfall. Soil was fine-silty, mixed, mesic Typic Hapludalf (silt-loam). The upper 18.3m of a field was maintained under continuous fallow, with cultivation every 3 weeks, weather permitting. The lower 18.3 meters was left as a filter strip dominated by bromegrass, but also with alfalfa and orchard grass. VFS plots had either a 7% or 12% slope. Initial sediment concentrations on the 12% slope were nearly double that of the 7% slope. The first three meters of both VFS plots accounted for most of the sediment reductions. On the 7% slope, the reduction was 70% at three meters. On the 12% slope, the reduction was 80% at 3m. Sediment reductions were >85% for both slopes at a distance of 9.1m. "Although the VFS removed 4% more sediment on the 12% slope than on the 7% slope, more total sediment remained in the runoff from the 12% slope." "The VFS promoted infiltration, reduced runoff volumes, and decreased runoff sediment concentration."

45. Roose, E. 1996. Land husbandry- components and strategy. 70 FAO Soils bulletin. Food and Agriculture Organization of the United Nations. ISBN 92-5-103451-6. Rome.

Value: 0 for sediment-buffer data analysis. This publication is sort of a manual for understanding and addressing soil erosion.

"Estimating the influence of the concavity, convexity, regularity or warp of a slope is a very delicate procedure. This factor is too often neglected, which in large part explains why authors come up with such divergent results. As eroding plots age and are exposed to severe erosion, they become more and more concave, since the base of the plot stays fixed (the runoff channel) and the middle of the plot erodes more quickly than the top. This means that each year the slope of the plots must be readjusted so that the results are not falsified by default. According to Wischmeier (1974), compared with a smooth average slope, sediment transport is reduced on a warped or concave slope (due to localized sedimentation), but increased on a convex slope due to the gradient of the steepest portion. The presence of concave slopes in a landscape indicates that there must be trapping, siltation and colluvial deposit in the valley. In general, erosion on the hillside exceeds the sediment transport in the river although this is not the case in the Mediterranean area, where the main cause of sediment transport is the energy and volume of runoff (Heusch 1971; Arabi and Roose 1989)."

46. **Rosa, D.J., Clausen, J.C., and Kuzovkina, Y. 2017. Water quality changes in a short-rotation woody crop riparian buffer. Biomass and Bioenergy, 107. 370-375.**

Value: 0 for sediment-buffer data analysis- suspended solids data and apparent math errors. Type: Experimental, treatment-control. Location: Connecticut. The authors studied how suspended solids and nutrient concentrations were affected by short-rotation biomass crops of willows used as riparian buffers. Soils were coarse-loamy, mixed, active, mesic Aquic Dystrudepts (fine sandy loam) with a 5% slope and underlain by densic glacial till 0.5 to 1.0m below the soil surface that resulted in a perched water table following precipitation. Three control (corn) and three treatment plots (willow) were established randomly in blocks that varied in elevation and soil moisture; each plot was 30m cross-slope by 10m down-slope and was positioned downslope of the upslope cornfield. In the willow plots the planting density was 10,000 cuttings per ha, with five sets of double rows, individual plant spacing of 0.61m, 076m between rows, and 1.5m between double rows. Watershed areas for individual plots ranged from 8.4 to 47.8 m2 as a result of microtopography. The study area was top-dressed with urea at 50kgN per hectare before plot establishment, treated with atrazine and glyphosphate. No fertilizer/herbicide was applied afterwards to the willow plots (but each was manually weeded each season), but "seasonal fertilization, herbicide, tillage, harvest, and cover crop of winter rye" occurred on the corn plots. ANOVA was used to determine whether or not significant differences occurred between treatments. Precip during the study (June 2013 – Nov. 2016) was 34% below normal. The willow plots decreased surface runoff concentrations by 41% for total nitrogen, 53% for total phosphorus, and 71% for suspended solids, but no differences were found between treatments for the masses of these parameters (checking the math for SSC concentrations comes out to 54% reduction, not 71% and 51% for TP instead of the reported 53%). Reducing concentrations but not mass suggests that dilution occurred or that statistical power was insufficient to detect a difference. For groundwater, the willow plots had decreases in total nitrogen and nitrate + nitrite, both by 41%, and a 31% increase in total P. **"Buffers improve water quality through several physical and biological mechanisms including infiltration, deposition of sediment, adsorption, nutrient uptake, and denitrification."** The effectiveness of a riparian buffer depends less upon buffer width than it does upon on the soils, hydrology, and biogeochemistry at a site.

47. **Sheridan, J.M., R. Lowrance and D.D. Bosch. 1999. Management effects on runoff and sediment transport in riparian forest buffers. *Transactions of the ASAE*. Jan-Feb 42(1): 55-64.**

Value: 1 for sediment-buffer data analysis- suspended solids data, field scale data incomparable to plot scale. Type: Experimental, treatment-control. Location: Georgia. This study evaluates the effectiveness of a USDA-style three-zone buffer.

Excerpt: "Zone 1 is a narrow zone of permanent, native riparian tree and shrub vegetation located adjacent to, or including, the stream channel. Zone 1 provides stream bank stabilization, moderation of stream temperatures by shading, as well as woody debris inputs to the stream ecosystem. Zone 1 is limited to sheet flow (diffuse surface runoff) or subsurface flow only; concentrated surface flow must be converted to sheet flow prior to entering Zone 1. Zone 2, the primary zone of pollutant removal, is a managed forest zone immediately upslope from Zone 1. Zone 2 provides opportunity for infiltration of surface flows and deposition of sediment and sediment-borne pollutants, as well as reduction of nutrients and other agrichemicals by vegetation uptake, denitrification, and other microbial processes. Periodic harvesting of timber is required to remove nutrients and pollutants sequestered in riparian forest growth. Zone 2 is limited to shallow, sheet flow or subsurface flow only. Zone 3 is an herbaceous filter strip located upslope from Zone 2, adjacent to the agricultural field. The primary purpose of Zone 3 is spreading concentrated storm flow, thereby providing greater infiltration as well as increased settling and deposition of sediments prior to flows entering Zone 2. While flow spreading is recognized as a primary Zone 3 function, use of appropriate in-field BMPs are also critical to reducing concentrated flow entering the buffer system. Vegetative growth in Zone 3 requires periodic harvest or removal of biomass."

Soil was a fine-loamy, siliceous, thermic, Plinthic Kandiudult (loamy sand). The upland crop field had an argillic horizon at 0.5 to 1.8m depth that restricts vertical water movement. Zone 3 of the buffer was an 8m wide grass filter strip, Zone 2 45 to 55m of slash pine managed for harvest, and Zone 1a 10m swath of hardwoods (average buffer width = 70m along an intermittent second order stream). Contributing field area = 0.93-hectare field successively planted to corn, millet, and peanuts using conventional agronomic practices for the region. Forest management treatment plots were clear-cutting, thinning, and mature forest 40m wide by 55m deep. Prior to the study, one-third of Zone 2 was clearcut, one-third was thinned according to forestry commission guidelines. Rainfall averaged 1127mm (but was 1526mm in 1994), less than the long-term average of 1208mm. Sampling position 1 was at upper edge of zone 3, position 2 at upper edge of zone 2, position 3 was midway into zone 2, position 4 was at upper edge of zone 1. For each position, there was no significant difference among the three zone 2 treatments for sediment concentrations and no difference for mean event sediment load except at position 4- which was attributed to greater runoff volumes for the selective and clearcut treatments. Among the three treatments, sediment concentrations decreased by an average of 73%, with a 63% reduction occurring across zone 3 alone. Total reductions in sediment loads were significantly different and were 68% for the selective thinned plot, 74% for the clearcut plot, and 95% for the mature forest plot. A 78-83% (78%- mature, 82%- clearcut, 83% selective thin) reduction in sediment load occurred in zone 1 for the three treatments, at position 3, the mature forest had approx. 82% reduction, selective thin approx. 93% reduction, and clearcut, approx. 90% reduction; for the latter two treatments, sediment load reduction decreased for the rest of zone 2, possibly affected by close proximity to an ephemeral channel. No evidence of concentrated flow through zone 1 was observed. The authors concluded that landowners can manage zone 2 for economic return without increasing sediment loads to streams- this seems to be an incorrect conclusion since the mature forest reduced loads by 95% and harvest resulted in much lesser sediment reductions. The authors basically extracted from the results the influence of potential saturation excess runoff occurring in zone 2, but only for the two harvest treatments, even though this occurrence should be considered part of natural hydrologic variability; perhaps not having saturation excess in the mature forest plot was an effect of having mature forest. Note: strangely, no measurements were taken at the stream-ward edge of zone 1.

48. Smith, C.M. 1989. Riparian pasture retirement effects on sediment, phosphorus and nitrogen in channellised surface run-off from pastures. *N. Z. J. Mar. Freshwater Res*. 23:139-146.

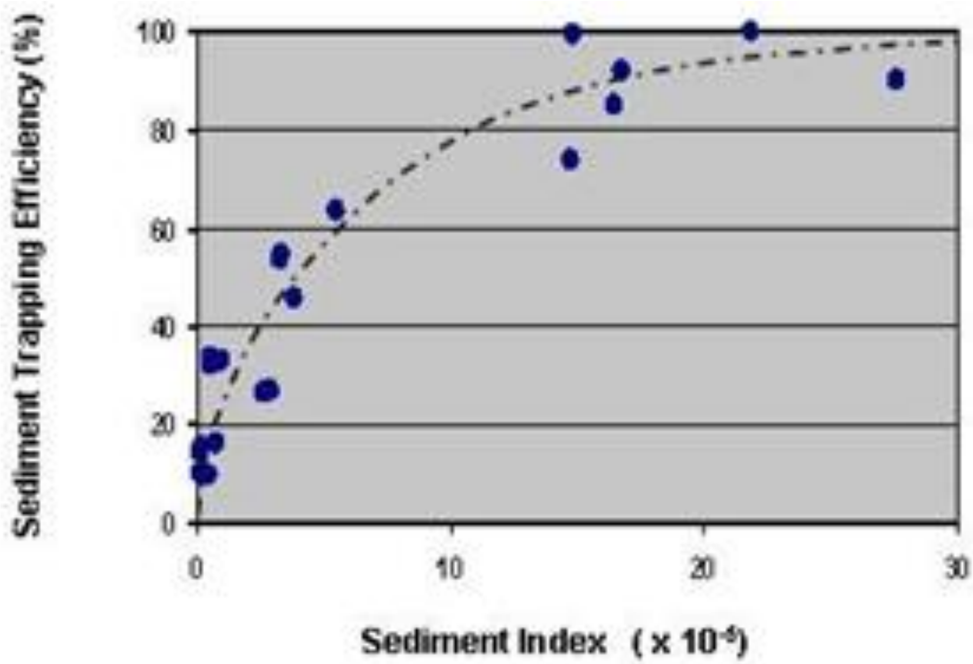
Value: 1 for sediment-buffer data analysis- suspended solids data, field scale data incomparable to plot scale, observational not experimental. Type: Observational, before-after. Location: New Zealand. An examination of changes in suspended solids and nutrients in channelized flow before and after livestock exclusion from riparian strips. South facing slope was 26.8% slope. North facing slope was 36.4%. 19 stock units per hectare stocking rate. Vegetation primarily perennial ryegrass and white clover. Silt-loam topsoil overlying mottled, gleyed silty-clay loam on 68% of both slopes, moderately well-drained silt-loam on remainder of slopes. Rainfall was 1447 and 1165mm in the two years monitored post-treatment (long-term average = 1401mm). Surface runoff intercepted by collectors, which were located just downslope of filter strips on each slope (10-13m wide). Median suspended solids concentrations were approx. 50% lower below filter strips; in most rainfall events, filter strips also reduced nitrate, TDP and on south facing sites, dissolved Kjeldahl nitrogen. Flow-weighted mean reductions for parameters varied between the two slopes for TDP, PP, PN, nitrate, SS, and VSS. For the two slopes average together percent reductions were: 34.5% for TDP, 63% for PP, 28% for DKN, 64% for PN, 60.5% for nitrate, 64% for suspended solids, and 53.5% for volatile SS.

49. Tomer, M.D., Dosskey, M.G., Burkhart, M.R., James, D.E., and Helmers, M.J. 2005. Placement of riparian forest buffers to improve water quality. In: Brooks, K.N. and Ffolliot, P.F. (eds). *Moving agroforestry into the mainstream. Proc. 9th N. Am. Agroforest. Conf., Rochester, MN. 12-15 June 2005* [CD-ROM]. Dept. Forest Resources, Univ. Minnesota, St. Paul, MN, 11p.

Value: 0 for sediment-buffer data analysis- case study, modelling. Type: Observational, case study. Location: Missouri, Iowa. The paper outlines techniques for identifying and mapping locations where riparian forest buffers can be effective. Effectiveness of riparian forest buffers is influenced strongly by soils, topography, hydrology, and surficial geology. One technique uses soil survey and climate information to rate soil map units for potential effectiveness, which can be used to prioritize buffer locations. A second technique uses topography and stream-flow information to identify where buffers would likely intercept runoff. The techniques are for buffer placement at the farm to small watershed scale. The case study described indicates that forest buffers have a greater potential to protect water quality along first order streams rather than larger order streams, and that buffers along stream orders one through three have a greater potential for sediment deposition. A model was used to rate sediment trapping efficiencies for soil map units based on soil attributes and slope. It relies upon a sediment index (SI) derived from the RUSLE equation where: SI = D50/(RKLS). D50 is median particle diameter on the soil surface. R = rainfall and runoff erosivity. K = soil erodibility. L = slope length. S = slope steepness. Table 1 in the paper indicated the D50 to be used for different soil textures. “R is obtained from the map in Figure 2-1 of Renard et al. (1997); K is obtained from tables in the county soil survey; L and S are computed according to Renard et al. (1997) for a 200 m field length using the mean of the slope range given for the map unit in the soil survey.” The second equation for the

model uses the SI value to estimate the sediment trapping efficiency, which is an output of the VFSMOD model (see Munoz-Carpena and Parsons, 2000). "In calculating both variables, standard conditions were assumed that include buffer design (12 m width with grass groundcover) and field conditions (200 m slope length; contour tillage with moderate residue; 2-yr frequency, 24-hr rainfall event for that location; wet antecedent soil conditions)."

Figure 17: Graph from Tomer et al. (2005) depicting sediment trapping efficiency % and sediment index



- "Factors that produce larger runoff loads, such as higher rainfall, higher soil erodibility, and steeper slopes will reduce buffer effectiveness. Conversely, coarser-textured soils promote greater buffer effectiveness by infiltrating more rainfall and runoff, thereby reducing erosion and sediment transport capacity, and by producing larger sediment particles that are readily deposited." For the topographic model, a discharge index is used to determine which riparian reaches have the greatest upslope contributing areas (and thus forest buffers would have higher relative effect), a wetness index (basically flat areas with large upslope contributing areas) is used to determine areas prone to soil saturation (and thus are good areas for buffers), and a sediment transport index is used to identify areas where deposition or erosion is probable.

50. **Uusi-Kamppa, J. and Ylaranta, T. 1992. Reduction of sediment, phosphorus and nitrogen transport on vegetated buffer strips. *Agric. Sci. Finl*. 1:569-574.**

Value: 1 for sediment-buffer data analysis- incomparable, suspended solids data and some of data is from dormant vegetation period. Type: Experimental, control-treatment. Location: Finland. The authors evaluated the effects of buffer strips at reducing solids and nutrients from crop fields. Soils had 54-63% clay in the 0-20cm plow layer. The cropland source area was flat, and had 10m wide buffers on slopes averaging 16%, but ranging from 12 to 18%. Two replicates each of: spring grain crop and timothy/fescue buffer; spring grain and no buffer; spring grain and shrubs, hardwoods, wild hay, and flowers in buffer. Experiment was based on natural rainfall with 460mm in calibration year and 354mm in experimental year. The buffers with tree/shrub were omitted from results because they "were poorly covered by vegetation and did not function properly." There was wide seasonal variation in the effectiveness of the grass buffer at trapping suspended solids (fall was 49% reduction, spring was 20% increase above the control). Overall, the grass buffer decreased total suspended solids by 23% (kg/ha). The grass buffer reduced total P by 6% overall (33% reduction in fall but 35% increase in spring (kg/ha). Losses of phosphate from grass buffer were 38% higher than the control. 47% reduction in total N in the grass buffer. 51% reduction in nitrate in grass buffer. **Note the spring (period of greatest runoff) measurements were taken while vegetation was still dormant.**

51. Verstraeten, G., Posen, J., Gillijns, K., and Govers, G. 2006. The use of riparian vegetative filter strips to reduce river sediment loads: an overestimated control measure? *Hydrological Processes*. 20: 4259-4267.

    Value: 0 for sediment-buffer data analysis- no useable data. Type: Observational, case study- modelling. Location: Belgium. The authors used modelling to compare the effectiveness of riparian filters strips at reducing sediment at the plot scale to the watershed scale (14,400m^2 to 13,599km^2). "The effectiveness of a VFS depends on many parameters, including characteristics of the VFS itself (width, slope, vegetation height, density, stiffness and species composition), of the inflow (runoff velocity, discharge, volume), of the sediment inflow (grain size, aggregation, concentration) and of the rainfall on the VFS." "Herron and Hairsine (1998) tried to illustrate the impact of flow convergence on the effectiveness of riparian zones using a simple hydrological approach and concluded that, in the case of strong flow convergence, unrealistic wide riparian buffers are needed, even up to 30% of total hillslope length." For the plot scale the upslope contributing area was 180m long by 80m wide with slopes between 5 and 9% (7% just above the filter strip); the filter strip slope was 3 to 3.4% and no flow convergence occurred uphill. The second scale included three catchments (23.2, 17.2, and 11.2km^2) on an undulating plateau with incised rivers (steep slopes adjacent to rivers). Several intermittent channels drain the crop fields. Approx. 56% is cropland (wheat, sugar beets, chicory, potatoes, corn) 12% orchards, 6% pasture, 2% forested, 24% residential. The third scale was all of Flanders; the south part was a plateau with incised channels and slopes locally up to 15% and highly erodible loess derived soils; the north part has slopes <2% and less erodible sandy soils. "Experimental studies have shown that the sediment trapping efficiency of VFSs does not significantly increase with filter width above a filter width of 10–15 m (e.g. Neibling and Alberts, 1979; Abu-Zreig et al., 2004)." Filter strips were only simulated for areas where cultivated fields are adjacent to perennial rivers. For scale 2, riparian filter strips were simulated for 43% of river length. For scale 3, filter strips are simulated along 20.5% of river length. For the plot scale sediment trapping efficiency (STE) was 78%, for scale 2, it was 35%, and for scale 3 it was 40%. Estimated sediment reductions were 70% for plot scale, 21% at catchment scale, 17% at watershed scale. The low STE and SR for scales 2 and 3 were attributed to the following reasons. First, flow convergence occurs for most of the runoff such that there are relatively few areas where uniform flow enters riparian zones. The authors suggest that filter strips are not effective where flow converges and that instead, upland BMPs are needed where flow convergence occurs. Second, once flow converges, the depth of flow limits the ability of filter strips to capture sediment. Third, runoff from fields bypasses buffers when it flows into roads, ditches and sewer systems. The authors suggest that watershed scale erosion control should focus on permanent vegetation on the most erodible soils (ranging from 17% if 5% of highly erodible lands are retired, to 35% of 20% of them are retired), no-till farming (estimated SR of 13% on highly erodible land and up to 33% if implemented on a crop fields), and upland grassed waterways, with riparian buffers where flow convergence does not occur. "These results suggest that an effective and efficient sediment control policy for rivers can best be achieved by taking measures on the land, not along the rivers itself."

52. Webber, D.F., Mickelson, S.K., Ahmed, S.I., and Russell, J.R. 2010. Livestock grazing and vegetative filter strip buffer effects on runoff sediment, nitrate, and phosphorus losses. *Journal of Soil and Water Conservation 65*, no. 1: 34-41.

    Value: 1 for sediment-buffer data analysis- suspended solids data. Type: Experimental, control-treatment. Location: Iowa. This study examined the effects of filter strips on sediment and nutrients in runoff from livestock pasture. N and P losses from pasture has been shown to increase with increasing grazing duration. "Cool-season grasses, such as smooth bromegrass, tend to lay over in runoff flow and are not considered appropriate grass species for vegetative buffers (Schultz et al. 1997)." Three 1.35-hectare plots were divided into three 0.4 hectare paddocks. The dominant soil was a fine-silty, mixed, mesic, Mollic Hapludalf. Terrain was uneven with slopes between 4 and 15%. Vegetation was nearly all grass and dominated by sod-forming smooth bromegrass. Diammonium phosphate was applied to plots to being them up to the "optimum" range of 11 to 15ppm P. Three treatments in each plot were- continuous grazing, rotational grazing to 5.1cm stubble height, and a non-grazed control. Three buffer area treatments were employed: a 1:0.2 paddock to buffer area ratio, a 1:0.1, and a 1:0 control. Three plots were used. Each plot had one of each buffer treatments, each with one of three grazing treatments; in other words, there were three replicates for each of the nine buffer/grazing treatments. Runoff from 12 natural rainfall events was analyzed. Runoff collection pipe leakage in 2001 resulted in separate analysis of this data from 2002 and 2003 data. There were no significant differences in runoff, total solids, nitrate, or phosphate in 2001. In 2002, runoff and total solids were significantly greater from the 1:0 rotational grazed control and the 1:0 continuous grazing control than from all other treatments. "Results from 2003 (table 3) showed significantly higher losses ($p \leq 0.10$) of runoff and total solids from 1:0 no buffer/no grazing (control) treatment combination plots compared among 2003 treatment combinations and 1:0.1 vegetative buffer/no grazing treatment combination plots compared among 2003 treatment combinations and with the respective 2002 treatment combination." (huh?) Paddocks with greater buffer area ratios had greater retention of total solids mass, but total solids in runoff was not consistently greater as grazing duration increased. For nitrate mass, the results were not consistent across buffer area ratio or grazing treatment. In year 1, the 1:0.2 buffer and the non-grazed paddocks had the greatest nitrate reduction, in year 2 the 1:0.1 buffer and continuous grazing paddocks had the greatest nitrate reductions, and in 2003, the 1:0.2 and continuous grazing paddocks had the greatest reductions; the only significant differences were among all grazing treatments and buffer area treatments in 2003. For phosphate mass, there were no significant differences in P reductions among buffer treatments in any year or in grazing treatment in any year.

For all year combined, there was more runoff volume from non-grazed treatments and from non-buffered paddocks. There were indications that concentrated flow may have led to greater runoff volumes and pollutant losses. "Consequently, the combined effects of these potential soil-water environmental conditions and effects documented in this study may have contributed to significantly higher 2003 project season runoff and contaminant losses from ungrazed treatment combination plots compared to respective 2002 season results."

53. Wissmar, R.C., Beer, W.N., and Timm II, R.K. 2004. Spatially explicit estimates of erosion-risk indices and variable riparian buffer widths in watersheds. *Aquatic Sciences.* 66: 446-455.

    Value: 0 for sediment-buffer data analysis. Type: Observational, case study (?). Location: Washington State. The authors present a method for determining variable width buffers (for forested areas) based on erosion-risk indices. Erosion related land cover information included areas of unstable soils, immature forest stands (<35yrs), roads, critical slope for land failure (>36%), and areas of rain on snow. A regression indicated that mean erosion risk explained 65% of the variation in sediment inputs to streams. Buffers prescribed ranged from a low of 30m for low-risk areas to 135m for high-risk areas (derived from timber company HCPs and FEMAT recommendations).

54. Witt, E. L., Barton, C. D., Stringer, J. W., Bowker, D. W., and Kolka, R. K. 2013. Evaluating Best Management Practices for Ephemeral Stream Protection following Forest Harvest in the Cumberland Plateau. *Southern Journal of Applied Forestry*, Volume 37, Number 1, pp. 36-44.

    Value: 0 for sediment-buffer data analysis- incomparable data. Type: Experimental, control-treatment. Location: Kentucky. Witt et al. (2013) conducted an experiment to evaluate SMZ (Stream Management Zone) effectiveness on ephemeral streams in southeastern Kentucky. Ephemeral SMZ treatments included (1) harvest with no equipment limitation, no forest over-story retention, and use of unimproved stream crossings (no-SMZ); (2) harvest with no equipment limitation, retention of channel bank trees, and use of improved stream crossings (SMZ1); (3) harvest with equipment restrictions within 7.6 m of the channel, retention of channel bank trees, and use of improved stream crossings (SMZ2); and (4) no harvest (control). Each treatment was replicated a minimum of three times (n of 3 to 6; 18 sites total) at the subwatershed level (0.75 to 8.92 ha). Water samples were taken during storm flows and were analyzed for total suspended solids (TSS), turbidity, settleable solids, and sediment transport rate. Both the SMZ1 and SMZ2 treatments significantly reduced TSS and turbidity over the no-SMZ treatment. Water in the SMZ1 treatment exhibited higher TSS and turbidity than the control, whereas the SMZ2 treatment was no different than the control for TSS but higher for turbidity. The authors assert their data indicate that "the extension of forestry BMPs to ephemeral streams is effective in reducing sediment from harvest operations".

55. Witt, E.L., Barton, C.D., Stringer, J.W., Kolka, R.K., and Cherry, M.A. 2016. Influence of variable streamside management zone configurations on water quality after forest harvest. *Journal of Forestry*, Volume 114, Number 1. pp. 41-51(11).

    Value: 0 for sediment-buffer data analysis- incomparable data. Type: Experimental, control-treatment. Location: Kentucky. Witt et al. (2016) evaluated three riparian treatments (T1, T2, and T3) that varied in width, canopy retention within the SMZ, and BMP utilization with replication in two watersheds each. Changes in total suspended solids, turbidity, nitrate, dissolved oxygen, and maximum stream temperature were detected for watersheds treated with T1 and T2. T1 consisted of 55-ft perennial SMZs with 50% canopy retention; 25-ft intermittent SMZs with no over-story retention; with stream fords and no over-story buffer requirements for ephemeral streams. Treatment T1 resulted in a 3.4°F (1.9°C) increase in mean maximum daily temperature and statistically significant increases in sediment. T2 consisted of 55-ft. perennial SMZ but required 100% canopy retention and 25% canopy retention in the 25-ft intermittent SMZ. In addition, elevated crossings were used to cross ephemeral streams and the nearest channel bank tree was retained. No significant difference was found between this and the control treatment. T3 increased the perennial SMZ width to 110-ft with 100% canopy retention. T3 also increased the intermittent SMZ width to 55-ft with 25% canopy retention and included a 25-ft SMZ around ephemeral streams that limited harvesting equipment to the crossings only. Elevated crossings were used to cross T3 ephemeral streams and the nearest tree to the channel was retained. Watersheds with wider SMZs (T3: 110 ft, 100% canopy retention) and improved crossings were not significantly different from unharvested control (C) watersheds for all parameters except nitrate and diurnal stream temperatures.

56. **Young, R.A., Huntrods, T., and Anderson, W. 1980. Effectiveness of vegetated buffer strips in controlling pollution from feedlot runoff. *Journal of Environmental Quality*. 9: 483-487**.

    Value: 1 for sediment-buffer data analysis- incomparable data- suspended solids from feedlot runoff. Type: Experimental, before/after (i.e. up/down of filters). Location: Minnesota. This study evaluated the effectiveness of vegetated plots at reducing bacteria, suspended solids, and nutrients in feedlot runoff. Soils not described. The feedlot was 111.25m long and 54.86m wide with 310 cattle. Six plots, each extending 27.43m downslope of the feedlot (4% slope). In the second year, plots had to be shortened to 21.34m. In the first year two of the plots were planted to corn (59,000 plants/ha), two of the plots planted to orchard grass and two plots planted to sorghum/Sudan grass mixture. In year 2, plots were planted to only corn or oats. Simulated rainfall was applied at a rate of 6.35cm/hr for 71minutes, at existing moisture conditions and again 24hrs later when the soil was saturated. For all vegetated strips combined, suspended solids was decreased by an average of 79%, TN by 84%, ammonia by 63%, TP by 83%, and phosphate by 76%; nitrate increased by an average of 9%. Runoff was reduced by 82% on corn only plots, 81% on orchard grass, 61% on sorghum-sudangrass, and 41% on oats plots. Suspended solids load reductions were: 93% for corn (27.43m plot), 66% for orchardgrass (27.43m plot), 82% for sorghum-sudangrass (27.43m plot), and 75% for oats (21.35m plot). 27.43m plots TN load reductions: corn- 98%; orchardgrass 68%; sorghum-sudangrass- 47%. 27.43m plots nitrate load reductions: corn- 95%; orchardgrass 8%; sorghum-sudangrass- 87% increase. 27.43m plots TP load reductions: corn- 98%; orchardgrass 76%; sorghum-sudangrass- 48%. 27.43m plots phosphate load reductions: corn- 98%; orchardgrass 77%; sorghum-sudangrass- 42%. 21.34m plots TN load reductions: corn- 76%; oats- 38%. 21.34m plots nitrate load reductions: corn- 341% increase %; oats-1035% increase. 21.34m plots TP load reductions: corn- 74%; oats-50%. 21.34m plots phosphate load reductions: corn- 41%; oats-3% increase. Bacteria: total coliform reduced by 71% for corn, 70% for oats (both for 21.34m plots); for fecal coliform 55% for orchardgrass, 83% for sorghum-sudangrass (both for 27.43m plots); for streptococcus 72% for orchardgrass, 68% for sorghum-sudangrass (both for 27.43m plots).

57. **Younos, T.M., Mendez, A., Collins, E.R., and Ross, B.B. 1998. Effects of a dairy loafing lot-buffer strip on stream water quality. *Journal of the American Water Resources Association*. 34: 1061-1069.**

    Value: 1 for sediment-buffer data analysis-suspended solids data. Type: Experimental, before-after. Location: Virginia. The study evaluated the effectiveness of a filter strip at reducing sediment and nutrients from dairy loafing lot runoff. Soil: fine sandy loam on a 6 to 16% slope (increasing with proximity to the stream). In April 1995, a 110m long 18m wide buffer strip was established by planting to tall fescue (62kg/ha seeding rate) The strip was fertilized with 10-10-10 at 340kg/ha. The post-GFSA period was set to August 1995- grass cover was 60% at that time. The stream running along the 110-filter strip, rather than the filter runoff, was sampled. Loads were standardized to account for differences in rainfall and runoff between pre and post filter establishment. Load reductions were: 95% for phosphate, 68% for total P, 54% for total suspended solids, 76% for nitrate, 72% for TN.

58. Zaimes, G.N., Schultz, R.C., and Isenhart, T.M. 2004. Stream bank erosion adjacent to riparian forest buffers, row-crop fields, and continuously grazed pastures along Bear Creek in central Iowa. *Journal of Soil and Water Conservation*. Vol. 59, No. 1.

    Value: 0 for sediment-buffer data analysis- no useable data.

    Abstract: "Row-crop agriculture, continuous-grazing, and stream channelization, have accelerated stream bank erosion and increased sediment load. Stream bank erosion rates and total soil loss were compared among riparian forest buffers, row-crop fields and continuously grazed pastures along a continuous 11 km (6.8 mi) stream reach in central Iowa. Exposed erosion pins were measured to estimate stream bank erosion rates, approximately every month from June 1998 to June 1999, except during the winter months. Total stream bank soil losses for each treatment were estimated from the mean bank erosion rate, mean bulk density, and the total stream bank eroding area. Row-crop fields had the greatest stream bank erosion rate and total soil losses followed by continuously grazed pastures while riparian forest buffers had the lowest. If riparian forest buffers had been established along all of the non-buffered segments of the 11 km (6.8 mi) stream reach, total stream bank soil loss would have been reduced by approximately 72%."

Soils at the study sites were Coland (fine-loamy, mixed, mesic Cumulic Haplaquolls) and Spillville (fine-loamy, mixed, mesic Cumulic Hapludolls). Both were alluvial soils on glaciated terrain with 0 to 2% slopes and moderate permeability. The Coland soil was deeper, of finer texture, and more poorly drained. Stream bank heights ranged from 1.8 to 2.3m. Stream channel width was not reported. The forested buffer consisted of 10m of trees adjacent to the channel, followed by 3.6m of shrubs, and 6.4m of native grasses and forbs. Fluid entrainment and freeze-thaw cycles were the erosional processes. Mean bank erosion rates for the one-year study period were: 387mm for row crops, 295mm for continuously grazed pasture, and 142mm for forested buffer. Erosion on forested meanders was 199mm less than the mean combined erosion rate on the crop and pasture meanders.

59. Zhang, X., Liu, X., Zhang, M., and Dahlgren, R.A. 2010. A review of vegetated buffers and a meta-analysis of their mitigation efficacy in reducing nonpoint source pollution. *Journal of Environmental Quality*. Vol. 39: 76-84.

    Value: 0 for sediment-buffer data analysis- meta-analysis, no useable data. Type: Meta-analysis. Location: N/A. The authors present a meta-analysis on the effectiveness of vegetated buffers at removing sediment, pesticides, nitrogen, and phosphorus from agricultural runoff. "The pollutant mitigation efficacy of vegetated buffers depends on three factors: (i) the physical properties of the buffer, such as width, slope, soil type, and vegetation cover; (ii) the properties of the pollutant in question, such as the sediment particle size, the form of N or P, or the biophysical properties of pesticides (e.g., water solubility and half-life); and (iii) the placement of the buffer, such as its proximity to pollutant sources (Norris, 1993)." "To obtain a systematic understanding of vegetated buffer mitigation efficacy, results from studies conducted under different experimental settings and site conditions should be compared with this in mind and synthesized to obtain general insights." "A total of 73 studies published in peer reviewed journals provided quantitative results on pollutant removal by vegetated buffers, of which 63 were original studies and 10 were literature reviews. These papers were carefully examined to record detailed information on author, year, location, buffer width, slope, area to source ratio, pollutant type, soil type, vegetation type, inflow pollutant mass and concentration, outflow pollutant mass and concentration, and percent of pollutants trapped by buffers." "Qualitatively, one would expect that the pollutant reduction would increase as width increases, at some point reaching a limit where further increasing the buffer width will not substantially increase the efficacy. This expectation was based on two reasons. First, while infiltration is taking place, pollution mass is lost to infiltration with each successive unit of buffer width. Second, the most easily trapped forms (e.g., large sediments) of pollutants will be easily trapped in the upper buffer while the smaller particles (or soluble forms) will be more difficult to trap. Therefore, a point will be reached where effectively all of the pollutant has been removed and additional buffer width will make little difference." The analysis was based on a (questionable) major assumption that the probability of pollutant removal remains constant per unit width of a buffer. Note: However, we know this not to be true since with sediment, for example, larger particles have a higher probability to settle out of suspension at the upper end of the buffer whereas smaller particles have a higher probability of settling out after a greater distance. It also does not account for field observations of increase in nutrients in runoff leaving a filter due to remobilization. In fact, other studies in this annotated bibliography have shown that mass removal is not constant per unit buffer. To examine the differences between and within study sites, a mixed effect model was first built with a random error associated with site. However, the parameter of site and its associated random error were found to be not significant with P values > 0.8 for all pollutant models. Therefore, site was removed from the models. Statistical diagnostics (including the normal probability plot of residuals, a plot of the residuals vs. the fitted values, and a histogram of the residuals) were used to determine whether the residuals met the statistical analysis assumptions (in particular the normality and constant variance assumptions)." The median removal efficiency across the studies reviewed was 88% for pesticides, 86% for sediment, 71.95 for P, and 68.3% for N. Sediment had the lowest standard deviation and range, N had the second highest standard deviation and range, P had the same standard deviation as N, but lower range, pesticides had the highest standard deviation. The parameter K in the models represents the maximum removal efficiency for buffers (an asymptote), basically the mean removal capacity among different buffers and experimental designs. K was 90.9% for sediment, 93.2% for pesticides, 92.0 for nitrogen, and 89.5% for P. The broken stick model for addressing slope effects on sediment removal suggests that sediment removal increases with slope to a maximum at 10% slope (95% CI 8.14 to 11.725), and then declines thereafter. The models suggest that grass or tree only buffers remove more sediment than mixed vegetation. For N and P, the models suggested that treed buffers remove more than grassed or mixed buffers. Soil drainage type was not significant and therefore excluded from the final model.

The model results indicate that sediment removal increases up to a distance of 20m and then does not significantly increase thereafter (max of 100% depending on slope and buffer vegetation type). Buffer width, vegetation type, and slope explained 65% of the variance in sediment removal efficacy (soil drainage was not significant factor for the model and buffer area ratio was not examined). The authors suggest that concentrated flow, which was not in the model, could account for a portion of the unexplained variability. For N and P, buffer width and vegetation type explained 50% and 48% of the variability, respectively. The model indicated that buffer widths beyond 20m did not appreciably increase N or P removal. "Denitrification rates are often greatest when the groundwater table is near the surface and when microbially labile carbon and nitrate N are in good supply (Bradley et al., 1992; DeSimone and Howes, 1996; Groffman et al., 2002). The presence of oxygen is often the controlling factor for nitrate removal since denitrification is an anaerobic process and oxygen inhibits the reaction." Findings from studies suggest that P removal can vary by grass species, but that trees generally remove more P. Soil drainage type was not significant in this meta-analysis although other studies found that it is a significant factor. The authors suspected that slope would have influenced the model for N and P, but this data was not uniformly available. The model for pesticide removal explained 60% of the variability and beyond 20m, the removal efficacy did not appreciably increase. The model was based on pesticides with soil and water partition coefficients between 100 and 1000, so it was thought that pesticides with higher coefficients (more strongly hydrophobic) would be removed at a greater rate than predicted since they would adsorb to sediment more readily. Vegetation type did not significantly affect the pesticide removal efficacy in the model; slope and soil data was unavailable but it was thought that it would affect the pesticide model since infiltration is an important removal process.

Table 38: Table from Zhang et al. (201) depicting predicted pollutant removal estimates

Table 4. Predicted pollutant removal efficacy.

		Predicted removal efficacy, %			
	Buffer width =	5 m	10 m	20 m	30 m
Sediment	(a) Slope = 5%; mixed grass and trees	67	76	78	78
	(b) Slope = 5%; grass/trees only	82	91	93	93
	(c) Slope = 10%; mixed grass and trees	77	86	88	88
	(d) Slope = 10%; grass/trees only	92	100†	100	100
	(e) Slope = 15%; mixed grass and trees	58	67	68	68
	(f) Slope = 15%; grass/trees only	73	81	83	83
Nitrogen	(a) Mixed grass and trees/grass only	49	71	91	98
	(b) Trees only	63	85	100	100
Phosphorus	(a) Mixed grass and trees/grass only	51	69	97	100
	(b) Trees only	80	98	100	100
Pesticide		62	83	92	93

† If predicted values exceed 100, the value of 100 was assigned instead.

Temperature (bolded citation means data extracted for analysis)

1. Albertson L.K., V. Ouellet, and M. D. Daniels. 2018. Impacts of stream riparian buffer land use on water temperature and food availability for fish. *Journal of Freshwater Ecology* 33:1:195-210.

   Value: 0- location/rigor/relevance. Type: Observational. Location: Pennsylvania. This study evaluated the influence of different stages of riparian forest restoration upon temperatures and brook trout aquatic food availability. Shade cover for the four sites was 0%, 10%, 50%, and 80%; corresponding buffer widths were 0m, 13-20m, 200-800m, and >800m. The more shade a site had; the lower its maximum water temperatures were. Evidence was found that temperature influence aquatic macroinvertebrate abundance and richness. This reference is not particularly useful.

2. Anbumozhi, V., Radhakrishnan, J., and Yamagi, E. 2005. Impact of riparian buffer zones on water quality and associated management considerations. *Ecological Engineering*. 24: 517-523.

   Value: 0- location/rigor/relevance. Type: observational; Location: Japan, Indonesia, India. The study evaluated water quality relative to riparian land use. Water quality was better where riparian buffers existed. This reference is not particularly useful.

3. Anderson, P.D., Larson, D.J. and Chan, S. 2007. Riparian buffer and density management influences on microclimate of young headwater forests of western Oregon. *Forest Science*. 53 (2).

   Value: 0 in terms of water temperature. Type: Experimental, control-treatment. Location: coast and west-Cascade ranges of Oregon. Anderson et al. (2007) evaluated the impact of variable density thinning and different no-thin buffer configurations on stream and riparian area microclimate of small largely intermittent (average 1.1 m (3.6 ft.) width and <10 cm (3.9 in.) depth) headwater streams in 30–70-year-old Douglas-fir stands in western Oregon. Stands were thinned to from 500-865 tph, (202-250 tpa) to 198 tph, (80 tpa) adjacent to uncut stream-side buffers ranging in width from <5 m (16.4 ft.) up to 150 m (492 ft.) width. The width of the unharvested buffer strips adjacent to the stream channel averaged 69 m (226.4 ft., one site potential tree height, B1), 22 m (54.3 ft, variable width, VB) or 9 m (29.5 ft., streamside retention, SR) width as measured from stream center. Microclimate gradients were strongest within 10 m (32.8 ft.) of stream center, and with thinning adjacent to 15m (49.2 ft.) or greater no-cut buffers, daily maximum air temperature above stream center was less than 1°C greater (statistically insignificant) and daily minimum relative humidity was less than 5% lower than for unthinned stands. Max air and soil temperatures increased with increasing distance from the stream. "Headwater riparian zones are characterized by microclimate gradients extending from the stream into the upslope forest." Cites Danehy and Kirpes (2000) as finding that humidity gradients on the more xeric eastern slope of the Cascades were changed the most within 5m of the stream, which was half that in this study. "We observed across these sites that percentage transmittances of indirect and direct light were strongly correlated in the buffer and in the upslope zones, but less so at stream center (data not shown). This suggests that while canopy cover may be a useful index of potential shading, aspect should also be accounted for, particularly under conditions where direct and indirect light are not strongly coupled." For headwaters streams: "Buffers of widths defined by the transition from riparian to upland vegetation or significant topographic slope breaks appear sufficient to mitigate the impacts of upslope thinning on the microclimate above the stream; there was no apparent increase in mitigation associated with wider buffers."

4. Bartholow, J.M. Estimating cumulative effects of clearcutting on stream temperatures. 2000. *Rivers*. Vol. 7, no. 4. Pp 284-297.

   Value/Relevance: 0, beyond general process associations between vegetation removal and water temperature changes, due to lack of real-word observations and linkage to riparian buffer characteristics. Type: Observational- modelling. Location: Oregon. This paper describes modelled temperature results in relation to landscape scale vegetation removal. The model results indicate that mean daily temps increase by 2.4°C and max temperatures increase by 3.6°C over a 10km reach. Shade reductions accounted for 1.48°C of the max temp increase, changes in width 1.35°C, and changes in air temp 0.61°C.

5. Barton, D.R., Taylor, W.D., and Biette, R.M. 1985. Dimensions of riparian buffer strips required to maintain trout habitat in southern Ontario streams. *North American Journal of Fisheries Mgmt.* 5: 364-378.

   Value- 0 for temperature-buffer analysis, 1 for hydro process info. Location: Southern Ontario. The authors examined the relationships between environmental attributes and riparian land use at 40 sites on 38 streams, which included both "cold" and "warm water" streams. Channel widths ranged from 0.1 to 14.5 m. The percentage of upstream watershed-scale riparian forest ranged from 6.3 to 95.8%. Channel segments in the watershed networks were classified as riparian zones consisting of forest, bush, bog, pond, grass, pasture, or cultivation. Temperature, suspended solids, and discharge were measured. Water temperature, fine particle suspended solids, and discharge variability were inversely correlated to the proportion of upstream riparian forest. Water temperature was found to have the greatest bearing on the presence or absence of trout. All but one stream with a trimean weekly maximum temperatures below 22°C had trout and all streams exceeding this value were marginal or without trout. Fifty-six percent of the variation in trimean weekly maximum temperature was explained by the proportion of forested riparian zone within 2.5km upstream; regression analysis indicated that 80% of the streambank within 2.5km upstream needed to be forested in order to prevent trimean weekly maximum temperatures from exceeding 22°C. The authors used the data to estimate the length and width of buffers needed to prevent weekly maximum temperatures from becoming too warm for brook, brown, and rainbow trout. The authors suggested that a 10m wide forested buffer extending 3km upstream of a site would be sufficient to keep the weekly maximum temperature below 22°C; however, they acknowledge that this is an extrapolation from their data and stated that their equation resulted in an unrealistic linear relationship between temperatures and buffer width, when there should be asymptotes for temperature at both extremes. Buffer widths were not directed measured, but were derived from the following equation: average width = riparian area/ (2 x stream length)

Stream sites had ≤30mg/L of fine particulate matter (FPM) concentrations when the riparian forest cover extended for at least 0.5km upstream of the monitoring site; grazing appeared to be related to FPM- 9 of the 15 sites with highest turbidity had pasture immediately upstream. All trout streams had low amounts of FPM, but many non-trout streams did as well. Coarse particulate matter concentrations did not differ between trout and non-trout streams.

Equation 3: From Barton et al. (1985)

In statistics the **trimean (TM)**, or **Tukey's trimean**, is a measure of a probability distribution's location defined as a weighted average of the distribution's median and its two quartiles:

$$TM = \frac{Q_1 + 2Q_2 + Q_3}{4}$$

6. Benedict, C. and Shaw, J. 2012. Agricultural Waterway Buffer Study. Unpublished.

   Value: 0 for buffer-temperature data analysis. Location: western WA. Type: Observational. This study examined effective shade and air temperatures associated with buffers on agricultural streams. Buffer widths were 0, 5, 15, 35, and 180ft wide. Effective shade was measured at the stream centerline. Summertime air temperatures were measured outside of the buffer, within the buffer and over the stream channels. The authors conclude that the 5 and 15ft buffers are as effective as 35 and 180ft buffers at reducing air temperature and creating effective shade. However, there are a number of serious problems with this study that completely invalidate these conclusions, as the following examples illustrate. First, stream size was not controlled for, and channel width increased as buffer width increased. Second, there was no replication of sites. Third, there was poor replication of vegetation transects and transects appear to be of different lengths for the different buffer widths. Fourth, it appears that the authors made direct comparisons of maximum air temperatures within buffers among sites; this is not appropriate because the outside of buffer temperature was different at every site. For example, the air temperature both in the 35ft buffer and above the stream is lower than for the 15ft buffer even though the temperature outside the 35ft buffer is greater. Fifth, averaging air temperatures over the entire summer is not appropriate because there is not an equal probability of differences between air temps inside vs. outside the buffers. For example, the temperature graphs show that on hotter days there is a greater temperature difference between outside and inside the buffer than there is on cooler days. Therefore, averaging over the summer masks important temperature differences on hotter days.

7. Beschta, Robert L. and R. Lynn Taylor. 1988. Stream temperature increases and land use in a forested Oregon watershed. *Water Resources Bulletin*. Volume 24:1:19-25.

   Value: 0, due to lack of specific linkage to effectiveness of riparian buffers (besides indicating that watershed scale vegetation mgmt. causes long-term changes in water temperature regimes0. Type: Observational. Location: Oregon. Beschta et al. (1988) examined 30 years of stream temperature, flow, and harvest data for a 325 km^2 watershed in the Cascade Mountains of western Oregon from 1955 to 1984. Average daily maximum and minimum stream temperatures, calculated from the 10 warmest days of each year, had risen 6C and 2C respectively. Regression analysis indicated a highly significant relationship between a cumulative index of forest harvesting and maximum stream temperatures. Salmon creek is a 4^{th} order watershed ranging from 400 to 2,200 m in elevation. Temperature increases tended to follow large peak flows and remained high with the authors inferring the temperature increase may be in response to mass soil failures and the resulting channel change associated with the high flows. *Notes: The study is gross-scale long term pre- versus post-harvest cumulative effects style study for a single watershed. Temperature data collected at one or both of the two fish hatcheries located at the mouth for most (a small time without data existed) of the time period.*

8. Bishaw, B., Emmingham, W., and Rogers, W. 2002. Riparian forest buffers on agricultural lands in the Oregon coast range: Beaver creek riparian project as a case study.

   Value: 0 for temperature-buffer data analysis, 1 for buffer-shading info. Location: western Oregon. Type: Observational/experimental control-treatment. This is a case study looking at shade cast by fast growing alders in narrow buffers during the first 5 years after planting. Channel width was 2.4 to 3.7m and down cut 3.1 to 4.6m into alluvial soils. A 3.1m wide grass strip was left between the channel and the tree plantings. 1, 3, or 6 rows of alders were planted, each row being 1.8m apart. A LI-COR LAI-2000 plant canopy analyzer was used to measure direct and diffuse light. After 5 years, Average tree height was 5.6, 6.1 and 7.4m for the 1, 3, and 6-row treatments, respectively. Beavers, cows, deer, and small rodents caused substantial damage and mortality to unprotect seedlings. Weed control fabric provided one year of control, after which invasions of weeds occurred (reed canary grass and Himalayan blackberry). Weed abundance and vigor started decreasing as shading from the alder increased. The 1 row treatment produced 22% shade at the streambank, the 3-row treatment produced 25%, and the 6-row treatment produced 34%. The overall cost (circa 2002) for fencing, site prep, weed control, trees, planting, tree protection, and maintenance for all treatments combined was about $4300 for 1100ft of stream; a 6-row system for 1100 ft of stream was estimated to cost about $5400, and less so if a landowner performed the labor themselves.

9. **Bisson, P.A., S.M. Claeson, S.M. Wondzell, A.D. Foster, A. Steel. 2013. Evaluating headwater stream buffers: lessons learned from watershed-scale experiments in southwest Washington. In: Anderson, P.D, K.L. Ronnenberg, eds. *Density Management in the 21st Century: West Side Story*. Gen. Tech. Rep. PNW-GTR-880. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 169-188.**

   Value: 2, due to rigor, location, buffer relevance, but only preliminary temperature data. Type: Experimental, BACI design. Location WA. Bisson et al. (2013) presented preliminary results from an experiment in which alternative forest buffer treatments were applied to clusters of watersheds in southwest Washington using a Before-After-Control-Impact (BACI) design. The treatments occurred on small (~2-9 ha) fishless headwater catchments, and compared continuous fixed-width buffered, discontinuous patch-buffered, and unbuffered streams to an adjacent unlogged reference catchment. Eight treatment clusters were monitored from 2001 to 2006; four were located in the Black Hills and four in the Willapa Hills of the Coast Range. Overall, results suggested that relatively small but measurable changes in ecological condition occurred in most catchments where logging occurred. Changes were most apparent in streams having no buffers. In catchments with no buffers, summer water temperature increases were largest, organic matter inputs declined, and drifting invertebrates increased or decreased depending on their trophic guild. Changes in catchments with discontinuous patch buffers were often complex and generally less detectable, and streams with continuous fixed-width buffers tended to exhibit the fewest changes in invertebrate communities and organic matter inputs relative to reference sites. Treatment objectives were 15-20 m continuous fixed-width buffers, discontinuous patch buffers (per WA state FP), and no buffers, with adjacent reference sites of mature second-growth forest. In first post-treatment year: fixed width buffers had a mean temp increase of 1.1°C, patch buffers had mean increase of 0.6°C, no buffer treatments had mean increase of 1.5°C. Channels occasionally became intermittent during the dry season and surface connections with the parent stream were often disrupted. Found that in addition to the presence or absence of forest canopy, the length of exposed stream channel and the amount of hyporheic water exchange are important factors regulating headwater stream temperatures.

10. **Bladon, K.D.; C. Segura; N.A. Cook; S. Bywater-Reyes. 2018. A multicatchment analysis of headwater and downstream temperature effects from contemporary forest harvesting. Hydrological Processes 1-12.**

Value: 2 for temperature-buffer data analysis, 1 for watershed process info. Bladon et al. (2018) used temperature data from 3 paired watershed studies (29 sites) in western Oregon to examine headwater and downstream temperature effects associated with contemporary forest harvesting. Authors evaluated the effects of forest management practices on stream temperature in small, headwater streams, and whether warmer stream water after harvesting was detectable in downstream fish bearing waters. They also examined the relative role of geology in influencing differential stream temperature responses. The median July through September 7-day moving average of daily maximum stream temperature ($T_{7DAYMAX}$) was greater during the post-harvest period relative to the pre-harvest period at 7 of the 8 harvested upstream study sites. The largest increases occurred within the Trask paired watershed study where the median $T_{7DAYMAX}$ had warmed from 2.4 to 3.9 C at the three study sites (mean of observations outside 95% CL was 1.8 -3.3 for the 7 sites where temperature was elevated). However, across their study, the authors found evidence of little downstream warming related to the harvesting activity; noting the $T_{7DAYMAX}$ cooled rapidly as stream water flowed into forested reaches ~370 -1,420 m (1,214 – 4,659 ft) downstream of harvested areas. The authors also found the magnitude of effects of contemporary forest management on stream temperature increased with the proportion of catchment underlain by more resistant lithology at both the headwater and downstream sites, potentially reducing groundwater sources of cooling. (*Study not designed to account for climatic changes*). Interestingly however, the authors found the temperature responses in the headwaters was not related to the percent of catchment harvested but only to the underling lithology, but at the downstream sites there was strong evidence of the stream temperature response to harvesting being influenced by the interaction between percent of catchment harvested and the underlying lithology.

11. **Bladon, K.D., Cook, N.A., Light, J.T., and C. Sequra. 2016. A catchment-scale assessment of stream temperature response to forest harvesting in the Oregon Coast Range. *Forest Ecology and Management* 379:153-164.**

Value: 3 due to location, rigor, buffer relevance. Type: Experimental, BACI design. Location: Oregon. This is a study of temperature responses to riparian forest removal. The study watersheds are headwaters catchments close to the Pacific Ocean with sedimentary geology, terrain that is highly dissected and with steep hill/mountain slopes. The treatment watershed area is 94 hectares with a mean wetted width of approx. 1 meter, a steep gradient, and north-south orientation. Summer baseflow was ~2.4 times greater in the post-harvest period. Slow, deep flowpaths provide groundwater to the streams due to the underlying geology. “There was no evidence that the (a) 7-day moving mean of daily maximum (T7DAYMAX) stream temperature, (b) mean daily stream temperature, or (c) diel stream temperature changed in the study stream reaches following contemporary forest harvesting practices. The only parameter of interest that changed after forest harvesting was the T7DAYMAX when analyses were constrained to the Oregon regulatory period of July 15 to August 15 and all sites in each catchment were grouped together—in this case stream temperature increased 0.6 ± 0.2 ^oC ($p = 0.002$).” Note: Under the Private Forest regulations, the riparian management areas (RMAs) are 15 m and 21 m (49.2 and 68.9 ft.)

wide around small and medium fish-bearing streams, respectively. Both small and medium streams have a 6 m (19.7 ft.) no-cut zone immediately adjacent to the stream. Harvesting is allowed in the remaining RMA to a minimum basal area of 3.7 m^2/ha (small streams) and 11.1 m^2/ha (medium streams) (16.12 and 48.35 ft^2/ac, respectively). The study shows that compared to historic harvesting activities in the same watersheds (ca 1960s), current buffer management practices protect much better against temperature changes.

12. Blann, K., Nerbonne, J.F., and Vondracek, B. 2002. Relationship of riparian buffer type to water temperature in the Driftless Area ecoregion of Minnesota. *North American Journal of Fisheries Mgmt.* 22: 441-451.

    Value: 0 due to location, lack of riparian buffer specifics. Type: Observational. Location: Minnesota. This study used stream temperature measurements and modelling to simulate temperatures under differing shade and channel morphology attributes. Study watershed is 21,000 hectares. Agriculture is 62% of the watershed, deciduous forest mainly on steeper valley side slopes accounts for 25%. Mean width of the 11km study reach was 6 -7m. Buffer types include grazed grass, forest buffers, and successional non-grazed areas with grass, shrubs, forbs. Buffer widths not provided. Shading was 49.2% in forested buffer areas, 25.0% in successional buffer areas, 15.3% in grazed areas. Temperature was weakly correlated with shade. The model indicated that achieving 50% shade along the reach would reduce weekly mean temperatures by 0.6 to 0.9°C. "Although our models indicated that wooded buffers provide the most shade, successional buffers with abundant grass may also provide sufficient shade to mediate temperatures along low-order streams (<2.5 m wide) or streams with low width: depth ratios."

13. Boggs, J., Sun, G., and McNulty, S. 2016. Effects of timber harvest on water quantity and quality in small watersheds in the Piedmont of North Carolina. *Journal of Forestry*. 114:1:27-40.

    Value: 0 for temperature-buffer data analysis. Boggs et al. (2016) found significant increases in stream flow following clear-cut harvesting associated with 15.2 m non-merchantable tree buffers (27% and 48% of basal area removed; consisting of high value merchantable trees). Authors noted the temperatures of the streams spiked after harvest but gave no values (referring to a supplemental figure S6a and b not in the report but available online where it showed no values but only a figure). Nitrogen export increased for the first two years post-harvest and then declined. Total suspended sediment also increased, likely due to the increase in flow. One site experienced 36% blowdown of stream bank trees post-harvest.

14. Bourque, C.P.-A., and J.H. Pomeroy. 2001. Effects of forest harvesting on summer stream temperatures in New Brunswick, Canada: an inter-catchment, multiple-year comparison. *Hydrology and Earth Systems Sciences*. 5:4:599-613.

    Value: 0 for buffer-temperature data analysis, 1 for hydrologic process info. Bourque and Pomeroy (2001) presented pre- and post-harvest comparisons of stream temperatures collected in five neighboring streams (sub-catchments) in New Brunswick, Canada, over a period of five years. The purpose was to determine if land cover changes from clear cutting in areas outside forest buffer (applied to streams >0.5 m wide) might contribute to an increase in summer mean stream temperatures in buffered streams down slope by infusion of warmed surface and sub-surface water into the streams. Mean temperatures down slope of harvest areas increased by 0.3 to 0.7°C. The greatest increase was associated with the catchment which had the greatest amount of its area harvested (16.8%) and the highest calculated potential solar loading. In general, increased mean stream temperature coincided with forest harvesting activities outside forest buffers, where conditions promoting stream warming were greatest. Near perfect linear relationship between stream temperature change and modeled insolation levels. No clear relationship was found between forest buffer strip width used in the study (ranging from 30-60 m) and the level of stream warming observed. Study area consisted of flat to rolling terrain with elevations from 25 m to 230 m. Soils well to imperfectly drained on slopes from 0 to 45°. Forest a mixture of shade intolerant hardwood and softwood species.

15. **Brazier, J.R. and Brown, G.W. 1973. Buffer strips for stream temperature control. Paper 865. April 1973. Forest Research Laboratory. School of Forestry. Oregon State University. Corvallis, OR.**

    Value: 0 for buffer-temperature data analysis, 2 for shading info Brazier and Brown (1973) using data from stands along nine steep v-shaped small mountain streams in western Oregon concluded that the maximum angular canopy density was reached within 80 feet.

16. **Brown, G.W. and Krygier, J.T. 1970. Effects of clear-cutting on stream temperature. *Water Resources Research*. Vol. 6. No. 4.**

    Value: 0 for buffer-temperature data analysis, 2 for shading info. Brown and Krygier (1970) found that the clear cut harvesting, stream clearing, and burning of one small watershed (Needle Branch) in the Alsea drainage of western Oregon increased average monthly maximum temperatures by 14°F (7.8^{o}C) annual maximum temperatures from 13.9 to 29.4°C, but patch cutting 25% of a neighboring watershed with 100 ft buffers along perennial streams was reported to not be associated with any significant increase in the mean monthly maximum temperature of the mainstem downstream.

17. Broderson, J.M. 1973. Sizing buffer strips to maintain water quality. M.S. thesis. University of Washington, Seattle, Washington.

    Value: 0 for buffer-temperature data analysis, 2 for shading info. For a stream 100 feet wide, "an old growth stands 200 feet tall on flat topography…" at a latitude of 45oN "…would only be effective in shading a stream in mid-July in a buffer strip with a maximum width of 89 feet." "Widths wider than this would be unnecessary, and shade provided would not cover the stream."

    As streams become wider, the effectiveness of shading by trees decreases. A stand 200 ft tall at 45^{o}N on flat topography provides shade 89 ft from the trunk in mid-July. In this scenario, trees more than 89 ft from the stream would not be providing any shade to the channel. On a 60% slope the effective shade increases to 120 ft. A stand 250 ft tall on 60%

slope has effective shade width of 195 ft. Therefore, recommends a maximum buffer width of 200 ft. States that a width of 50ft has been found to provide 85% of maximum shade for small streams. Recommends a minimum of 50ft for sediment control with a max of 200ft on slopes of 50% and greater but increased to encompass highly unstable and poorly drained areas. Says streams in V-notched valleys should have buffers extended 25ft beyond the change in slope. On highly erosive or unstable areas, the author recommends 200ft buffer to inhibit excessive windthrow.

18. Brown, G.W. and Brazier, J.R. 1972. Controlling thermal pollution in small streams. *Environmental Protection Technology Series.* EPA-R2-72-083. Office of Research and Monitoring. U.S. Environmental Protection Agency. Washington, D.C.

    Value: 0 for temperature-buffer data analysis, 1 for general process info. Type: observational. Location: western Oregon. This publication addresses the same data as presented in Brazier and Brown (1973). The authors assert that angular canopy density is the only parameter that is "strongly correlated with stream temperature control." The authors indicate that the maximum angular canopy density for the Oregon study sites is reached estimated to be reached within a buffer width of 80ft. They also indicate that due to the shape of the curve, 90% of maximum shade is attained within a buffer of 55ft. It is recommended that in order to protect streams temperatures, angular canopy density should be maintained at 80% where stream size and vegetation permit and should not be reduced below the "natural condition" where pre-vegetation removal is less than 80%.

19. Burton, T.M., and G.E. Likens. 1973. The effect of strip-cutting on-stream temperatures in the Hubbard Brook experimental forest, New Hampshire. *BioScience* 23:7:433-435.

    Value: 0 for temperature-buffer data analysis, 1 for hydro process info. Burton and Likens (1973) found that temperature in a small stream could rise by 4-5ºC as it passed through 25 m (82 ft) wide clearcuts during the month of July in a hardwood forest in New Hampshire. Where a 10 m (32.8 ft) buffer was employed, these extreme spikes were not observed. Some cooling occurred in the uncut strips downstream of the cut strips.

20. **Cole, L, and M. Newton. 2013. Influence of streamside buffers on stream temperature response following clear-cut harvesting in western Oregon. *Canadian Journal of Forest Research*. 43(11): 993-1005.**

    Value: 1 for buffer-temperature data analysis due to incomparable study design, otherwise value is a 2 for temperature effects data/information. Cole and Newton (2013) examined three types of buffer retention treatments on four small streams in Western Oregon. The treatments were all tested in series along each of the four treatment streams creating seven contiguous units of approximately equal length – 257 to 371 feet. Buffer type 1 (no tree buffer) was all merchantable trees removed to the bank and chemical treatment beyond 3 m (9.8 ft). Buffer type two (BMP buffer) was two sided 15 and 30 m (49 and 98 ft.) buffers that conformed to the Oregon forestry rules. Buffer type three (Partial buffer) was all residual trees and shrubs within 12 m (39.4 ft.) of the bank south (120º to 270° azimuth) of open water. Trends for daily maximum and mean stream temperature significantly increased after harvest in No Tree buffer units (up to 3.8ºC). Partial Buffers led to slight (<2 °C) or no increased warming (two of four were significantly positive). BMP Buffer units led to significantly increased warming, slight, or no increased warming (with no warming associated with the one 30 m BMP buffer tested, and three of the four 15 m buffers warming and one increasing the daily maximum temperature of 5.3°C. Temperature responses in uncut units appeared to be linked to responses in upstream harvested units. In many instances, when harvested units exhibited significantly higher post-harvest trends, lower trends were observed in the uncut units downstream (evidence of what should have been an expected study design bias).

21. Cristea, N. and Janisch, J. 2007. Modeling the effects of riparian buffer width on effective shade and stream temperature. *Publication No. 07-03-028*. Washington Department of Ecology, Olympia, Washington.

    Value: 0 for buffer-temperature data analysis, 2 for shading info. Cristea and Janisch (2007) combined a shade model with a water temperature model to evaluate the effects of converting hardwood-dominated stands to coniferous-dominated stands on western Washington streams under three buffer width scenarios. The authors estimated that temperatures of the 10-ft wide stream was more sensitive to buffer width than the 20-foot wide stream. In contrast, once heated, all buffer scenarios cooled the 20-foot-wide stream less effectively. Overall, N-S oriented channels over the width range examined receive the least shade; however, channel width and orientation interact to determine effective shade. For channels less than 10 meters wide, the orientation effect was small (about 5% or less). Narrow N-S channels received slightly less shade than other orientations. In contrast, effective shade declined by 25% as channel width increased from 0-10 m, suggesting width exerts greater control on channel shade than orientation. For channel widths greater than 10 m, however, effective shade for E-W oriented channels declined sharply relative to other orientations. Streams less than 3 m wide receive the maximum daily average effective shade; streams 16-18 m wide receive about one-half this value. Prior to harvest, streams 10-20 feet wide receive about 85-95% of interior forest shade levels. Narrow streams would receive similar or greater amounts of shade. Small streams therefore are potentially very sensitive to riparian canopy removal (due to less thermal inertia). Authors found that wind speed, channel roughness, and increasing gradient had generally negligible effect on warming. Model simulations indicate as flow decreased; downstream heating increased. Stream temperature protection generally increased as buffer width and density increased. Riparian vegetation as short as approx. 1.4 times bankfull width can provide about 75% of the shade provided by taller vegetation of similar canopy density. Below this height, however shading effectiveness begins to decrease regardless of canopy density. Small streams are most sensitive to riparian vegetation removal. Streams with low velocities increase travel time and favor downstream heating.

22. Cristea, Nicoleta C. and Stephen J. Burges. 2010. An assessment of the current and future thermal regimes of three streams located in the Wenatchee River basin, Washington State: some implications for regional river basin systems. *Climatic Change*. 102: 493

    Value: 0 for buffer-temperature data analysis, 2 for shading info. Cristea and Burges (2010) … "We examine summer temperature patterns in the Wenatchee River and two of its major tributaries Icicle and Nason Creeks, located in the Pacific Northwest region of the United States. Through model simulations we evaluate the cooling effects of mature riparian vegetation corridors along the streams and potential increases due to global warming for the 2020s–2080s time horizons. Site potential shade influences are smaller in the mainstream due to its relatively large size and reduced canopy density in the lower reaches, proving a modest reduction of about 0.3°C of the stream length average daily maximum temperature, compared with 1.5°C and 2.8°C in Icicle and Nason Creeks. Assuming no changes in riparian vegetation shade, stream length-average daily maximum temperature could increase in the Wenatchee River from 1–1.2°C by the 2020s to 2°C in the 2040s and 2.5–3.6°C in the 2080s, reaching 27–30°C in the warmest reaches. The cooling effects from the site potential riparian vegetation are likely to be offset by the climate change effects in the Wenatchee River by the 2020s. Buffers of mature riparian vegetation along the banks of the tributaries could prevent additional water temperature increases associated with climate change. By the end of the century, assuming site potential shade, the tributaries could have a thermal condition similar to today's condition which has less shade. In the absence of riparian vegetation restoration, at typical summer low flows, stream length average daily mean temperatures could reach about 16.4–17°C by the 2040s with stream length average daily maxima around 19.5–20.6°C, values that can impair or eliminate salmonid rearing and spawning. Modeled increases in stream temperature due to global warming are determined primarily by the projected reductions in summer stream flows, and to a lesser extent by the increases in air temperature. The findings emphasize the importance of riparian vegetation restoration along the smaller tributaries, to prevent future temperature increases and preserve aquatic habitat." The authors conduct a sensitivity analysis to examine the relative effect on water temperature of the increase in air temperature versus the decrease in water flows associated with climate change. They illustrate in Table 4 that the reduction in flow has a proportionately greater effect on maximum daily water temperatures under the climate scenarios examined (air-change-only resulted in maximum water temperature increases from 0.18-0.62C, while stream-flow-only resulted in changes of 0.66-2.35C in the Wenatchee River (at estimated site potential shade).

23. **Cupp, C.E. and T.J. Lofgren. 2014. Effectiveness of riparian management zone prescriptions in protecting and maintaining shade and water temperature in forested streams of Eastern Washington. *Cooperative Monitoring Evaluation and Research Report CMER 02-212*. Washington State Forest Practices Adaptive Management Program. Washington Department of Natural Resources, Olympia, WA.**

    Value: 3 for buffer-temperature data analysis. Cupp and Lofgren (2014) used a replicated BACI study to test effectiveness of two eastern Washington riparian prescriptions for protection of shade and stream temperature at 30 study sites in eastern Washington. Study sites were 1,000 ft. test reaches on small streams in mixed fir zone mid-successional forests. These sites were examined for at least two years before and at least two years after riparian timber harvest. Eastern Washington riparian timber harvest prescriptions differ depending on whether or not a harvest unit is within a Bull Trout Habitat Overlay (BTO). When a harvest unit is located within the BTO, "all available shade" (ASR) must be retained within

75 feet of the stream. When a harvest unit is located outside the BTO, prescriptions fall under the standard rule (SR), which may allow for harvest within 75 feet or 100 feet (small versus large streams) down to 70, 90, or 110 ft2 basal area and a minimum 50 TPA depending on elevation and canopy cover existing prior to harvest (Actual average TPA retained was 109, and average basal area retained was 122 ft2). As operationally applied the ASR limited the mean decrease in shade to 1%, with a maximum decrease of 4%. Under the SR, shade was reduced by a mean of 4%, with a maximum reduction of 10%. Stream temperature response was evaluated by fitting pre-harvest calibration relationships between upstream and downstream monitoring stations. Mean daily maximum stream temperature increased 0.16°C in the SR harvest reaches, whereas stream temperatures in both the ASR sites and in the no-harvest reference reaches increased on average by 0.02°C. (There was a Median 5% (0-27%) reduction in BA/acre and median 13% (2-19%) reduction of TPA within 75 ft of the stream in the ASR. Median 26% (5-56%) reduction in BA/acre and median 39% (10-62%) reduction of TPA within 75 ft of the stream in the SR.)

24. Curry, R.A., D.A Scruton, and K.D. Clarke. 2002. The thermal regimes of brook trout incubation habitats and evidence of changes during forestry operations. Canadian J. For. Res. 32:1200-1207.

    Value: 0 for temperature-buffer data analysis due to problems noted below. Curry et al. 2002 examined surface water temperatures and interstitial water temperatures within brook trout redds at three sites in Western Newfoundland, Canada. Two of three sites were harvested and the third left untreated as a control. Treatments consisted of a 20-acre clearcut harvest, and a 74-acre thinning harvest that included a 20-m buffer strip adjacent to the stream. ANOVA and Tukey's pairwise comparisons were used to identify mean temperature changes with significance > 0.05. Authors found that surface water temperatures were surrogates for redd temperatures in the down-welling redds characteristic of these streams. Temperature was elevated and more variable in redds during harvesting when no riparian buffer strip was present and to a lesser degree when a 20 m buffer strip was present in at least the first 2 years post-harvest. By the third-year temperatures appeared to have returned to pre-harvest regimes. (*Problems: Environmental setting described does not match typical situations in the PNW. Study results were highly variable between years and between all three sites with no clear trends. The size of the harvest areas, and the streams were supplied from upland ponds which would have influenced the ability to detect any warming downstream (generally they would be expected to follow a cooling trend as they enter a buffered forest) were highly variable and the simple statistical method may not have been suitable to separate out natural from anthropogenic effects. Use of mean temperatures may have masked changes in daily maximum temperatures. No canopy cover information was provided nor description of harvest techniques – were only commercial trees taken, was more than 20 m left along part of the streams even if the prescription was 20 m?*)

25. **De Groot, J.D., S.G. Hinch, and J.S. Richardson. 2007. Effects of logging second-growth forests on headwater populations of Coastal Cutthroat Trout: A 6-Year, Multistream, Before-and-After Field Experiment. Trans. Amer. Fish. Soc. 136:211-226.**

Value: 3 for data analysis. De Groot et al. (2007) used a BACI design to examine the effect of clear cut logging of two streams in the coastal western Hemlock zone of British Columbia Canada, and found that carefully logging the merchantable trees (over story with minimal disturbance to brush) resulted in a mean daily maximum (MDMT) and mean daily average (MDAT) temperatures increasing of 1°C to 2°C over the summer season (60 days) in the two treatment sites respectively having treatment segments of approximately 381m and 509m in length. No change in abundance or body condition of resident cutthroat trout was detected during the 4 years post-harvest monitoring. One of the treatments was to be a 10 m buffer, but essentially all of the trees blew down in the first-year post-harvest (loss of approximately 40%), so it was treated as a replicate of the clear-cut treatment by the authors.

26. Dignan, P. and Bren, L. 2003. Modelling light penetration edge effects for stream buffer design in mountain ash forest in southeastern Australia. *Forest Ecology and Management*. 179. Pp95-106.

    Value: 0 for temp/buffer data analysis, 1 for shading info. Location: Australia. Dignan and Bren (2003) examined the light environment of a wet sclerophyll forest of south-east Australia before and after clearcut harvesting. The authors used hemispherical photography taken at 1, 3.4, and 6.6 m heights at 10 m intervals along 100 m transects to describe the spatial variation in forest understory light along a gradient from streamside vegetation to the upslope eucalypt-dominated forest. Post logging photographs taken at the same points were used to model the light penetration edge effects. The natural understory light environment was influenced by proximity to the streamline to about 50 m upslope, with light penetration increasing at a relative rate of about 9% for every 10 m from the streamline. Light penetration was influenced by topography and vegetation characteristics. Creation of a sharp edge by logging of the upslope forest resulted in major changes in light penetration.

27. Fleuret J.M. 2006. Examining effectiveness of Oregon's forest practices rules for maintaining warm-season maximum stream temperature patterns in the Oregon Coast Range. Master of Science. May 12, 2006. Oregon State University, School of Forest Engineering. Corvallis, Oregon.

    Value: 2 or 3 for buffer-temperature data analysis, 2 for shading info. Fleuret (2006) analyzed data from twenty-two headwater streams, on either private- or state-owned forest lands in the Oregon Coast Range that encompassed a range of RMA widths and harvest prescriptions to evaluate the effectiveness of RMAs on stream temperature. A BACI Intervention design was used, and each stream had an upstream control and a downstream treatment reach. Temperature was monitored from June to September for four years. All but one stream had at least two years of pre-treatment data and one year of post-harvest temperature data. Warm-season maximum temperature patterns were not maintained when mean values in treatment reaches across all study streams were considered. Difference in temperature gradients between control and treatment reaches averaged 0.6C. This indicates that more warming and less cooling occurred in treatment reaches than occurred in control reaches, suggesting the current RMAs for small and medium fish-bearing streams of the Oregon Coast Range were not effective for maintenance of warm-season maximum temperature patterns. (Notes: This appears to be part of the same data set used by Groom and others, so better to rely on those published works).

28. Gravelle, J.A. and T.E. Link. 2007. Influence of timber harvesting on headwater peak stream temperatures in a Northern Idaho watershed. Forest Science. April 2007 53:2:189-205.

    Value: 0 for temperature/buffer data analysis because buffer/temperature response information not reported in a useable format. Location: northern Idaho. The authors concluded that despite estimated increase of up to 3.6C in the directly impacted non-fish bearing reaches there was no significant increase in water temperature maxima at the downstream fish-bearing sites. They also note that potential shade value of understory vegetation in harvested areas should not be overlooked. [Very messy study design]

29. Groom, J.D., Madsen, L.J., Jones, J.E., and Giovanini, J.N. 2018. Informing changes to riparian forestry rules with a Bayesian hierarchical model. *Forest Ecology and Management* 419-420:17-30.

    Value: 0 for buffer-temperature data analysis, modelled results. Groom et al. (2018) used previously collected field data from Oregon streams to develop a statistical model to simulate prescribed harvests. The authors combined two earlier stream temperature and shade models from Groom et al (2011b) into a Bayesian hierarchical model. The predictive model produced parameter estimates and temperature change metrics that aligned with the previous findings. The model predicted that harvest according to a full implementation of the state forest harvest plan would on average result in a 0.19C increase, while the model predicted that a similarly scaled harvest to current private forest regulation specifications would lead to an average increase of 1.45°C**.** Further simulations suggested that employing a no-cut slope-distance riparian zone of 27.4 m (89.9 ft) would result in average warming below 0.3°C of unharvested conditions, with the range of distances that contain 0.3°C in their 95% credible interval ranging from 22.8 m (74.8 ft) to 33.5 m (114.8 ft).

30. Groom, J.D., Dent, L., and Madsen, L.J. 2011a. Stream temperature change detection for state and private forests in the Oregon Coast Range. *Water Resour. Res*., 47.

    Value: 0 for temperature/buffer data analysis because temperature *response* not reported for the differing buffer treatments; value is 2 for general effects of vegetation removal on stream temperatures. Location: western Oregon. Groom et al. (2011a) evaluated temperature responses to timber harvest at 33 privately owned and state forest sites against Oregon's water quality temperature antidegradation standard. The harvest rules for privately owned lands exhibited a 40% probability of exceedance, while the more stringent state forest riparian standards did not exhibit exceedance rates that differed from pre-harvest, controls. Forest Practices on Private Sites require RMAs of 15 m (49.2 ft.) and 21 m (68.9 ft.) wide around small and medium fish-bearing streams, respectively. No harvest is permitted within 6 m (19.7 ft.) immediately adjacent to the stream and harvesting is in the remaining RMA is allowed to a minimum basal area of 10.0 (small streams) and 22.9 (medium streams) m2/ha. Forest Practices on State Sites require RMAs of 52 m (170.6 ft) wide for all fish-bearing streams, with an 8 m (26.2 ft.) no cut zone. Limited harvest is allowed within 30 m (98.4 ft.) of the stream only when needed to create mature forest conditions. Harvest operations in this zone must maintain 124 trees per hectare (50 TPA) and a 25% Stand Density Index. Additional retentions of 25-111 conifer trees and snags/hectare (10-45 TPA) are required between 30 and 52m. The authors note that riparian buffers retained on private lands were larger than required by rule; with a mean of 31.0 m (101.7 ft.) and a 95% CI of 26.7 m and 35.3 m.

31. **Groom, J. D., Dent, L., Madsen, L.J., and Fleuret, J. 2011b. Response of western Oregon (USA) stream temperatures to contemporary forest management. *Forest Ecology and Management* 262 (2011) 1618-1629.**

    Value: 0 because incomparable results: temperature data collected year-round, so the effect reported is not just change in max summer temps. Location: western Oregon. Groom et al. (2011b) used a replicated BACI study design to examine the effectiveness of two forest harvest prescriptions on 33 sites in the coastal Douglass fir forests of western Oregon. Forest Practices on Private Sites require RMAs of 15 m (49.2 ft.) and 21 m (68.9 ft.) wide around small and medium fish-bearing streams, respectively. No harvest is permitted within 6 m (19.7 ft.) immediately adjacent to the stream and harvesting is in the remaining RMA is allowed to a minimum basal area of 10.0 (small streams) and 22.9 (medium streams) m2/ha. Forest Practices on State Sites require RMAs of 52 m (170.6 ft) wide for all fish-bearing streams, with an 8 m (26.2 ft.) no cut zone. Limited harvest is allowed within 30 m (98.4 ft.) of the stream only when needed to create mature forest conditions. Harvest operations in this zone must maintain 124 trees per hectare (50 TPA) and a 25% Stand Density Index. Additional retentions of 25-111 conifer trees and snags/hectare (10-45 TPA) are required between 30 and 52m. The authors note that riparian buffers retained on private lands were larger than required by rule; with a mean of 31.0 m (101.7 ft.) and a 95% CI of 26.7 m and 35.3 m. Overall, they found no change in the 40-day average summer maximum temperature (July 23-August 15) in treatments conducted under the state-land forestry prescriptions, but an increase (mean 0.7C, range -0.9-2.5°C) in the treatment conducted under private-land prescriptions. The best supported shade models indicated that the lowest observed shade value of 50% is associated with a predicted increase in the maximum stream temperatures by as much as 2ºC, while at the greatest observed shade levels (96%) the predicted response for maximum temperature was -0.7°C. Generally observed an increase in maximum temperatures post-harvest for sites that exhibited an absolute change in shade of >6%, otherwise directionality appears to fluctuate.

32. Guenther, S. M., 2007. Impacts of partial retention harvesting with no buffer on the thermal regime of a headwater stream and its riparian zone. *M.S. Thesis*. University of British Columbia.

    Value: 0 for temperature-buffer data analysis because this was a study of buffer thinning effects do not buffer width effects; Value 1 or 2 for showing that removing 1/2 of vegetation in riparian area leads to substantial stream warming, indicating the need for a no touch buffer zone. Type: experimental, BACI design. Location: SW British Columbia. Guenther (2007) used a BACI design to examine the effect of partial retention harvesting

(50% removal of basal area) along 300 m of a channel of a headwater stream (Griffith Creek) within the Malcom Knapp Research Forest in SW British Columbia, Canada. Griffith creek is a first order stream with a basin area of 10 ha. Treatment included the riparian zone and consisted of a thinning designed to remove 50 percent of the basal area. Stream temperature, bed temperature, riparian microclimate and stream hydrology were monitored before and after harvest. Daily maximum stream temperatures increased by up to over 7°C during summer. Summer bed temperatures increased by as much as 6°C (at 1 cm depth and slightly greater than 3°C at 15 cm depth) in the low reach (mid reach bed temperatures warmed only 2°C even despite increases in stream temperature of up to 5°C – this reach received a greater proportion of its discharge from lateral inflow compared to the low reach which tended to lose flow), with the greatest warming in areas of down-welling flow into the stream bed. Heat budget components responded in variable ways depending on the reach, date, and weather. Incoming solar radiation was the largest input of energy into the stream following harvesting, while latent heat, hyporheic heat, groundwater heat, and bed heat exchanges tended to reduce the amount of daytime stream heating after harvest.

The effect of logging appears to have increased ventilation of the riparian zone, thus coupling it more strongly to the regional climate and disconnecting it from the local influence of the stream. The end result of harvesting was increased solar radiation, daily maximum air temperature and wind speed, with decreased humidly, both relative and absolute. Summary: net radiation was the dominant flux driving post logging warming. Sensible heat flux was negligible before harvesting and became a small cooling flux in the post-harvest period, indicating that advection of warm air from the harvested areas cannot be invoked as a cause of stream heating. Although, the temperatures of lateral inflow (shallow groundwater) increased by about 2°C after logging, it remained lower than stream temperature during the day and thus did not contribute to stream warming (?-statement of author is too strong since warmer inflow would reduce the cooling effect-? It does support position that net radiation is the main driver in stream warming) other than possibly influencing daily minimum temperatures which increased by up to about 2°C during summer. Latent heat accounted for about 25% of the calculated cooling fluxes.

33. Guoyuan, L., Jackson, C.R., and Kraseski, K.A. 2012. Modeled riparian stream shading: agreement with field measurements and sensitivity to riparian conditions. *Journal of Hydrology*. 428-429.*

    Abstract: "Shading by riparian vegetation and streambanks reduces incident solar radiation on channels, and accurate estimation of riparian shading through the sun's daily arc is a critical aspect of water temperature and dissolved oxygen modeling. However, riparian trees exhibit complex shapes, often leaning and growing branches preferentially over channels to utilize the light resource. As a result, riparian vegetation cast complex shadows with significant variability at the scale of meters. Water quality models necessarily simplify factors affecting shading at the expense of accuracy. All models must make simplifying assumptions about tree geometry. Reach-based models must average channel azimuth and riparian conditions over each reach, and GIS models must also accept errors in the channel-riparian relationships caused by the DEM grid detail. We detail minor improvements to existing shade models and create a model (SHADE2) that calculates shading ratio (%) by riparian canopy at any time and location for given stream characteristics including stream azimuth, stream width, canopy height, canopy overhang, and height of maximum canopy overhang. Sensitivity of simulated shade to these variables is explored. We also present a new field photographic technique for quantifying shade and use this technique to provide data to test the SHADE2 algorithm. Twenty-four independent shade measurements were made in eight channels with mature hardwood riparian trees at different times of the summer and at different times of the day. Agreement between measured and modeled shade was excellent, with r2 of 0.90."

34. Harris, D.D. 1977. Hydrologic changes after logging in two small Oregon coastal watersheds. *Geologic Survey Water-Supply Paper 2037*.

    Value: 0 for temperature-buffer data analysis, 2 for showing that buffers only on perennial reaches with no buffers on non-perennial tributaries does not prevent temperature impacts in the perennial reaches. Type: Observational. Location: western Oregon. Harris (1977) found that clear-cutting with burning resulted in a 5.5°C increase in the monthly mean maximum temperature post-harvest in the Needle Branch watershed (502 acres) in SW Oregon with temperatures still elevated 7 years after harvest and broadcast burning, and patch cutting 25% of the Deer Creek watershed (750 acres) with 100 ft buffers only on the perennial stream reaches (2 of the three patch cuts) resulted in a 2.0°C increase in the monthly mean maximum temperature. Sediment yields increased 181 percent over the 7-year post-harvest period in the Needle Branch but was not significant in Deer Creek. Similarly, flows increased significantly (26%) only in the Needle Branch in response to its broad scale clear-cut harvest.

35. Hatten, J.R. and Conrad, R.H. 1995. A comparison of summer stream temperatures in unmanaged and managed sub-basins of Washington's western Olympic Peninsula. Project Report Series No. 4. *Northwest Fishery Resource Bulletin*. Northwest Indian Fisheries Commission. Olympia, WA.

    Value: 0 for temperature-buffer data analysis, 2 for watershed scale effects of vegetation removal. Location: Western WA. Type: Observational. Abstract: "A study was conducted to evaluate the effects of timber harvest on summer stream temperatures in the temperate rain forests of the Olympic Peninsula, Washington. Temperatures of 11 streams in unmanaged (unlogged) sub-basins and 15 streams in managed (logged) sub-basins were monitored continuously from July 9 through August 16, 1992. Thirteen variables describing either the sub-basin, or the reach of stream where monitoring occurred, were measured at each study site. Independent variables measured included: sub-basin size, proportion of sub-basin classified as late seral stage forest, stream elevation, stream gradient, amount of shade in the temperature reach, and summer discharge. Five water temperature variables and four air temperature variables were used to characterize the temperatures at each site. These dependent variables included: mean hourly water and air temperature, mean daily high water and air temperature, and mean daily low water and air temperature.

    No significant differences in mean air temperatures were found between the monitoring sites in unmanaged and managed sub-basins. Significant differences were found, however, between group means of all five variables used to characterize the water temperatures of the study sites. For all water temperature variables, the managed group had significantly warmer mean temperatures than the unmanaged group. These significant differences between group means persisted even when the effects of environmental variables that may influence water temperatures, such as stream elevation and amount of shade in the temperature reach, were removed. Only after controlling for the differences between the unmanaged and managed groups in the proportion of each sub-basin classified as late seral stage forest did the differences in mean stream temperatures become nonsignificant.

The proportion of sub-basin classified as late seral stage forest was also the best single variable for predicting mean average hourly and mean daily maximum water temperatures at both unmanaged and managed sites.

We feel that the proportion of sub-basin classified as late seral stage forest is an indicator of the cumulative effects of logging activities within a sub-basin. A cumulative effect could explain the linear relationship between this variable and the stream temperature variables. Managed sites with high values (65-90%) of stream shade generally had warmer mean water temperatures than unmanaged sites with similar stream shade values. Similarly, managed sites at low elevations (< 100 m) had higher mean water temperatures than unmanaged sites at similar or greater elevations. We feel this demonstrates that managing for stream temperature at the reach level will not be successful unless logging activity throughout a sub-basin is considered.

Maximum temperatures in the streams draining managed sub-basins exceeded the Washington State water temperature criterion of 16.0° C ten times more often, on average, than the streams in unmanaged sub-basins during the monitoring period. Since the managed sites of this study are representative of low-elevation (less than 260 m above sea level), managed sites in the area, it is reasonable to assume the majority of the low-elevation, managed stream channels on the Western Olympic Peninsula are not in compliance with the provisions of the Clean Water Act or Washington State Administrative Code."

36. Herunter, H.E., J.S. Macdonald, and E.A. MacIsaac. 2004. Effectiveness of variable-retention riparian buffers for maintaining thermal regimes, water chemistry, and benthic invertebrate communities of small headwater streams in central British Columbia. Pages 105-113 in G.J. Scrimgeour, G. Eisler, B. McCulloch, U. Silins, and M. Monita. Editors. Forest Land-Fish Conference II – Ecosystem Stewardship through Collaboration. *Proc. Forest-Land Conf. II*, April 26-28, 2004, Edmonton, Alberta.

Value: 0 for temperature-buffer data analysis, no temperature data for intact, but variable width buffers. Location: central BC. Type: Experimental. Herunter et al. (2004) used a subset of the study sites examined in Macdonald et al. (2003) to examine the effects of different variable-retention riparian buffer treatments applied to small sub-boreal headwater streams on stream temperature, water chemistry, and benthic invertebrates. Seven years after harvesting completion, none of the treatments showed temporal recovery in stream temperatures. Stream water chemistry changed in all treatments examined with significant increases in total dissolved phosphorus and nitrate (NO3-) observed. However, a lack of correlation with treatment type suggests watershed scale processes, and not riparian processes are largely responsible for water chemistry changes. Benthic invertebrate abundance and biomass changed only in the high retention buffer (large trees only within 20-30 m). The authors concluded that while offering some mitigation, the three types of variable-retention buffers tested do not appear to fully protect headwater streams from changes to thermal regimes, water chemistry, and invertebrate communities.

37. Hewlett, J.D. and J.C. Fortson. 1982. Stream Temperature under an Inadequate Buffer Strip in the Southeast Piedmont. *Water Resources Bulletin*. 18(6): 983-988.*

    Value: 0 for temperature-buffer data analysis. Location: SE U.S. type: Experimental: before-after paired watershed. ABSTRACT: "*A paired watershed experiment on the southeastern Piedmont to determine the effect of clearcutting loblolly pine on water quantity, quality, and timing has shown that stream water temperatures increased as much as 20°F even though a partial buffer strip of trees and shrubs were left in place to shade the stream. Wintertime minimum stream temperatures were lowered as much as 10°F by the same treatment. A stream temperature model now in use did not predict such elevated temperatures. The authors suggest that forest cover reductions in areas of gentle land relief may elevate the temperature of shallow ground water moving to the stream, even with a substantial buffer strip in place.*"

38. **Janisch, J.E., S.M. Wondzell, W.J. Ehinger. 2012. Headwater stream temperature: Interpreting response after logging, with and without riparian buffers, Washington, USA. *Forest Ecology and Management* 270. 302-313.**

    Value: 3 for temperature-buffer data analysis. Location: Western WA. Type: Experimental, BACI design. Janisch et al. (2012) used a before-after-control-impact design to examine stream temperature response to forest harvest in small (<9 ha) forested headwater catchments (these were 1st and 2nd order catchments that ranged from 2.2 to 21 acres). For continuous buffers, the riparian forest in an approximately 10-15 m wide zone on each side of the channel was left unharvested along the full length of the headwater stream. For patch buffers, portions of the riparian forest approximately 50-110 m long were retained in distinct patches with the remaining areas clearcut harvested. All treatments resulted in significant increases in stream temperature. In the first year after logging, daily maximum temperatures during July and August increased in clearcut catchments by an average of 1.5°C (range 0.2 to 3.6°C), in patch-buffered catchments by 0.6°C (range -0.1 to 1.2C), and in continuously buffered catchments by 1.1°C (range 0.0 to 2.8°C). Temperature responses were highly variable, with stream temperature after logging increasing in direct proportion to the area of exposed water surface area and saturated soils (wetlands) upstream of monitoring stations. Length of continuously wetted stream channel above the stream-temperature monitoring stations ranged from as little as 34 meters to as much as 203 m, and coarse textured streams all had wetted stream lengths of 85-90 m and showed no post-logging increase in temperature and lacked wetlands. Canopy and topographic density (CTD) averaged 94% over the stream channels before logging and changed from 95 to 93% in the reference sites from pre- to post-harvest. In contrast the CTC decreased in all treatment catchments after logging. The CTD decreased significantly for both the clear-cut treatments (averaged 53%) and the patch-buffers (76%) but decreased insignificantly in the continuously buffered treatments (86%). Temperature changes in the clearcut remained significantly over zero in all three post treatment years. Temperature for the continuously buffered catchments treatments were significant only in the first two years post-harvest. For the patch treatments temperature increases were significant in the first three years post-harvest.

39. Kaylor, M.J.; D.R.Warren; and P.M. Kiffney. 2017. Long-term effects of riparian forest harvest on light in Pacific Northwest (USA) streams. Freshwater Science. 36:1:1-13. In File

Value: 0 for temperature-buffer data analysis, 2 for shading related info. Kaylor et al. (2017) measured light and canopy cover along in a 4th order stream basin dominated by late-successional riparian forests that included 7 streamside harvest units 50 to 60 years old in Western Oregon. Bankfull widths at the harvest sites ranged from 2.8 to 10.12 m (median approximately 8 m). Estimated light fluxes were lower in harvest units than in up- and downstream sections bordered by old-growth forests. The authors also conducted a space for time analysis based on a literature review of Douglas fir-dominated forests of the US Pacific Northwest. Canopy closure generally occurred without 30 years of harvest and was followed by a period of maximum canopy cover that lasted from 30 to 100 years. Data were limited for stand in the 100- to 300-year-old range, but openness and variability were greater in late-successional forests (dominant canopy trees >300 years old) than in stands that were 30 to 100 years old (18% versus 8.7%). Suggesting that streams with mid-successional riparian forests probably are in a period of minimal summer light flux. (Notes: Only about 30-45% of the differences were significant, leaving to question the strength of the reported trends. Only two sites were in the 100–300-year-old range, which when considered along with their use of a mean to represent all >300-year-old age class stands makes asserting a trend difficult to accept. I did not see where they present the results from their use of the photo-decay rate of fluorescein dye. Within sampled sites: Canopy openness explained 36%of the variation in PAR. When streams were evaluated separately canopy openness explained 0.44 in McRae and 0.02 in MCTE. See page 6-7 for comparisons. Percent openness was 6.1% greater on average (range -2.2-14.5%) in old growth sections than in adjacent harvest units with 5 of 14 comparisons being statistically significant. Recorded reach-average canopy openness values ranged from 6.5-22.4% with a general trend of greater openness for wider stream channels (3.1 – 10 m bankfull width).

40. Kiffney, P.M., J.S. Richardson, and J.P. Bull. 2003. Responses of periphyton and insects to experimental manipulation of riparian buffer width along forest streams. *Journal of Applied Ecology*. 40:1060-1076.

Value: 0 for temperature-buffer data analysis because of non-BACI design, only comparison of control-treatment post-harvest. Location: SW British Columbia. Type: Experimental, control-treatment. Kiffney et al. (2003) examined three riparian buffer strategies along 13 headwater stream reaches in southwestern British Columbia, along with unharvested controls the study used 30-m buffer, 10-m buffer, and clear-cut to the stream edge treatments. Only 20-25% the watershed were logged with stream lengths logged ranging from 215 m to 650 m and elevations ranging between 110m to 555 m. They found that photosynthetically active radiation, mean and maximum water temperature, periphyton biomass, periphyton inorganic mass, and Chironomidae abundance all increased as buffer width narrowed. Overall, the authors concluded that uncut riparian buffers of 30m or more on both sides of the stream were needed to limit biotic and abiotic changes associated with clear cut logging in headwater, forested watersheds. The authors suggested that increased light reaching the streams came through the sides of the buffers. Maximum water temperature in summer was 4.8°C higher in the clear-cut treatment, 3°C higher in the 10m treatment, and 1.6°C higher in the 30m treatment compared with controls. Dissolved NO3-N concentrations were significantly higher in controls prior to treatments but not after logging. Dissolved NO3-N and PO4-P concentrations were significantly different among seasons after logging, with NO3-N concentrations highest in autumn and PO4-P highest in winter. Multilinear regression showed that variation in light level among streams was important in structuring stream communities. Diatoms dominated the low light tile community (99.9% abundance) of the controls and the 30 m buffers. A filamentous chrysophyte was more abundant in the high light environment. Filamentous algae made up 20% of the periphyton community at the 10-m buffer site and 45% at the clear-cut site. Mayflies were less likely to colonize tiles with high loads of periphyton inorganic mass. A strong correlation was found between water temperature and PAR (r=0.92, n=13). Mean solar flux in the clear-cut treatment was 58 times greater and 16 times greater in the 10-m treatment compared with the controls. Light flux was 5 times greater in the 30-m buffer treatment compared with the controls. Photosynthetically active radiation, water temperature, periphyton biomass and periphyton inorganic mass were significantly greater in the 30-m buffer treatment than in controls in some seasons. Chironomidae abundance was generally greater in the 10-m and 30-m buffer treatments than in controls, where this was not always the case in the clear-cut treatment –perhaps due to the high sediment content of the periphyton mat in the clear-cut treatments. Mayfly abundance also increased as buffer width narrowed, but there were no statistical differences among treatments. Summer chironomid abundance was higher in the clear-cut, 10 m and 30-m buffer treatments compared with controls in the replicated experiment, and even higher during the summer colonization study (see figure 6 on page 1070). Mayflies showed similar patterns.

41. Kreutzweiser, D, S.S. Capell, and S.B. Holmes. 2009. Stream temperature responses to partial-harvest logging in riparian buffers of boreal mixed wood forest watersheds. *Canadian Journal of Forest Research*. 39 (3). 497-506.

    Value: 0 for temperature-buffer data analysis because the effect of riparian tree removal cannot be separated from the buffer widths, which were provided as a range from 30 to 100m. Location: Ontario, Canada. Type: Experimental, treatment-control. Kreutzweiser et al. 2009 evaluated the effect of partial-harvest logging in riparian buffers along boreal mixed-wood forest streams (stream BFW 2.6–6.4 m) near Ontario, Canada. Three logged study reaches were compared (t-tests and RM-ANOVA) with three reference reaches over two pre-logging and two post-logging summers. Partial harvest logging in (30-100 m wide riparian buffers) resulted in an average removal of 10.8%, 20.4%, and 28.6% of the basal area from riparian buffers (550-600 m in length) at the three logged sites. At the two more intensively logged sites, there were small (<10%) reductions in canopy cover (P=0.024) but no significant changes in light (PAR) at stream surfaces (P>0.18). There were no measurable impacts on stream temperatures at two of the three logged sites. At the most intensively logged site, daily maximum temperatures were significantly higher (approx. 4°C) for about 6 weeks in the first summer after logging (P<0.001). This effect was not observed by the midsummer of the first post-harvest year and was assumed the result of a logging-induced temporary disruption in cool water inputs from ground disturbance in a lateral-input seep area.

42. Levno, A. and Rothacher, J. 1967. Increases in maximum stream temperatures after logging in old-growth Douglas-fir watersheds. *Research Note. PNW-65*. Forest and Range Experiment Station. USDA. Portland, OR

    Value: 0 for temperature-buffer data analysis. Location: western Oregon. This is an evaluation of the effects of logging in western Oregon on non-buffered streams.

43. Lynch, J.A. and Corbett, E.S. 1990. Evaluation of best management practices for controlling nonpoint pollution from silvicultural operations. *JAWRA* Vol. 26 No. 1.

    Value: 1 for temperature-buffer data analysis due to location, rigor, treatment relevance/comparability. Type: Experimental, control-treatment. Location: Pennsylvania. The study evaluated the efficacy of forest harvesting BMPs at preventing nitrate, temperature, suspended sediments, and turbidity in streams. See summary in sediment section.

44. Lynch, J.A., Corbett, E.S., Mussallem, K. 1985. Best management practices for controlling nonpoint-source pollution on forested watersheds. *Journal of Soil and Water Conservation*. 40: 164-167.

    Value: 1 for temperature-buffer data analysis location, rigor, treatment relevance/comparability. Type: Experimental, control-treatment. Location: Pennsylvania. See summary in sediment section.

45. Lynch, J.A., G.B. Rishel, and E.S. Corbett. 1984. Thermal alteration of streams draining clearcut watersheds: Quantification and biological implications. *Hydrobiologia* 111:161-169.

    Value: 1 for temperature-buffer data analysis location, rigor, treatment relevance/comparability. Type: Experimental, control-treatment. Location: Pennsylvania. The study evaluated the efficacy of forest harvesting BMPs at preventing temperature increases in streams.

46. **MacDonald, J.S., E.A. MacIsaac, and H.E. Herunter. 2003. The effect of variable-retention riparian buffer zones on water temperatures in small headwater streams in sub-boreal forest ecosystems of British Columbia. *Can. J. For. Res.* 33:1371-1382.**

    Value: 0 for temperature-buffer data analysis due to incomparable T-stat- used weekly average temp, otherwise, 3 for temperature-buffer response. Macdonald et al. (2003) used a BACI study design to investigate three variable-retention harvest prescriptions on the

temperature of 8 first-order streams in the interior sub-boreal forests of northern British Columbia. Streams had bankfull widths ranging from 0.6 to 3.2 m with gradients of 3-30%. 1) A 20 m riparian management zone comprised only of non-merchantable trees and a 5 m equipment exclusion zone resulted in summer maximum mean weekly temperature increases of 3 to >5°C. The stream with greatest temperature impact extended 185 m through the cut-block in a small (25 ha) watershed experiencing a 90 percent harvest (treatments ranged from 40-90 percent harvest). 2) A 20-30 m riparian management zone comprised of only large merchantable timber >30 cm DBH and a 5 m equipment exclusion zone resulted in temperature increases from <1°C to approximately 2°C. Initially the high-retention treatment mitigated the temperature effects, but 3 years of wind-throw reduced canopy density and caused temperature impacts. The authors noted the stream having the lowest temperature response was the largest in the study (2.8 m), had a deeply incised channel, less stream length in the cut-block, and had the least amount 6% of watershed harvested (the other treatment stream was had 38% of watershed harvested). 3) A 20-30 m riparian management zone comprised of only large merchantable timber >30 cm DBH and a 5 m equipment exclusion zone applied only to the lower 60% of the stream and removal of all riparian vegetation in the upper 40% of the watershed resulted in a summer maximum mean weekly temperature increase of nearly 4°C. The percent of watershed harvested was 89%. The authors credit wind-throw as impacting the thermal recovery of streams in their study. Five years after harvest, temperatures remained four to six degrees warmer, and diurnal variation remained higher than in the control streams regardless of treatment.

47. Malcolm, I. A., Hannah, D. M., Donaghy, M. J., Soulsby, C., and Youngson, A. F. The influence of riparian woodland on the spatial and temporal variability of stream water temperatures in an upland salmon stream. Hydrology and Earth System Sciences Discussions, European Geosciences Union, 2004, 8 (3), pp.449-459.

    Value: 0 for temperature-buffer data analysis due to location, type of study, 1 for info on watershed processes. Location: Scotland. Type: Observational. This study evaluates the spatial and temporal variability in stream temperatures relative to the location of heather moorland and riparian forest in the study watershed. Riparian woodlands reduced diel variability and dampened maximum temperatures.

48. McCabe, D.J. 1998. Biological communities in springbrooks. Pages 221-228 *in* L. Botosaneanu (ed.). Studies in Crenobiology: The Biology of Springs and Springbrooks. Backhuys. Leiden, The Netherlands (https://www.researchgate.net/publication/236596705).

    Value: 0 for temperature-buffer data analysis due to location, 2 for info on ecology of spring creeks. This is a review of the ecology of spring creeks. Headwater stream often have a larger proportion of flow derived from groundwater, causing them to be cooler than streams with lesser groundwater influence. With increasing distance from groundwater inputs, spring creeks change to become more like surface water fed streams.

49. McGreer, D., Bonoff, M., Gravelle, J., Schult, D. and Canavan, S. 2012. Evaluation of the Effectiveness of the Current TFW Shade Methodology for Measuring Attenuation of Solar Radiation to the Stream. *Cooperative Monitoring Evaluation and Research Report CMER 02-*

214. Washington State Forest Practices Adaptive Management Program. Washington Department of Natural Resources, Olympia, WA.

McGreer et al. (2012) conducted a companion study to Cupp and Lofgren (2014) to determine if prescriptions requiring retention of all available shade within 75 feet of bull trout streams (harvest guided by use of a handheld densiometer) was effective in solar radiation reaching the stream. Based on the average pyranometer response at 16 sites, forest harvest conducted in accordance with all available shade rule did not significantly alter the amount of solar radiation reaching the stream.

50. McIntyre, A.P., Hayes, M.P., Ehinger, W.J., Estrella, S.M., Schuett-Hames, D.E., and Quinn, T. (technical coordinators). 2018. Effectiveness of experimental riparian buffers on perennial non-fish-bearing streams on competent lithologies in western Washington. *Cooperative Monitoring Evaluation and Research Report #18-100*. Washington State Forest Practices Adaptive Management Program, Washington Department of Natural Resources, Olympia, WA.

Value: 3 of 3 for buffer-temperature data analysis. McIntyre et al. (2018) used a Before-After-Control-Impact study design to estimate the changes in riparian cover and stream temperature after timber harvest in non-fish bearing, headwater streams in western Washington. The study included eleven treatment sites that received a clear-cut harvest with one of three riparian buffer treatments. The treatments were a minimum 50-foot-wide buffer along each side of the perennial stream for 100% of its length, a similar buffer along at least 50% of its length (Forest Practices-FP), and no buffer (0%). Shade decreased significantly post-harvest in all treatments with the greatest change seen in the 0% treatment and the least (5-10%) in the 100% treatment. Significant post-harvest increases in the 7-Day Average Daily Maximum Temperature Treatment Response (7DTR) were observed in all treatments. The 7DTR was 1.2°C higher in each post-harvest year in the 100% treatment; 1.4°C and 1.0°C higher in Post 1 and Post 2, respectively, in the FP treatment; and 3.4 and 3.0°C higher in Post 1 and Post 2, respectively, in the 0% treatment. Even small (less than 10%) decreases in shade were noted as causing measurable increases in summer maximum stream temperature. Average changes in maximum stream temperature at the downstream boundary of fish-bearing waters in the first two years post-harvest were 0.9°C and 0.6°C in the 100%, 1.4°C, and 1.0°C in the FP, and 3.1°C and 2.7°C in the 0% treatment. These were slightly lower than at the buffer treatment locations because the fish boundary was sometimes situated in reaches with buffer widths much greater than 50 feet, allowing for more thermal recovery. Maximum stream temperature showed clear signs of being on a recovery trend, decreasing by 0.3°C to 3.2°C after flowing through 100-138m (328-452.8 ft.) of unharvested forest. However, stream temperature was still elevated significantly above pre-harvest levels at five of the six sites where the extent of recovery could be assessed.

51. Rishel, Gregg B., James A. Lynch, and Edward S. Corbett. 1982. Seasonal stream temperature changes following forest harvesting. J. Environ. Qual. Vol. 11, No. 1.

Value: 0 for temperature-buffer data analysis due to location, non-buffering of non-perennial channels. Rishel et al (1982) used a BACI design to compare the effects of a clearcut-herbicide treatment to a commercially clearcut watershed where a 30 m wide buffer zone was left only along perennial stream channels. Temperatures in the clearcut-herbicide treatment increased with Spring to Fall average monthly maximum stream temperatures increasing 4.4ºC, and minimum temperatures increasing on average 2ºC in the summer months but decreasing as much as 3.9°C in the fall and winter. Temperatures in the treatment using 30 m buffers along perennial streams experiences an average increase in the monthly average maximum temperatures from Feb through October that ranged from 0.6 to 2.2°C (would be a summer average of 1.1ºC).

52. Rutherford, J. C., N. A. Marsh, P. M. Davies, and S. E. Bunn. 2004. Effects of patchy shade on stream water temperature: how quickly do small streams heat and cool? Marine and Freshwater Research 55:737-748.

    Value: 0 for temperature-buffer data analysis, 1 for hydrological process info. Location: Australia. Type: Observational. This study examined rates of change in stream temperature in narrow/shallow 2nd order streams in relation to longitudinal changes in shading. They found that maximum temperatures can increase or decrease by 4ºC in a 600 to 960m distance (2-3hr travel time). They used a model to estimate that a temperature equilibrium relative to local conditions is reached after about 4 hrs (1200m) travel time.

53. Ryan, D.K., Yearsley, J.M., and Kelly-Quinn, M. 2013. Quantifying the effect of semi-natural riparian cover on stream temperatures: implications for salmonid habitat management. *Fisheries Management and Ecology*.

    Value: 0 for temperature-buffer data analysis, 1 for hydro process info. Location: Ireland. Type: Observational. Ryan et al. (2013) used upstream-downstream monitoring to examine the relationship between stream temperature variability and local climatic conditions for 17 sites over discrete 300-m sections of a watercourse. Seventeen stream sections were chosen within the Slaney catchment in Ireland on the basis of cover and size. Continuous monitoring over a 2-year period found that riparian cover had a measurable cooling effect on water temperatures at small spatial scales. The magnitude of the effect was dependent on-stream size and local climatic conditions. The analysis focused on months from June to August. The 300 m long stream sections were grouped by size (large or small) and riparian cover (shaded or unshaded) giving a total of nine shaded sections (four large and five small) and eight unshaded sections (four large, four small). Large stream sections had a mean wetted width of ≥8 m (range 8-11 m) and a mean pool depth of ≥0.6 m. Small stream sections had a mean wetted width ≤4 m (range 3-4 m) and a mean pool depth ≤0.4 m. Temperature collected every 30 minutes. All study sites were adjacent to improved agricultural grassland. Riparian corridor widths rarely exceeded 1-2 trees deep and were made up predominantly of alder and willow with typical tree heights varying from 8-15 m. Temperature differential across all 300-m stream sections varied significantly with year, sunshine, flow, and upstream water temperatures. Increasing sunshine generally increased the temperature differential, but this effect was weakened by increasing flow and increasing upstream temperature. Decreasing flow also increased temperature differentials in small stream sections but not in large stream sections. No effect of air temperature could be detected once the effects of upstream temperature, sunshine, flow and year had been accounted for. After taking account of all confounding variables, a significant effect of riparian cover remained. The effect of sunshine in increasing temperature differential was weaker, but still significant for shaded stream sections. Based on text and discussion summary the authors found that short strips (300 m) of semi-natural riparian buffer can cool small (wetted ≤4 m, range 3-4 m) nursery streams by up to 1C, and cool large streams (wetted ≥8 m, range 8-11 m) by approximately 0.5C. (Notes: They did not measure shade, nor do they give statistically based results describing the difference in cooling for buffered versus unbuffered large and small streams (so I used Figure 2 and some of the text statements summarizing the results). When authors describe small spatial scales this is meant as a comparison to catchment wide studies. Noted confounding by macrophytes in some unshaded streams.)

54. Seixas, Gustav B., Timothy J. Beechie, Caleb Fogel, and Peter M. Kiffney, 2018. Historical and Future Stream Temperature Change Predicted by a Lidar-Based Assessment of Riparian Condition and Channel Width. Journal of the American Water Resources Association (JAWRA) 54 (4): 974–991.
    Value: 0 for temperature-buffer data analysis, 2 for temperature-watershed relationships. Location: western Washington. This is a modeling study of water temperatures in the Chehalis River Basin relative to climate change and riparian buffers. The results show that if forested riparian buffers were fully implemented, then maximum water temperatures in 2080 would be similar to today's temperatures in streams less than approx. 50m wide. For channels larger than 50m wide, buffer restoration would not offset water temperature increases due to climate change because the potential shading is limited by channel size.

55. Shaw, J. L. 2018. The Effectiveness of Forested and Hedgerow Riparian Buffers for Buffering Water Temperature and Improving Fish Habitat in Agricultural Waterways in Western Washington. Master's Thesis. *WWU Graduate School Collection*. 650. Western Washington University. Bellingham., WA.

    Value: 0 for temperature-buffer data analysis as the data is incomparable. Since the control reaches were unbuffered, the treatment effect on temperature is negative rather than positive; therefore, it is not possible to determine if the narrow buffers were effective at preventing temperature increases because there is no reference condition for a warming rate for a fully buffered channel. Type: Observational, control-treatment. Location: western WA. This study examined the effectiveness of narrow buffers at providing shade and inhibiting temperature increases in agriculturally ditched streams. The study methods were problematic. The results do not show that the 4.6 or 10.7m hedgerow buffers were effective at preventing water temperature increases.

56. Sridhar, V., Amy l. Sansone, Jonathan LaMarche, Tony Dubin, and Dennis P. Lettenmaier. 2004. Prediction of stream temperature in forested watersheds. *JAWRA* 40(1):197-213

    Value: 0 for temperature-buffer data analysis- modelling. Sridhar et al. (2004) used an energy balance model to predict stream temperatures in forested headwater watersheds to evaluate the performance of buffers along stream corridors in moderating temperature increases. The authors used a sensitivity analysis to assert that buffer width beyond 30 meters did not significantly decrease stream temperatures, and that "other vegetation parameters such as leaf area index, average tree height, and to a lesser extent streamside vegetation buffer width, more strongly affected maximum stream temperatures". "Overall, the results show that canopies close to the stream, with buffer widths of at least 30 m, play an important role in modulating the temperature of the stream". Notes: authors chose not to include diffuse radiation, and also chose to hold LAI constant when altering buffer height and width in their sensitivity analyses. Authors found that the use of an LAI of 7 maximized shading – no improvement in temperature protection than testing with LAIs to over 10. This is very important and explains the insensitivity to increasing buffer widths since a near complete shade curtain is assumed at LAI regardless of the width of the buffer. A drop from LAI 7 to LAI 4 was associated with estimated stream heating of 1.63-1.88°C and described as fitting immature or sparse vegetation. With 30 m wide buffers stream temperature increases ranged from 1.1 to 1.5ºC as test reaches were increased from 0.5 to 15 km demonstrating relative insensitivity of increasing buffer width- all other factors held constant.

57. Steinblums, I.V. 1977. Streamside buffer strips: survival, effectiveness, and design. *Master's Thesis.* Oregon State University. Corvallis, OR

    Value: 0 for temperature-buffer data analysis, 1 for shading info. Location: Western Oregon. Type: Observational. This is an evaluation of the factors that influence tree losses in riparian buffers. Wind was the primary cause of tree mortality in buffers (accounting for 94%). For the buffer strips sampled, tree losses ranged from 0% to 78%. Taller trees and wetter soils were correlated with lower tree survival rates. The author estimated that an 85-foot buffer provides as much shade as an undisturbed riparian area and that a buffer 52ft wide can provide 75% of the shade provided by an undisturbed buffer.

58. Sullivan, K., Tooley, J., Doughty, K., Caldwell, J.E., and Knudson, P. 1990. Evaluation of prediction models and characterization of stream temperature regimes in Washington. *Timber/Fish/Wildlife Rep. No. TFW-WQ3-90-006*. WA Dept. Nat. Res. Olympia, WA. 224 pp.

    Value: 0 for temperature-buffer data analysis, 3 for watershed process info. Location: WA. Type: Modeling. This paper estimates the amount of shade needed to keep water temperatures below a given level at varying elevations. The effect of shade upon water temperatures decreases as elevation increases. This means that a stream at a higher elevation requires less shading to remain below a given rate of warming than is required for a similar stream at a lower elevation. Very low elevation: <300ft above sea level; High elevation: >2400ft. Low temperature criterion = 16.3C, moderate criterion = 18.3C, high = 21.3C. The graph on page 209 suggests that: 0% shading is needed to keep a stream below 18.3C at an elevation of 700m (2300ft); 45% shading is required to keep a stream below 16.3C at 700m elevation; 80% shade is needed to keep a stream below 18.3C at 100m elevation; 95% shade is needed to keep a stream below 16.3 at 100m elevation. "At some location along a river, channels are sufficiently wide that the influence of riparian shading on water temperature is negligible." Modeling indicates that the importance of shading as a

control upon water temperature becomes insignificant along stream reaches located more than 25 miles (~40km) downstream of the watershed divide. Based on a graph of wetted width vs. distance from watershed divide (pg 49) the estimated corresponding channel width is about 49 ft (~15m). This suggests that shade does not exert a strong control upon water temperature once channels are wider than roughly 50ft.

Note: Probably >95% of agricultural lands in WA state are located below an elevation of 2400ft.

59. Swift, Jr., L.W., and Messer, J.B. 1971. Forest cuttings raise temperatures of small streams in the southern Appalachians. *Journal of Soil and Water Conservation*. Vol. 26. No 3.

    Value: 0 of buffer-temperature data analysis. Location: North Carolina. The effect of clearcutting on stream temperatures was examined. Summertime maximum water temperatures increased by 7 degrees Fahrenheit or more.

60. UCD. 1997. Sacramento River temperature modeling project. University of California- Davis, Center for Environmental and Water Resources Engineering, Department of Civil and Environmental Engineering Modeling Group. Davis, CA. 175 pp. & app.(cf. http://www.krisweb.com/biblio/sactorvrtempmodel/ccv_ucd_cewre_1997_sactorvrtempmodel.htm).

    Value: 0 for temperature-buffer data analysis. Location: California. Type: modelling. This publication examines water temperature dynamics in relation to variable flow conditions in the Sacramento River drainage

61. Veldhuisen, C., and Couvelier, D. 2006. Summer Temperatures of Skagit Basin Headwater Streams: Results of 2001-2003 Monitoring. Unpublished Report of the Skagit River System Cooperative.

    Value: 0 for temperature-buffer data analysis, 1 for watershed process info. Location: Western WA. Type: Observational, upstream-downstream. Veldhuisen and Couvelier (2006) conducted temperature monitoring in the western and central portions of the Skagit River basin in northwestern Washington over a three-year period. Channel bankfull widths average about 2 m (0.4 - 4.8 m) and gradients at the 2003 measured sites ranged from 8 to 44% and averaged 28%. Shade and buffer widths recorded (n = 14) were used to plot the relationship between buffer width and percent shade. This curve indicated that a 10 m (33 ft) buffer (on each side) provided about 70% of the shade of a mature forest, but that a buffer 20 m (66 ft) or wider is needed to be equivalent to a forest. The authors found that while upstream shade was the strongest predictor of stream temperature, stream gradient created a significant inverse response (slower flows at low gradient allowing for longer exposures to heat inputs).

62. Webb, B.W., Crisp. D.T. 2006. Afforestation and stream temperature in a temperate maritime environment. *Hydrological Processes.* 20: 51-66.*

    Value: 0 for temperature-buffer data analysis, 1 for watershed process info. Location Scotland. Type: Observational. Abstract: “There have been few long-term investigations of the effects of afforestation on stream temperatures in the UK, and the present study uses

the results of continuous monitoring of water temperatures in a forest and a moorland stream of the Loch Grannoch area in southwest Scotland over a 4-year period to investigate the effects of planting coniferous forest on stream thermal regime. The presence of a coniferous tree canopy resulted in a lowering of mean water temperatures by ~0·5 °C but larger reductions in summer monthly mean maxima and diel ranges of up to 5 °C and 4 °C respectively. The diel cycle in the forested stream lagged behind that of the moorland site in all months of the year, but the delay in timing was greater for the peak than for the trough in the diel cycle. Mean water temperatures were higher in the forest stream during the mid-winter months, reflecting higher minimum values. Contrasts in stream thermal regime between forest and moorland showed relatively little interannual variability over the study period. Continuous monitoring of air temperatures during 2002 revealed contrasts between the study sites that were less pronounced for air than for water temperature, and suggested it is the shading of incoming solar radiation that has a strong effect in determining the water temperature behavior of the forested stream. Although the biological impact of the observed contrasts in stream temperature between land uses is likely to be relatively modest, the presence of forest cover moderates the occurrence of high summer temperatures inimical to the survival of some salmonid species."

63. **Wilkerson, E., J.M. Hagan, D. Siegel, and A. Whitman. 2006. The effectiveness of different buffer widths for protecting headwater stream temperature in Maine. *Forest Science*. 52:3:221-231.**

    Value: 2 or 3 for temperature-buffer data analysis. Type: BACI design. Location: Maine. Wilkerson et al. (2006) tested three replicates of harvest prescriptions for 300 m (984 ft) two-sided 6 ha (14.8 ac) patch cuts along 1st order tributaries in Maine. The authors found that: 1) Clearcutting adjacent to 11 m (36 ft) partially harvested (31% reduction in basal area) (leaving appx. 15.06 m2/ha BA)(65.06 ft2/ac) resulted in an 11% reduction in canopy cover and an increase in the seasonal average maximum of 1.4-2.5°C. 3) Clearcutting with 23 m (75.5 ft) partially harvested buffers resulted in a 21% reduction in basal area within the buffer (leaving appx.19.9 m2/ha BA)(86.7 ft2/ac) a 4% reduction in canopy cover and no increases in either the 7DADMax or summer average maximum stream temperature, 4) Partial cuts with no designated buffer resulted in an average 26% reduction in basal area (leaving appx.15.76 m2/ha BA in harvested areas)(68.7 ft2/ac) and a 4% reduction in canopy closure with no increase in either the 7DADMax or summer average maximum stream temperature.

64. Witt, E.L., Barton, C.D., Stringer, J.W., Kolka, R.K., Cherry, M.A. 2016. Influence of variable streamside management zone configurations on water quality after forest harvest. *Journal of Forestry*, Volume 114, Number 1. pp. 41-51(11).

    Value: 0 for temperature-buffer data analysis due to non-BACI design and incomparable T-stat- used avg. daily max temp for mid- Feb thru mid-Dec combined. Location: Kentucky. Witt et al. (2016) evaluated three riparian treatments (T1, T2, and T3) that varied in width, canopy retention within the SMZ, and BMP utilization with replication in two watersheds each. Watersheds with wider SMZs (T3: 110 ft. 100% canopy retention) and improved crossings were not significantly different from unharvested control watersheds for all parameters except nitrate and diurnal stream temperatures. Changes in total suspended solids, turbidity, nitrate, dissolved oxygen, and maximum stream temperature were detected for watersheds treated with T1 and T2. T1 consisted of 55-ft perennial SMZs with 50% canopy retention; 25-ft intermittent SMZs with no over-story retention; with stream fords and no over-story buffer requirements for ephemeral streams. Treatment T1 resulted in a 3.4°F (1.9°C) increase in mean maximum daily temperature and statistically significant increases in sediment. T2 consisted of 55-ft. perennial SMZ but required 100% canopy retention and 25% canopy retention in the 25-ft intermittent SMZ. In addition, elevated crossings were used to cross ephemeral streams and the nearest channel bank tree was retained. No significant difference was found between this and the control. T3 increased the perennial SMZ width to 110-ft with 100% canopy retention. T3 also increased the intermittent SMZ width to 55-ft with 25% canopy retention and included a 25-ft SMZ around ephemeral streams that limited harvesting equipment to the crossings only. Elevated crossings were used to cross T3 ephemeral streams and the nearest tree to the channel was retained.

65. Zwieniecki, M.A. and Newton, M. 1999. Influence of streamside cover and stream features on temperature trends in forested streams of western Oregon. *WJAF* 14(2).

Value: 2 for temperature-buffer data analysis- study design is somewhat weak, but results are consistent with other studies. Location: western Oregon. Type: Observational, before-after (upstream-downstream). Zwieniecki and Newton (1999) examined the effect of clear-cut harvesting along 14 low elevation (<300 m) potential fish bearing streams in northwestern Oregon on water temperature. Harvest units spanned or were adjacent to the streams for distances of 350 to 1,600 m (three of the units were one-sided and 800 m long). Study included variety of silvicultural harvest types and buffer widths (one and two sided, buffers within treatments ranging from 8.6 to 30.5 m, hardwood conversions and standard conifer harvests). Thermisters were placed above and below harvest units and at two locations downstream. The authors examined the 7-DADMax period assuming it would best represent effects of concern. Buffer width and cover was determined at 30 m intervals. They could not find trends in warming in relation to gradient, wetted width, bank height, bottom substrate, and depth. Distance from divide was highly significant. Used the general warming equation for distance to divide to create a correction factor to adjust downstream observed temperatures at the treatment site (*note that it appears that two general equations – one for a high-discharge stream and one for low-discharge stream were created and used to adjust the actual monitored temperature data after treatments had occurred for all streams dependent on their classification as either a high flow or low flow stream type. This is a very questionable way to adjust individual stream data. Figure 3 shows observed temperature data, and it does not seem to support the authors approach to adjusting temperature. Substantial variation was observed which negate the hypothesis of a change per unit length adjustment factor*). Within the units the average buffer was 21.1 m wide with a range of 8.6-30.5 m. Cover was 78% within units and 83% above and below harvest units. Cover change was reported as being not significant between the harvest and unharvested sections (no data provided). The average temperature rose 1.09°C in the harvest unit and decreased by 0.69°C in the first 150 m of the recovery zone. Within 650 to 1,900 m of the study reaches the absolute temperature rose within the combined harvest unit and the 300 m recover zone by 0.55°C. After correcting for the natural expected rates of downstream warming based on the two stream types (low flow and high flow) low flow streams showed a 0.21°C non-significant increase above the presumed uncut trend. High flow streams showed a net temperature increase of 0.82°C. Both types of streams combined showed an average net temperature increase of 0.52°C. The authors also concluded that they could not reject the hypothesis that harvesting with modest buffers and even gaps, leads to an accumulation of heat that persists 300 m below the harvest unit to a greater degree than expected from natural warming. *Notes: Really a series of case studies given the huge range of uncontrolled variation in buffering, and a general warming model was used to adjust results rather than models for each stream which were highly varied in their buffering and their responses. In effect the prediction model supplants the actual results. Authors acknowledge streams have individual signatures but use an average response to compare with post-harvest temperatures. No controls, and no pre-harvest temperatures provided. Also appears harvest occurred upstream of the treatments as the average buffers upstream were 30.1 m thus introducing another uncontrolled variable.*

Toxics

1. **Arora, K., Mickelson, S.K., and Baker, J.L. 2003. Effectiveness of vegetated buffer strips in reducing pesticide transport in simulated runoff. *Transactions of the American Society of Agricultural Engineers*. 46: 635-644**.

   Value: 1 for buffer-toxics data analysis- did not use natural rainfall. Type: Experimental, before-after, plots with simulated runoff; location: Iowa. This study evaluates the effectiveness of buffer strips at removing atrazine (Koc = 100mL/g), metolachlor (Koc = 200 mL/g), and chlorpyrifos (Koc = 6070 mL/g) from runoff. Buffer strips were pre-wetted to simulate antecedent moisture that would occur after a large rainfall just prior to runoff initiation. Buffer area ratios were set at 15:1 for three buffer strips and 30:1 for an additional three buffer strips; buffer strips were 20.12m in length; plot slope not reported but estimated to be approx. 3% based on the field set-up diagram. Loam soil, 3% OM content. Vegetation was 81% brome grass, 12% bluegrass, 5% fescue, 2% other (tiller density = 8.82 million/ha). The experiment simulated 10.7mm of runoff. For the 15:1 treatment, buffers retained 52.5% of atrazine mass and 46.8% for the 30:1 treatment (includes in-solution + sediment adsorbed). For metolachlor mass buffers retained 54.4% for 15:1 treatment and 48.1% for 30:1. For chlorpyrifos mass (strongly sediment adsorbing) buffers retained 83.1% for 15:1 treatment and 76.9% for 30:1. Approx. 5% of atrazine and metolachlor was removed through sediment trapping, while for chlorpyrifos, it was 75%. Difference between buffer area ratios were not significant at the 0.10 level. Removal of pesticides is not constant per unit length of buffer. Sediment deposition accounted for chlorpyrifos retention while infiltration accounted for removal of the other two pesticides. Note that infiltration is not necessarily removal since a pesticide with a low Koc may continue to be transported towards surface waters through subsurface flow. Since the first few meters of a buffer retain 50% or more of the sediment mass, removal of pesticides with high Koc values will be similar to sediment removal patterns.

2. **Arora, K., Mickelson, S.K., Baker, J.L., Tierney, D.P., and Peters, C.J. 1996. Herbicide retention by vegetative buffer strips from runoff under natural rainfall. *Transactions of the American Society of Agricultural Engineers*. 39: 2155-2162**.

   Value: 3 for buffer-toxics data analysis. Type: Experimental, before-after. Location: Iowa. The authors investigated removal of herbicides and sediment from agricultural field runoff. See summary under sediment section.

3. Asmussen, L. E., White, Jr., A.W, Hauser, E.W., and J.M. Sheridan. 1977. Reduction of 2,4-D load in surface runoff down a grassed waterway. *J. Environ. Qual.* 6:159-162.*

   Abstract: "The effectiveness of a grassed waterway in decreasing 2,4-D [(2,4-dichlorophenoxy) acetic acid] content in surface runoff was investigated. Corn (Zea mays L.) plots were treated with 2,4-D (0.56 kg/ha) and runoff produced by applying simulated rain was directed through a 24.4-m-long grassed waterway. The 2,4-D concentrations were measured under wet and dry antecedent waterway and plot conditions. Reduction in 2,4-D load in waterways results from water loss by infiltration, sediment loss, and by attachment-absorption on vegetative and organic matter. Of the simulated rainfall applied 1 day after application of 2,4-D, 50% of the water ran off the plots under dry antecedent soil conditions, and 78% ran off under wet conditions. Infiltration reduced runoff flowing down the waterway an additional 25% under dry conditions and 2% under wet conditions. Suspended sediment reduction in the waterway was 98 and 94% of the total amount moving from the plot for the dry and wet waterway conditions, respectively. The total loss (on sediment and in solution) of the applied 2,4-D from the plot in the dry and wet states was 2.5 and 10.3%, respectively. Of the 2,4-D lost from the plots and entering the 24.4-m waterway, approximately 30% reached the end of the waterway, regardless of antecedent soil moisture."

4. **Boyd, P.M., Baker, J.L., Mickelson, S.K., and Ahmed, S.I. 2003. Pesticide transport with surface runoff and subsurface drainage through a vegetative filter strip. *Transactions of the American Society of Agricultural Engineers*. 46: 675-684.**

   Value: 1 for buffer-toxics data analysis- good study design but used simulated runoff which is incomparable to natural rainfall/runoff data. Type: Experimental, before-after, simulated runoff. location: Iowa. This study evaluates the effectiveness of buffer strips at removing atrazine (1.68 kg/ha app. rate), acetochlor (1.96 kg/ha app. Rate) and chlorpyrifos (1.22 kg/ha app. rate) from runoff. Soils: silty clay loam. Source area was a .58 ha corn field (3.5% avg. slope) with pesticides applied at time of planting. Filter strips were 20.1m long (slope approx. 2%), three with 15:1 buffer area ratio (BAR) and three with 45:1 buffer area ratio. Vegetation was 81% bromegrass, 12% bluegrass, 5% fescue, 2% other. Tiller density was 8.82 million/ha. Water infiltration ranged from 56.1% to 81.9%. For the 45:1 BAR, runoff event 3 (only one event reported) : atrazine reductions were 60.4% in water and 90.0% in sediment; acetochlor reductions were 73.9% in water and 80.5% in sediment; chlorpyrifos reductions were 72.4% in water and 78% in sediment; sediment reduction was 77.6%. For the 15:1 BAR, runoff event 3: atrazine reductions were 79.8% in water and 80.7% in sediment; acetochlor reductions were 83.7% in water and 94.0% in sediment; chlorpyrifos reductions were 83.3% in water and 94.0% in sediment; sediment reduction was 91.3%. A greater mass of atrazine and acetochlor was removed from water than from sediment. Sediment deposition accounted for chlorpyrifos retention while infiltration accounted for removal of the other two pesticides. Data collected from a tile drain indicated subsurface drainage of the moderately adsorbed pesticides (e.g. acetochlor). The authors note that since Arora et al. (1996) did not find a difference in effectiveness between 15:1 and 30:1 BAR, but this study found a difference between 15:1 and 45:1 BAR, that the maximum BAR that should be used for filter strips to remove pesticides should be between 30:1 and 45:1.

5. Delphine, J-E. and Chapot, J-Y. 2001. Leaching of atrazine and deethylatrazine under a vegetative filter strip. *Agronomie* 21:461-470.

   Value: 0 for buffer-toxics data analysis because subsurface data is incomparable to surface runoff, 3 otherwise due to good data on subsurface transport. Type: Experimental, before-after, natural rainfall. Location: NE France. This is a study of how atrazine and deethylatrazine (DEA) leach beneath filter strips. Soils: silt loam. Five plots, 18m in length at 2% slope. Crop field- planted to corn, slope = 4%. Measurements made at 0, 6, 12, and 18m distance. Filter strip vegetation was 80% ryegrass, 20% white clover. Depth of soil solution sampling was 60cm and 120cm. Atrazine and DEA losses due to leaching during summer were 0 to 5% of the annual losses; this low amount was due to evapotranspiration in the grass strip which limited water percolation. Twice as much DEA was lost than atrazine because DEA has a longer persistence in the soil at the 120cm depth. Some of the leaching was from pesticide applied in prior years. Outside of the growing season, leaching is driven by the volume of water draining through the soil and “environmental conditions”. Reducing runoff to the filter strips and maintaining optimal grass growth helps to limit the amount of water in the filter strip that will leach atrazine and its metabolite DEA.

6. De Snoo, G.R. and De Wit, P.J. 1998. Buffer zones for reducing pesticide drift to ditches and risks to aquatic organisms. *Ecotoxicol. Environ. Safety* 41:112-118.*

   Value: 0 for buffer-toxics surface runoff data analysis, 2 for aerial drift. Abstract: “Pesticide drift from field sprayers fitted with different types of spray nozzles was investigated under various wind speed conditions. Droplet drift was measured adjacent to the sprayed field, on the ditch bank, and in the ditch. Measurements were carried out in the normal sprayed situation and with an unsprayed buffer zone 3 or 6 m wide. The results indicate that there are major differences between spray nozzles. Drift deposition increases with wind speed. In the sprayed situation and with a wind speed of 0.5 m/s, there was a maximum of 6.0% drift deposition halfway down the ditch bank and no drift deposition in the ditch. At 3 m/s wind speed these figures are 25.1 and 2.2%, respectively. At 5 m/s wind speed, 7.2% drift deposition was measured in the ditch. Risk assessment (cf. SLOOTBOX model) carried out with 17 pesticides used in the study area indicated that at this wind speed, 8 of the 17 pesticides investigated posed a risk to aquatic organisms. Creation of a 3-m buffer zone decreases drift deposition in the ditch by a minimum of 95%. Adjacent to the buffer zone only 4 of the 17 pesticides investigated posed a (minor) risk to aquatic organisms. With a 6-m buffer zone no drift deposition in the ditch could be measured (wind speed maximum, 4.5 m/s). Creating unsprayed crop edges offers good possibilities for the protection of aquatic ecosystems. Socioeconomic research among farmers indicates that buffer zones, such as unsprayed cereal edges and unsprayed grass strips, could well be adopted in agricultural practice."

7. Franks, C.G., Pearce, D.W., and Rood, S.B. 2019. A prescription for drug-free rivers: uptake of pharmaceuticals by a widespread streamside willow. *Environ. Management*. 63 (1): 136-147.

   Value: 0 for buffer-toxics data analysis, 1 for toxics removal process info. Type: Experimental, control-treatment, laboratory. The study evaluated short-term uptake rates of 17α-ethynylestradiol (EE2- synthetic estrogen), diltiazem (ant-hypertensive drug), diazepam (anti-anxiety drug), and atrazine (as a postive control since it's known to be uptaken and translocated by plants) by sandbar willows. EE2 uptake was approx 88%, diltiazem uptakes was approx. 76%, diazepam uptake was approx. 50%, atrazine uptake was approx. 49%.

8. Hancock, J., Bischof, M., Coffey, T., and Drennan, M. 2019. The effectiveness of riparian hedgerows at intercepting drift from aerial pesticide application. *Journal of Environmental Quality*. Published online July 11, 2019.

   Value: 0 for buffer-toxics surface runoff data analysis, 2 for aerial drift. Type: Observational; location: WA state. This study evaluated the effectiveness of riparian buffers at intercepting aerial drift from malathion and malaoxon (a malathion degradate) applied to blueberry orchards. Two "non-vegetated" sites were on ditches that had reed canary grass and Himalayan blackberry along the banks. One of these sites had all the grass mowed in between the first and second malathion applications, effectively eliminating all canopy cover. Three "vegetated" sites were along streams with riparian vegetation dominated by willow, spiraea, dogwood, and alder; two of these sites had riparian hedgerows established 13 yrs prior and the third site had naturally established vegetation including mature cottonwood and cedar. At the vegetated sites, the vegetation width averaged 6.62m and had an average height of 6.60m. The average distance form field edge to center of channel was 16.49m for the vegetated sites and 6.59m for the non-vegetated sites. Stream canopy cover and site canopy cover averaged 90% and 91% at the vegetated sites and 46% and 23% at the non-vegetated sites. Canopy cover, bank slope, and distance from field edge to riparian/stream edge influenced malathion deposition into the streams/ditches. The vegetated sites had an average of 96% less malathion deposition than the vegetated sites.

9. Krutz, L.J., Gentry, T.J., Senseman, S.A., Pepper, I.L., and Tierney, D.P. 2006. Mineralisation of atrazine, metolachlor and their respective metabolites in vegetated filter strip and cultivated soil. *Pest Management Science.* 62: 505-514.*

   Value: 0 for buffer-toxics data analysis, 1 for transport process info.

   Abstract: "In vegetated filter strips (VFS) the presence of perennial vegetation, rhizodeposition of labile organic substrates and the accumulation of an organic residue thatch layer may enhance microbial numbers and activity, thereby increasing the potential for mineralisation of herbicides and herbicide metabolites retained during run-off events. The objective of this laboratory experiment was to compare the mineralisation of atrazine and metolachlor with that of their respective metabolites in VFS and cultivated soil. With the exception of total bacteria, propagule density of the microbial groups, endogenous soil enzymes and microbial diversity were higher in the VFS soil. This correlated with increased mineralisation of metolachlor and its metabolites in the VFS soil and indicates potential for VFS to curtail the subsequent transport of these compounds. In contrast, the mineralisation of atrazine and the majority of its metabolites was substantially reduced in VFS soil relative to cultivated soil. Consequently, the potential for subsequent transport of atrazine and many of its metabolites may be greater in VFS soil than in cultivated soil if reduced mineralisation is not offset by increased sorption in the VFS."

10. Krutz, L.J., Senseman, S.A., Dozier, M.C., and Hoffman, D.W. 2003. Infiltration and adsorption of dissolved atrazine and atrazine metabolites in buffalograss filter strips. *Journal of Environmental Quality*. 32: 2319-2324.*

    Value: 0 for buffer-toxics data analysis, 1 for transport process info.

    Abstract: "Vegetated filter strips (VFS) potentially reduce the off-site movement of herbicides from adjacent agricultural fields by increasing herbicide mass infiltrated ($\mathbf{M}_{inf}$) and mass adsorbed ($\mathbf{M}_{as}$) compared with bare field soil. However, there are conflicting reports in the literature concerning the contribution of $\mathbf{M}_{as}$ to the VFS herbicide trapping efficiency (TE). Moreover, no study has evaluated TE among atrazine (6-chloro-**N**-ethyl-**N**′-isopropyl-[1,3,5]triazine-2,4-diamine) and atrazine metabolites. This study was conducted to compare TE, $\mathbf{M}_{inf}$, and $\mathbf{M}_{as}$ among atrazine, diaminoatrazine (DA, 6-chloro-[1,3,5]triazine-2,4-diamine), deisopropylatrazine (DIA, 6-chloro-**N**-ethyl-[1,3,5]triazine-2,4-diamine), desethylatrazine (DEA, 6-chloro-**N**-isopropyl-[1,3,5]triazine-2,4-diamine), and hydroxyatrazine (HA, 6-hydroxy-**N**-ethyl-**N**′-isopropyl-[1,3,5]triazine-2,4-diamine) in a buffalograss VFS. Runoff was applied as a point source upslope of a 1- × 3-m microwatershed plot at a rate of 750 L h^{-1} The point source was fortified at 0.1 µg mL^{-1} atrazine, DA, DIA, DEA, and HA. After crossing the length of the plot, water samples were collected at 5-min intervals. Water samples were extracted by solid phase extraction and analyzed by high performance liquid chromatography (HPLC) photodiode array detection. During the 60-min simulation, TE was significantly greater for atrazine (22.2%) compared with atrazine metabolites (19.0%). Approximately 67 and 33% of the TE was attributed to $\mathbf{M}_{inf}$ and $\mathbf{M}_{as}$, respectively. These results demonstrate that herbicide adsorption to the VFS grass, grass thatch, and/or soil surface is an important retention mechanism, especially under saturated conditions. Values for $\mathbf{M}_{as}$ were significantly higher for atrazine compared with atrazine's metabolites. The $\mathbf{M}_{as}$ data indicate that atrazine was preferentially retained by the VFS grass, grass thatch, and/or soil surface compared with atrazine's metabolites."

11. Lowrance, R., Vellidis, G., Wauchope, R.D., Gay, P., and Bosch, D.D. 1997. Herbicide transport in a managed riparian forest buffer system. *Transactions of the American Society of Agricultural Engineers*. 40: 1047-1057.*

    Value: 0 for buffer-toxics data analysis because the reduction in concentration could have been due to dilution. Type: Observational (?). Location: Eastern U.S.

    Abstract: "Effect of a riparian forest buffer system (RFBS) on transport of two herbicides, atrazine and alachlor, was studied during 1992-1994. Herbicides were applied to an upland corn crop in March of each year. The buffer system was managed based on USDA recommendations and averaged 50 m in width. The system included a grass buffer strip immediately adjacent to the field (Zone 3); a managed pine forest downslope from the grass buffer (Zone 2); and a narrow hardwood forest containing the stream channel system (Zone 1). After the first year of the study, the managed forest was clear-cut in 1/3 and thinned in 1/3 of Zone 2. The other 1/3 of Zone 2 was left as mature forest. Most of the herbicide transport in surface runoff occurred before 30 June with about 25 cm of cumulative rainfall after herbicide application. During this period of higher herbicide transport, atrazine and alachlor concentrations averaging 34.1 µg L–1 and 9.1 µg L–1 at the field edge, respectively, were reduced to 1 µg L–1 or less as runoff neared the stream. There were generally no differences among the mature forest and the two treatment areas (clear-cut and thinned) for either concentration or load in surface runoff. Using precipitation data collected on site, the effects of dilution versus other concentration reduction factors (infiltration, adsorption) was estimated for surface runoff. Concentration reduction was greatest per meter of flow length in the grass buffer adjacent to the field. There was only minor transport of herbicides through the buffer system in shallow groundwater and little difference between the Zone 2 treatment areas. In 1992 and 1993, herbicide concentrations in shallow groundwater in the RFBS and at the edge-of-field were generally at or below detection limits. In 1994, well concentrations of both herbicides increased, probably in response to infiltration of surface runoff containing high herbicide concentrations. Average herbicide concentrations were at or below detection limits in groundwater near the stream for most of 1994."

12. **Mersie, W., Seybold, C.A., McNamee, C., and Lawson, M.A. 2003. Abating endosulfan from runoff using vegetative filter strips: the importance of plant species and flow rate. *Agriculture, Ecosystems and Environment*. 97: 215-223**.

    Value: 1 for toxics/buffer analysis- good study design but used simulated runoff which is incomparable to natural rainfall/runoff data. Location: Virginia. Type: Experimental, control-treatment.

    Abstract: "Vegetative filter strips (VFS) can reduce the load of agricultural chemicals from runoff. Despite their heavy promotion, quantitative data is lacking on the performance of different grass species in filter strips and their effectiveness under different flow rates. The purpose of this study was to compare and determine the effectiveness of switchgrass (Panicum virgatum L.) and tall fescue (Festuca arundinacea Schreb) filter strips in removing dissolved endosulfan from runoff flowing at different rates. Aluminum tilted beds filled with Bojac soil, set at 3% slope and planted to switchgrass or tall fescue or bare soil were used.

Runoff was simulated by applying runon containing endosulfan (mixture of α and β isomers) at the up-slope section of the beds at 2.7 or 6 l min−1 over 0.9 m wide soil surface. Results indicate no preferential removal of one endosulfan isomer over the other. Total endosulfan removed ranged from 98 to 100% (percent of applied) for the 2.7 l min−1 runon application rate, and 39–54% for the 6.0 l min−1 runon application rate. All the applied runon infiltrated tall fescue planted beds at the slower flow rate whereas at the faster flow rate, only 29% penetrated the fescue bed. Endosulfan was filtered out of the surface runoff and leachate collected. From overland flow, concentrations of endosulfan were reduced by about 60–80% at the 2.7 l min−1 application rate and by 27–39% at the 6.0 l min−1 runon application rate. Adsorption to soil is the primary mechanism for removal of endosulfan from overland flow and from leachate. The effectiveness of the grasses was more important when the runon moves fast. At both flow rates, more endosulfan adsorbed to the soil in the first 0–67 cm section of the beds than from the down slope (67–133 or 133–200 cm) sections and adsorbed to the soil in the top 0–10 cm depth. Results indicate that most of the insecticide was removed in the first one-third of the filter strip."

13. Mersie, W., Seybold, C.A., McNamee, C, and Huang, J. 1999. Effectiveness of switchgrass filter strips in removing dissolved atrazine and metolachlor from runoff. J. Environ. Qual. 28:816 - 821.*

    Abstract: "The effectiveness of switchgrass (Panicum virgatum L.) filter strips in removing dissolved atrazine (2-chloro-4-ethylamino-6-isopropylamino-1,3,5-triazine) and metolachlor (2-chloro-N-2-ethyl-6-methylphenyl-, V-2-methoxy-1-methylethyl acetamide) in runoff was investigated using aluminum-tilted beds set at 1% slope, filled with Emporia sandy loam soil (fine-loamy, siliceous, thermic Typic Hapludults) and planted to switchgrass. Solution containing herbicides, followed by water alone after 2 and 4 wk were applied on the up slope of beds with and without switchgrass. Water samples from surface flow, lateral, and vertical leachates as well as soil samples were analyzed for the two herbicides using a gas chromatograph. Switchgrass filter strips reduced the mass of dissolved atrazine and metolachlor by 52 and 59% from the applied runon, respectively. The bare soil strips removed 41% of atrazine and 44% of metolachlor. Less than 0.5% of the applied herbicide was released by the two water runons 2 and 4 wk after herbicide-solution application. The average concentrations of both herbicides in surface runoff were greater than in leachate samples. Herbicides were removed by the soil as runon moved through the soil profile. The concentration of either herbicide on the top surface (0-2.5 cm) was greater than in the soil immediately below it (2.5-5 cm). Degradation of both herbicides was faster in beds with switchgrass than without. Greater amounts of both herbicides were retained in the first 67-cm section of beds with the grass than without. Switchgrass helped to remove the herbicides by slowing runoff velocity and increasing their retention by soil."

14. **Mickelson, S.K., Baker, J.L., and Ahmed, S.I. 2003. Vegetative filter strips for reducing atrazine and sediment runoff transport. *Journal of Soil and Water Conservation*. 58: 359-367**.

Value: 1 for toxics/buffer analysis- good study design but used simulated rainfall which is incomparable to natural rainfall/runoff data. Type: Experimental, before-after. Location: Iowa.

Abstract: "A rainfall simulation study was performed on twelve vegetative filter strips (VFS), six 1.5 × 4.6 m (5 × 15 ft) long, and six 1.5 × 9.1 m (5 × 30 ft) long, to determine: (1) the effects of vegetative filter strips on atrazine and sediment transport in runoff inflow with an average of 7,650 mg L-1 sediment (WS) and no-sediment (NS), and (2) the effects of vegetative filter strips length (4.6 and 9.1 m) (15 and 30 ft), and thus area ratio (with constant width), on atrazine and sediment transport. Herbicide runoff losses were simulated by adding a dilute atrazine solution as inflow (with sediment and without sediment) to the upper end of the vegetative filter strips. The with-sediment treatment was used to represent conventional tillage, while the without-sediment treatment represented no-tillage. Atrazine, and bromide (Br) as a hydrologic tracer, were dissolved in the inflow to the vegetative filter strips at a concentration of approximately 1 and 23 mg L-1, respectively. The results showed that for the with-sediment inflow treatment, the 87% reduction in sediment transport for the 9.1 m (30 ft) vegetative filter strips was significantly (P = 0.05) greater than the 71% reduction for the 4.6 m (15 ft) vegetative filter strips. There was no significant difference in atrazine transport between the with-sediment and without-sediment treatments, but the 80% reduction in atrazine transport for the 9.1m (30 ft) vegetative filter strips was significantly greater than the 31% reduction for the 4.6 m (15 ft) vegetative filter strips. Infiltration of inflow was a dominant factor in reducing atrazine transport with vegetative filter strips, and the Br data showed that a higher proportion of inflow infiltrated than did rainfall."

15. **Misra, A., J.L. Baker, S.K. Mickelson, and H. Shang. 1996. Contributing area and concentration effects on herbicide removal by vegetative buffer systems. *Trans. of the ASAE* 39(6):2105-2111.**

Value: 1 for toxics/buffer analysis- good study design but used simulated runoff which is incomparable to natural rainfall/runoff data. Type: experimental, before-after, simulated rainfall; Location: Iowa. This is a study of the effectiveness of buffer strips at removing dissolved herbicides- atrazine, metolachlor, cyanazine. Soil: loam, 2-3% slope. 12 plots, 12.2m long. Inflows were manipulated to simulate either 15:1 or 30:1 buffer area ratio (BAR). Four treatments replicated three times. Simulated rainfall was 6.35cm/hr for 1 hr. Inflow concentrations were manipulated to be either 0.1mg/L or 1.0mg/L. At the 15:1 BAR, atrazine mass removal was 31.2% at the low concentration and 49.8% at the higher concentration. At the 30:1 BAR, atrazine mass removal 26.4% at the low concentration and 47.5% at the higher concentration. At the 15:1 BAR, metolachlor mass removal was 31.5% at the low concentration and 46.8% at the higher concentration. At the 30:1 BAR, metolachlor mass removal was 27.4% at the low concentration and 41.8% at the higher concentration. At the 15:1 BAR, cyanazine mass removal was 30.1% at the low concentration and 46.6% at the higher concentration. At the 30:1 BAR, cyanazine mass removal was 25.6% at the low concentration and 42.4% at the higher concentration. A steady-state infiltration rates the removal rates were substantially lower than the removal rates noted above. Infiltration accounted for most of the removal, adsorption to vegetation was estimated to account for 0 to 10% of removal.

16. **Nichols, D.J., Daniel, T.C., Edwards, D.R., Moore Jr., P.A. and Pote, D.H. 1998. Use of grass filter strips to reduce 17β-estradiol in runoff from fescue-applied poultry litter. *J. Soil Water Conserv*. 53(1):74-77.***

    Value: 1 for toxics/buffer analysis- good study design but used simulated rainfall which is incomparable to natural rainfall/runoff data. Type: Experimental before-after.

    Abstract: "Discharge of hormones contained in poultry litter into the environment may disrupt the health and reproduction of fish and other animals. A runoff study was conducted to evaluate grass filter effectiveness in reducing transport of the estrogen hormone 17β-estradiol in runoff from pasture-applied poultry litter. The study objectives were to determine the effects of source (litter-treated) length and grass filter length on runoff concentrations and losses of 17β-estradiol from poultry litter applied to tall fescue (Festuca arundinacea Schreber) plots. Litter was applied at 5 Mg/ha (2.2 ton/ac) to the upslope 6.1, 12.2, and 18.3 m (20, 40, and 60 ft) of 24.4-m (80-ft) long grass strips. The corresponding grass filter lengths were 18.3, 12.2, and 6.1 m (60, 40, and 20 ft), respectively, with the downslope edge of source areas evaluated as a 0-m long filter. Simulated rain was applied at 50 mm/h (2 in/h) to produce runoff samples for 17β-estradiol analysis. Runoff concentrations and mass losses were not significantly affected by source length and averaged 3.5 µg/L (ppb) and 1413 mg/ha (0.02 oz/ac), respectively. Runoff concentrations were reduced by 58, 81, and 94% and mass losses by 79, 90, and 98% by filter lengths of 6.1, 12.2, and 18.3 m (20, 40, and 60 ft), respectively. The data from this research indicates that grass filter strips can effectively reduce runoff transport of 17β-estradiol from tall fescue-applied poultry litter."

17. Paterson, K.G. and Schnoor, J.L. 1992. Fate of alachlor and atrazine in a riparian zone field site. *Water Environ. Res*. 64(3):274-283.*

    Value: 0 for buffer-toxics data analysis, 1 for transport process info.

    Abstract: "A field site was established and instrumented in Amana, Iowa to investigate the fate and transport of the pesticides alachlor and atrazine in the unsaturated zone adjacent to a drainage lake. The pesticides were applied to a barren plot, a plot planted with corn, and a plot planted with deep-rooted poplar trees (Populus spp.) to study the characteristic behaviors of a typical agricultural environment (corn plot) and a novel pollutant interception technique (poplar plot) in comparison to unmanaged land (barren plot). A mass balance model was developed and solved for the pesticides on each of the three plots. While the majority of alachlor and atrazine adsorbed to the soil and eventually degraded or accumulated in the unsaturated zone, portions of the pesticides remained in the aqueous phase and subsequently were transported in the surface runoff and to the water table. Alachlor was found to be more mobile and more quickly transformed than atrazine. Plant uptake was an important process in the fate of the pesticides, and hence, vegetative buffer strips hold promise for protecting water supplies."

18. **Patty, L., B. Real, and J.J. Gril. 1997. The use of grassed buffer strips to remove pesticides, nitrate and soluble phosphorus compounds from runoff water. *Pesticide Sci.*49:243-251.**

Value: 3 for toxics/buffer analysis. Location: France. Type: Experimental, control-treatment, before-after.

Abstract: "Experiments on grassed buffer strips have been conducted since 1993 by ITCF (Institut Technique des Céréales et des Fourrages) at three research farms (La Jaillière, Bignan and Plélo). Literature data and conclusions drawn from previous work with isoproturon and diflufenican were confirmed in a range of soil and cropping conditions: grassed buffer strips are effective in restricting pollutant transfer in runoff; those with widths of 6, 12 and 18 m reduced runoff volume by 43 to 99·9%, suspended solids by 87 to 100%, lindane losses by 72 to 100% and loss of atrazine and its metabolites by 44 to 100%. More than 99% of isoproturon and 97% of diflufenican residues in runoff were removed by buffer strips. Nitrate and soluble phosphorus in runoff were reduced by 47 to 100% and by 22 to 89%, respectively. At La Jaillière, a rainfall simulator was used in 1995 to verify that buffer strips are still effective in conditions of intense runoff. Investigation of the influence of sowing direction during the 1994–95 cropping period at Bignan showed that sowing perpendicular to the slope seemed to be beneficial in reducing pesticide content in runoff."

This study used natural rainfall which ranged from 650 to 920mm/year among the three study sites. Soil types among the three study sites were silt loams with 12 to 20% clay and 3 to 7% organic matter. Mean plot slope ranged from 7 to 15% among the three sites. The 6,12, and 18, m filter strips had rye grass strips that ranged in age from 1.5 to 3.5 yrs among the sites.

The Koc of the pesticides examined are: Isoproturon = 120cm^3/g^{-1}; Diflufenican = 1990cm^3/g^{-1}; Lindane = 1100cm^3/g^{-1}; Atrazine= 100cm^3/g^{-1}. Less than 1% of the pesticide mass applied to the cropped area of the plots was transported by runoff into the filter strips.

The average mass removal effectiveness among the study sites was as follows:

- Lindane- 6m filter strip = 82.5%; 12m strip = 99.5%; 18m strip = 100%
- Atrazine- 6m strip = 70.5%; 12m strip = 79.9%; 18m strip = 98.5% (results for 2 atrazine metabolites are also reported and show very similar results.
- Isoproturon- 6m strip = 99.7%; 12m strip = 99.9%; 18m strip = 99.9%
- Diflufenican – 6m strip = 97.4%; 12m strip = 99.8%; 18m = 99.9%.

19. Payne, N.J., Helson, B.V., Sundaram, K.M.S., Fleming, R.A. 1988. Estimating buffer zone widths for pesticide applications. *Pesticide Science.* 24: 147-161.

Value: 0 for buffer data analysis, 2 for info linking buffer width to pesticide application effects upon aquatic life. Type: Experimental, control-treatment. Location: Ontario, Canada.

Abstract: "A technique for estimating the width of buffer zones required around sensitive areas during pesticide applications has been devised and tested. The technique has been used to estimate the buffer width required around water bodies during ground-based

permethrin applications in Canadian forests to prevent significant impact on fish and their food populations. A worst- case scenario was developed for environmental impact in water bodies resulting from ground-based permethrin applications, and a spray application was made under these worst-case conditions. Permethrin deposit on ground sheets was measured downwind of overlaid crosswind swaths. From these measurements the deposit at various downwind distances from a single crosswind swath was calculated, and a curvilinear regression line fitted to these values. Permethrin deposit downwind of multiple-swath applications was computed by adding the contributions from individual swaths. Mortality resulting from various permethrin concentrations was measured for Aedes aegypti larvae. Although these larvae are not an important food species for the fish species of interest, salmon and trout, they are more sensitive to permethrin than most aquatic invertebrates. Predicted mortality in populations of this species and Salmo gairdneri, rainbow trout, at various downwind distances from the permethrin application was calculated from the toxicological and spray-cloud dispersal data. Buffer width was estimated by choosing an acceptably low mortality and determining the downwind distance at which this value was obtained. For example, a 20 m swath width was found to be adequate to limit mortality in A. aegypti and S. gairdneri populations to 10 and 0.1% during ground-based permethrin applications."

The vegetation was white spruce, quaking aspen, and jack pine averaging 0.8, 2.6, and 1.3m in height, respectively. Permethrin is relatively insoluble in water and readily adsorbs onto sediment.

20. Popov, V.H., Cornish, P.S., and Sun, H. 2006. Vegetated biofilters: the relative importance of infiltration and adsorption in reducing loads of water-soluble herbicides in agricultural runoff. *Agriculture, Ecosystems and Environment*. 114: 351-359.

Value: 1 for toxics/buffer analysis- good study design but used simulated rainfall which is incomparable to natural rainfall/runoff data; simulated rainfall and runoff are typically applied at much greater than natural rates, which causes much variability in the results. Location: Australia. Type: Experimental, before-after.

Abstract: "Runoff from cropland containing agricultural pesticides is the main contributor to poor water quality on the Liverpool Plains, Australia. The potential for vegetated biofilters to reduce the loads of two moderately soluble herbicides (atrazine and metolachlor) in runoff water was studied in grassed filter strips (1.25 m × 4 m) on cracking vertisol soil. Run-on with known concentrations of herbicide and sediment was introduced to field plots as surface flow. Cumulative depths of 80, 160, 320 and 800 mm were applied to dry, cracked soil, and 20, 40, and 80 mm to plots that had previously been watered in an attempt to induce crack closure. Volumes of runoff and pollutant concentrations were measured to allow load reduction to be partitioned between infiltration and reduced concentration. Biofilters reduced total loads by 40–85% for atrazine, 44–85% for metolachlor and 57–93% for sediment, demonstrating their benefits even where run-on depths are high. The reduction in atrazine and metolachlor concentrations was substantial (∼25–49% and ∼30–61%, respectively) for run-on depths of 80 mm or less, despite the moderate solubility of atrazine (∼33 mg L^{-1}) and high solubility of metolachlor (520 mg L^{-1}). Loads of sediment were reduced at even greater total run-on depths (up to 320 mm). Where run-on depths were in the range 160–800 mm, infiltration was the only mechanism that significantly reduced herbicide loads. The possible errors associated with small plot studies are discussed. The clarification of role of adsorption and infiltration in filtering processes provides a foundation for improving simulation models in order to produce realistic appraisal of biofilter effectiveness.”

Infiltration played a major role in buffer retention of both chemicals and sediment adsorption appeared to be important at low run-off depths.

21. Reungsang, A., Moorman, T.B., and Kanwar, R.S. 2001. Transport and fate of atrazine in midwestern riparian buffer strips. *Journal of the American Water Resources Association*. 37: 1681-1692.

    Value: 0 for toxics-buffer data analysis, 1 for atrazine leaching process info. Type: Observational. Location: Iowa. This was a study of atrazine leaching and degradation in crop fields versus buffer strips. Soil: sandy loam. Buffer strips were 3-, 5-, and 9-year-old switchgrass buffers with shrubs and trees. Crop field was in corn-soybean rotation. A grass-alfalfa pasture was also examined. Organic carbon was approximately twice as high in the buffer strip. Evidence of increased preferential flow as age of grassed buffer increased. Atrazine leaching was about the same in the two older buffer strips and pasture. Atrazine was degraded more rapidly in the crop field, which was thought to be due to much higher density of atrazine-degrading microorganisms in the crop field. Lower degradation and more leaching in the older buffer strips theoretically increase the risk of groundwater contamination, but this was thought to be offset by the greater capacity of the buffer strip soils to adsorb atrazine, thus suggesting equivalent hazard for crop soils and buffer soil.

22. Rice, C., Bialek, K., Hapeman, C. J., and McCarty, G. W. 2016. Role of Riparian Areas in Atmospheric Pesticide Deposition and Its Potential Effect on Water Quality. *JAWRA*. 52(5):1109-1120.

    Value: 0 for buffer-toxics data analysis, 2 for pesticide volatization/transport info. Type: Observational? Location: Maryland. This study measured atrazine and metolachlor in throughfall and stemflow of a forested riparian buffer adjacent to a corn field. Red maple was the dominant tree species in the riparian zone. The riparian zone width varied from 60 to 250m in width (appears to be the two-sided width). The crop field of interest was a 20-hectare corn field. In years 1, 3, and 4, metolachlor and atrazine were applied to bare soil soon after planting; in year 2, a wet spring delayed application until July when plants were 3 in. tall. Herbicide drift after application typically lasts a day or less (sometimes 2-3) while transport by volatilization can last for roughly one week (sometimes >20 days). Stemflow and throughfall in a riparian zone can be the primary source of herbicide delivery to streams during non-runoff events. Stemflow concentrations were larger than throughfall concentrations. Metolachlor fluxes and concentrations were generally greater than that of atrazine, likely due to greater solubility and Koc (which would cause it to adsorb to tree surfaces more readily). The largest fluxes occurred at the beginning of the growing season during precip events. The study indicates that throughfall and stemflow can serves as a direct path for pesticides to enter surface waters even during precip events that do not generate non-runoff.

23. Sabbagh, G.J., Fox, G.A., Kamanzi, A., Roepke, B., and Tang, J. –Z. 2009. Effectiveness of vegetative filter strips in reducing pesticide loading: quantifying pesticide trapping efficiency. *J. Environ. Qual*. 38: 762-771.

    Value: 0 for buffer-toxics data analysis, 2 for pesticide transport process info. Type: Meta-analysis, modelling. This is a meta-analysis that employed modelling to identify what influences the effectiveness of buffers for pesticide removal. Data was compiled from 127 published journal articles; only five had data deemed essential for performing the analysis- water volume, sediment masses, sediment-bound pesticide masses, buffer strip size, soil characteristics. Buffer width was not a significant factor in the model. Sediment reduction, phase distribution (i.e., ratio of mass of pesticide in dissolved vs. sorbed fractions- volume of water divided by the product of sorption coefficient and sediment mass entering the buffer), infiltration, and % clay content in the soil were significant factors. The adjusted R^2 of the model was 0.84. For pesticides with high mobility (i.e., Koc ≤ 147 L/kg), the phase distribution, sediment reduction, and % clay became insignificant factors- such that only infiltration mattered. For low mobility pesticides (i.e., Koc ≥9930 L/kg), phase distribution and sediment reduction were the only significant factors. Insufficient data was available to evaluate the model for pesticides with mid-range Koc values. This model outperformed the SWAT model, which is based on buffer width. This indicates that buffer width can provide general estimates of pesticide reductions, but not accurate site- or event-specific reduction estimates. However, the authors recognized that the data needed to perform the model (in particular infiltration rates and sediment mass reductions in a buffer- which would require a buffer to be pre-established) would generally be unavailable for site specific applications.

24. **Schmitt, T.J., Dosskey, M.G.G., and Hoagland, K.D. 1999. Filter strip performance and processes for different vegetation widths and contaminants. *Journal of Environmental Quality*. 28: 1479-1489.**

    Value 1 for toxics/buffer analysis- good study design but used simulated runoff which is incomparable to natural rainfall/runoff data; simulated rainfall and runoff are typically applied at much greater than natural rates (e.g., “worst case scenario designs”), which causes much variability in the results. Type: Experimental, before-after. Location: Nebraska. The effectiveness of different filter strip designs at removing permethrin, atrazine, alachlor, nitrate, and phosphorus was evaluated. Soils: fine, montmorillonitic, mesic, Typic Argiudoll (silty clay loam); hydrologic soil group B. Slope = 6-7%. Plot age was 15 months. Forty plots, with lengths of either 7.5m or 15m. Study design was randomized complete block with 2 x 4 factoral design. Plots were either 25yr old grass plots, 2yr old switchgrass/tall fescue with volunteer plants (70-100% cover), 2yr old ½ switchgrass/fescue on upper half and ½ shrub/tree on lower half (honeysuckle, currant, cottonwood, silver maple), or annually planted sorghum. Simulated rainfall at rate of 25.4mm in 30 minutes (1 yr return frequency for study area). Buffer width had a significant effect on concentrations of all contaminants except atrazine, upon which a significant effect occurred only for 25yr old grass and sorghum plots. Sediment trapping was lower in the sorghum plots. Infiltration did not differ among vegetation types. Dilution occurred in the plots. TN, TP, and dissolved phosphorus had moderate reductions in concentrations due to duel dissolved/sediment-bound phases. Sediment-bound P and permethrin were reduced less than sediment, likely because of adsorption to the finer particle fraction. The 15m long strips had greater infiltration and dilution but did not increase sediment trapping. Adding trees and shrubs did not improve effectiveness (although the plants were young). The filter strips reduced sediment-associated, but not dissolved contaminants and runoff volume relative to the sorghum plots.

Combined mass reductions for the 25yr old grass plots (from bar graphs)- 7.5m plots: nitrate + nitrite- ~65%; TN- ~70%; atrazine- ~62%; alachlor- ~70%; permethrin- ~85%; dissolved P- ~62%; bioavailable P- ~75%; total P- ~85%; TSS- ~95%.

Combined mass reductions for the 25yr old grass plots (from bar graphs)- 15m plots: nitrate + nitrite- ~90%; TN- ~90%; atrazine- ~88%; alachlor- ~92%; permethrin- ~95%; dissolved P- ~88%; bioavailable P- ~92%; total P- ~95%; TSS- ~98%.

Combined mass reductions for the sorghum plots (from bar graphs)- 7.5m plots: nitrate + nitrite- ~55%; TN- ~58%; atrazine- ~58%; alachlor- ~60%; permethrin- ~45%; dissolved P- ~62%; bioavailable P- ~65%; total P- ~70%; TSS- ~78%.

Combined mass reductions for the sorghum plots (from bar graphs)- 15m plots: nitrate + nitrite- ~86%; TN- ~88%; atrazine- ~82%; alachlor- ~85%; permethrin- ~90%; dissolved P- ~90%; bioavailable P- ~88%; total P- ~90%; TSS- ~92%.

25. **Seybold, C., Mersie, W., and Delirem, D. 2001. Removal and degradation of atrazine and metolachlor by vegetative filter strips on clay loam soil. *Communications in Soil Science and Plant Analysis*. 32: 723-737.**

Value: 1 for toxics/buffer analysis- good study design but used simulated rainfall which is incomparable to natural rainfall/runoff data; simulated rainfall and runoff are typically applied at much greater than natural rates, which causes much variability in the results. Location: Virginia. Type: Experimental, before-after.

Abstract: "The effectiveness of filter strips, with and without vegetation, in removing dissolved atrazine and metolachlor in runoff was investigated using aluminum tilted beds set at 1% slope on Cullen clay loam soil. Runon containing atrazine and metolachlor was applied on the up-slope end of the simulated filter strips. Water samples from surface runoff, lateral subsurface movement, and leachates as well as filter strip soil samples were collected, and herbicide concentrations determined. The filter strips reduced the amount of dissolved atrazine and metolachlor in runoff by about 6% of the amount applied. The absence or presence of switchgrass did not affect the amount of herbicide filtered. About 56 to 82% of the runon volume leached through the 30-cm soil depth of the filter strips. In the leachate, about 72 to 88% of the amount of applied herbicide was filtered or adsorbed to the soil. The presence of switchgrass reduced the amount of runoff volume and increased the amount of leachate volume. In total, about 53 to 73% of the amount of herbicide applied was removed by the filter strips. The primary mode of dissolved herbicide removal in applied runon was by infiltration and soil adsorption mechanisms. Soil herbicide

concentrations were greatest at the 0 to 10 cm depth, decreased to less than 50 µg kg−1 over a 7-week period. In the filter strip soil, the presence of switchgrass significantly increased the degradation rate of metolachlor, but not atrazine. Infiltration of runoff into the filter strips is key to reducing dissolved herbicides from moving offsite. The presence of surface connected macropores is important in facilitating this process on heavier textured soils."

26. **Syversen, N., and Bechmann, M. 2004. Vegetative buffer zones as pesticide filters for simulated surface runoff. *Ecological Engineering*. 22: 175-184.**

    Value: 1 for toxics/buffer analysis- due to lack of infiltration data and use of simulated runoff which is incomparable to natural rainfall/runoff data; simulated rainfall and runoff are typically applied at much greater than natural rates, which causes much variability in the results. Type: Experimental, before-after, simulated runoff. Location: Norway. This is an evaluation of buffer removal of glyphosate, fenpropimorph, propiconazole, and sediment in simulated runoff. Field and buffer slope = 14%. Soil = silty clay loam. Buffer zones were 5m wide and vegetated with several grasses. Runoff during the four trial runs was maintained at 0.4L/s. The buffer was saturated with water to facilitate surface runoff. Surface runoff and preferential runoff occurred, but the paper presents only the surface runoff results. Average reductions in concentrations were: 39% for glyphosate; 71% for fenpropimorph; 32% for propiconazole (63% when an outlier was omitted by the authors); 62% for sediment. Soluble fraction concentration reductions were: 24-70% for glyphosate, 32-78% for propiconazole and 61-73% for fenpropimorph.

27. **Tingle, C.H., Shaw, D.R., Boyette, M., and Murphy, G.P. 1998. Metolachlor and metribuzin losses in runoff as affected by width of vegetative filter strips. *Weed Science*. 46: 475-479.**

    Value: 1 for toxics/buffer analysis- used simulated rainfall which is incomparable to natural rainfall/runoff data; simulated rainfall and runoff are typically applied at much greater than natural rates, which causes much variability in the results. Abstract: "Tall fescue vegetative filter strips 0.5 to 4.0 m wide were evaluated for their ability to reduce losses of metolachlor, metribuzin, and runoff (water and sediment) in conventionally tilled soybean. Differences in the parameters studied were significant between filter and no filter strips, regardless of filter strip width. Two days after treatment, metribuzin concentration in runoff from the unfiltered treatment was 231 ng ml-1; filter strips reduced this amount to 119 ng ml-1 or less. Similar trends were observed with metolachlor, with concentrations of 1,009 ng ml-1 from the unfiltered, whereas filter strips of any width reduced this to 523 ng ml-1 or less. Metribuzin loss during the growing season was 41 g ha 1, or 9.8% of the amount applied when no filter strip was present. The addition of a filter strip, regardless of width, reduced cumulative metribuzin losses to 11 g ha-1 or less. Similar results were noted with metolachlor. Filter strips, regardless of width, reduced cumulative runoff and sediment loss at least 46 and 83%, respectively."

28. **Vellidis, G., Lowrance, R., Gay, P., and Wauchope, R.D. 2002. Herbicide transport in a restored riparian forest buffer system. *Transactions of the American Society of Agricultural Engineers*. 45: 89-97**.

Value: 3 for buffer-toxics data analysis.

Abstract: "Little is known about the effects of restored riparian forest buffers on transport of herbicides. The effect of a restored riparian forest buffer system (RFBS) on transport of two herbicides, atrazine and alachlor, was studied during 1993–1994. Herbicides were applied above a restored 3–zone riparian buffer system in April of 1993 and 1994. Bromide was applied as a tracer with the April 1993 herbicide application. The buffer system was managed based on USDA recommendations and averaged 38 m in width. The system included a grass buffer strip immediately adjacent to the application area (zone 3), an area of planted pines downslope from the grass buffer (zone 2), and a narrow area of planted hardwoods containing the stream channel system (zone 1). Most of the herbicide transport in surface runoff occurred before June 30 with about 250 mm of cumulative rainfall after herbicide application. During this period of higher herbicide transport, atrazine and alachlor concentrations averaging 12.7 g L –1 and 1.3 g L –1 , respectively, at the field edge were reduced to 0.66 g L –1 and 0.06 g L –1 , respectively, as runoff neared the stream. The effect of dilution versus other concentration reduction factors (infiltration, adsorption) was estimated for surface runoff using the bromide concentration data. Concentration reduction was greatest per meter of flow length in the grass buffer adjacent to the field. There was only minor transport of herbicides through the buffer system in shallow groundwater. Average herbicide concentrations were at or below detection limits in groundwater near the stream for the entire study period. The restored riparian forest buffer had similar effects on herbicide transport as a mature buffer."

29. **Vianello, M., Vischetti, C., Scarponi, L., and Zanin, G. 2005. Herbicide losses in runoff events from a field with low slope: role of a vegetative filter strip. *Chemosphere* 61: 717-725.**

    Value: 1 for toxics/buffer analysis- good study design but used simulated runoff which is incomparable to natural rainfall/runoff data; simulated rainfall and runoff are typically applied at much greater than natural rates, which causes much variability in the results. Type: Experimental, control-treatment. Location NE Italy. This is a study of the effectiveness of filter strips at reducing metolachlor, terbuthylazine, and isoproturon from natural and simulated runoff. Soil: fulvi-Calcaric Cambisol (silty-loam) with medium low hydraulic conductivity (4.7 x 10^{-4} cm/s). Slope= 1.8%. Plots were 20m x 35m, with two plots having no filter strip, two plots with a 6m grass filter with two shrub/tree rows (planted 3 yrs prior to experiment). Plots were rotated from corn to winter wheat to soybeans, with herbicides applied at various times. The two simulated rainfall events were 52mm at 43mm/hr intensity and 87mm at 82mm/hr intensity. In 2000, Metolachlor average mass reduction was 85.7%, Terbuthylazine (the least soluble/most adsorbed chemical of the three) average mass reduction was 91.9%. In 2001, Isoproturon (the most soluble/least adsorbed) average mass reduction was 97.9% and metolachlor average mass reduction was 93%. There was some evidence of remobilization of isoproturon and metolachlor in successive runoff events. Herbicide losses were less than 0.5% of the applied dosage. High concentrations of isoproturon and Terbuthylazine were observed during the first rainfall after application.

30. Wu, J., Mersie, W., Atalay, A., and Seybold, C.A. 2003. Copper retention from runoff by

switchgrass and tall fescue filter strips. *Journal of Soil and Water Conservation*. 58: 67-72.*

Value: 1 for toxics/buffer analysis- used simulated runoff which is incomparable to natural rainfall/runoff data; simulated rainfall and runoff are typically applied at much greater than natural rates, which causes much variability in the results. Type: Experimental, control-treatment.

Abstract: "Vegetative filter strips are recommended to reduce the load of agricultural chemicals in surface runoff. Quantitative data, however, is still needed on the performance of various grass species in filter strips and their effectiveness under different runoff flow rates. A study was conducted to compare the effectiveness of switchgrass (Panicum virgatum L.) and tall fescue (Festuca arundinacea Schreb.) filter strips in removing dissolved copper pesticide from runoff flowing at 2.7 L (0.7 gallon min−1) or 6 L (1.6 gallon min−1) over 0.9 m (3 ft) soil surface area. Runoff was simulated by applying 82-L (22 gallon) solutions containing 6.9 mg L−1 (6.9 ppm) Copper (Cu) on aluminum tilted-beds set at 3% slope, filled with Bojac soil, and planted to switchgrass or tall fescue. The total infiltrated (leached plus retained) expressed as percent of applied was 21% for soil beds having no grass, 33% for switchgrass beds, and 28% for tall fescue beds at 6.0 L min−1 (1.6 gallon min−1) flow rate. At the slow flow rate (2.7 L min−1, 0.7 gallon min−1), 77%, 97% and 100% of the applied runon infiltrated in no grass, switchgrass and tall fescue beds, respectively. About 60% of the applied Cu was removed by both grasses from runoff at 6.0 L min−1 (1.6 gallon min−1) flow rate whereas at the slow flow rate, grasses helped remove all the applied Cu. Average concentration of Cu in surface runoff from all beds was 3.3 mg L−1 (3.3 ppm) whereas for leachate samples it was 0.2 mg L−1 (0.2 ppm). Adsorption to soil appeared to be the primary mechanism of removal of Cu from overland flow and leachate. When runoff moved at 2.7 L min−1 [0.7 gallon min−1) in the tall fescue filter strips, greater amounts of Cu were retained in the up-slope one third of the filter strips. This indicates that a relatively small, tall fescue filter strip would be adequate to remove Cu in areas where runoff is expected to move at slow flow rate. The grass filter strips reduced dissolved Cu in runoff by increasing its infiltration and its retention by soil."

31. Zhang, X., Liu, X., Zhang, M., and Dahlgren, R. A. 2010. A review of vegetated buffers and a meta-analysis of their mitigation efficacy in reducing nonpoint source pollution. *Journal of Environmental Quality*. Vol. 39: 76-84.

    This paper describes a meta-analysis of pesticide reductions in buffers. See summary in sediment section.

Section 2: Additional Primary Literature Relevant to Riparian Management Zones

Large Wood Recruitment

1. Bahuguna, D.; S.J. Mitchell; and Y. Miquelajauregui. 2010. Windthrow and recruitment of large woody debris in riparian stands. Forest Ecology and Management 259:2048-2055.

   Value: 0 for data analysis. Bahuguna et al. (2010, *published*) monitored nine streams to examined impacts of windthrow in riparian leave streams. Three used 10 m 2-sided buffers, three used 30 m buffers, and three were controls. Authors report there was very little windthrow or recently downed material prior to harvesting. After the 1998 harvest, 11% of initially standing trees were blown down in the first and second years in the 10 m buffer treatment compared with 4% in the 30 m buffer and less than 1% in unharvested controls. There was minimal new windthrow again until a storm occurred in 2006. There was reported to be a significant amount of annual mortality in standing trees, particularly in the unharvested control, amounting to 30% of initially live trees in the control and 15% each in the 10 m and 30 m (32.8 and 98.4 ft.) buffers after 8 years. The second growth trees in this study produced LWD that was in the 10 – 30 cm class (3.9 -11.8 in.). Few logs had dropped into the stream channel in any of the treatments. The dominant fall direction was as would be expected given the dominant wind direction from the southwest. Stands were described as dense young stands and the streams were all under 5 m (16.4 ft.) wide and described as incised and constrained, which would favor a greater proportion of wood spanning the channel. Stands were 51% western hemlock, 38% red cedar, 6% Douglas-fir and 5% other species. Researchers rely on decay class to place wood in a time since harvest time frame, so this might affect strength of estimates on wind fall post-harvest over time. Variability between replicates is not described.

2. Beechie, T.J.; G. Pess; P. Kennard; R.E. Bilby; and S. Bolton. 2000 Modeling Recovery Rates and Pathways for Woody Debris Recruitment in Northwestern Washington Streams. North American Journal of Fisheries Management 20:436–452, 2000.

   Value: 0 for data analysis. Beechie et al. (2000, *published*) Modelled large woody debris (LWD) recruitment and pool formation in northwestern Washington streams after simulated stand-clearing disturbance using two computer models: Forest Vegetation Simulator for stand development and Riparian-in-a-Box for LWD recruitment, depletion, and pool formation. The authors evaluated differences in LWD recruitment and pool formation among different combinations of channel size, successional pathway, and stand management scenario. The models predicted the time to first recruitment of pool-forming LWD is about 50% shorter for red alder Alnus rubra than for Douglas-fir Pseudotsuga menziesii at all channel widths. Total LWD abundance increased faster in red alder stands than in Douglas-fir stands but declined rapidly after 70 years as the stand dies and pieces decompose. Initial recovery is slower for Douglas-fir stands, but LWD recruitment is sustained longer. Total LWD abundance increases faster with decreasing channel size, and pool abundance increases faster with decreasing channel width and increasing channel slope. The models predict thinning of the riparian forest does not increase recruitment of pool forming LWD where the trees are already large enough to form pools in the adjacent channel and that thinning reduces the availability of adequately sized wood. Thinning increases LWD recruitment where trees are too small to form pools and, because of reduced competition, trees more rapidly attain pool-forming size. On channels less than 20 m (65.6 ft.) wide, thinning of red alder and under planting shade-tolerant conifers will reduce near-term alder recruitment and increase long-term conifer recruitment. However, the same treatment on channels more than 20 m (65.6 ft.) wide may increase both near-term and long-term recruitment. The authors suggested that compared with the natural fire regime, timber harvest rotations of 40–80 years during the past century have reduced the percentage of riparian stands that can provide LWD of pool-forming size to streams, especially in channels at least 20 m wide.

3. Benda, L.E.; S.E. Litschert; G. Reeves; and R. Pabst. 2016. Thinning and in-stream wood recruitment in riparian second growth forests in coastal Oregon and the use of buffers and tree tipping as mitigation. J. For. Res. 27:4:821-836.

   Value: 0 for data analysis. Benda et al. (2016, *published*) used a forest growth model coupled with a wood recruitment model to explore riparian management alternatives in a Douglas-fir plantation in coastal Oregon. Alternatives included: 1) no treatment, 2) single and double entry thinning with and without a 10 m (32.8 ft.) buffer, and 3) thinning combined with mechanical introduction of trees directly into the stream. In model simulations, stands were thinned from below from an initial tree density of 687 tph (278 tpa) to 225 tph (91 tpa). The models predicted a cumulative loss in the volume of in-stream wood of 33% integrated over a century with thinning on one stream side, and a 66% loss if thinning occurs on both sides. Adding a 10 m (32.8 ft.) wide no-treatment buffer reduced cumulative loss of wood storage to 7% (or 14% if stands on both sides are thinned). Authors also suggest that doubling the no-cut buffer to 20 m (65.6 ft.), or approximately 2/3 a tree height, increases the maintenance of in-stream wood beyond 95% in thinning on one or both sides of the channel. Based on the above, the authors appear to have modeled a stand with 30 m (98.4 ft.) tall trees. *Of note, no validation of this model is presented or referenced, and simulation was based on forest conditions occurring at a single site in western Oregon.*

4. Benda, L.; and P. Bigelow. 2014. On patterns and processes of wood in northern California streams. Geomorphology 209:79-97.

   Value: 0 for data analysis. Benda and Bigelow (2014, published) examined recruitment across 77 sites in coastal and inland forests of northern California that included a range of management histories. Streams varied in gradient (2.6-10.1%) and channel width (3.5-15.8 m, 9.8-51.8 ft.). The dominant source of variability in stream wood (>10 cm and 1.5 m, 4 in. by 4.9 ft.) storage and recruitment is driven by local variation in rates of bank erosion, forest mortality, and mass wasting. Wood recruitment mortality (wind throw, disease, senescence) was substantial across all sites (mean 50%) followed by bank erosion (43%) and more locally by mass wasting (7%). The distance to sources of stream wood recruitment occurs within 10 to 35 m (32.8 to 114.8 ft.) of channels in managed and less-managed forests and upward of 50 m (164 ft.) in unmanaged Sequoia and coast redwood forests. Forest management influences stream wood dynamics, where smaller trees in managed forests often generate shorter distances to sources of stream wood, lower stream wood storage, and smaller diameter stream wood. Authors' notes 90% of the wood volume originates from within 30 m (98.4 ft.) of the channel in managed coastal forests where landslides comprise 22% of recruitment rate. In less managed forests with taller trees and smaller contributions (0-18%) from landslides, 90% of the wood volume is derived from within 15-35 m (49.2-114.8 ft.) of the channel. In unmanaged and taller coastal redwood and Sierran sequoia forests, the source distance for 90% of wood recruitment is between 35-50 m (114.8-164 ft.). The authors did not detect a relationship between LWD volume and channel size (width and drainage), noting that spatial variation in wood recruitment processes is driven primarily by local variation in watershed attributes such as earthflows, debris flows, streamside landslides, valley width, channel morphology, tributary junctions, and canyons. The one exception was in a managed forest site where bank erosion was greater in small basins compared to larger watersheds.

5. **Burton, J.I.; D.H. Olson; and K.J. Puettmann. 2016. Effects of riparian buffer width on wood loading in headwater streams after repeated forest thinning. Forest Ecology and Management 372:247-257.**

   Value: 1 for data analysis- wood volume data (not enough studies reporting volume data to perform an analysis). Burton et al. (2016, published) examined recruitment in 34 small headwater stream reaches at six forested sites in a replicated field experiment in the Cascade and Coast Ranges of western Oregon and southwest Washington. The treatments were in young second growth forests (controls ~400-600 tph, ~162-243 tpa). The authors' compared three no-harvest streamside buffer treatments (~6m, 15m, and ~70m widths; 20, 50, and 230 ft.), adjacent to which 45 m (150 feet) of forest were thinned twice; first to 200 tph (81 tpa) and then approximately 10 years later to 85 tph (34 tpa). Wood loading (m3/100m) was measured: (1) prior to thinning; (2) year 5 post 1st thinning; (3) immediately prior to the 2nd thinning; and (4) year 1 post 2nd thinning. Thirty-three of the 34 stands were between 44 – 56 years of age and consisted of Douglas-fir with QMDs ranging from 37 to 44 cm (14.6 – 17.3 in). Stream widths ranged from 0.1 – 3.4 m (0.3-11.2 ft.) with portions of all but one stream being less than a foot in width. While the majority of instream wood (10 cm in diameter and 1 m in length, 4 in. and 3.3 ft.) was in late stages of decay and assumed to be biological legacies from the previous forest stand, only 45% of wood in late stages of decay could be associated with a particular source. This contrasts with wood in early stages of decay that could be identified to source over 90% of the time. Wood volume increased exponentially with drainage basin area, suggesting to the authors that instream wood loading depends on management across the entire watershed, however, no improvement of their wood loading model was observed by incorporating gradient or width: depth ratio. The authors note that past harvests and decay may have removed the evidence of the sources for legacy LWD. The authors found that wood in the early stages of decay appeared to be influenced by the thinning treatments and was greatest in reaches with the narrowest buffer width (6m, 20 ft.). The increase in loading of wood in the early stages of decay remained higher than controls until after the second thinning. Relative to the total volume of instream wood, these volumes were small, and their ecological benefit considered uncertain ass the pieces were consisted too small to stabilize other debris in logjams or provide many of the habitat benefits of large diameter pieces. Thinned stands were observed to experience lower mortality rates than the controls, likely due to reduced competition. The decomposition of legacy wood observed paired with reduced recruitment trends raised a concern by the authors that wood loads in the streams may be depressed long term.

6. **Grizzel, J.; M. McGowan; D. Smith; T. Beechie; 2000. Streamside buffers and large woody debris recruitment: Evaluating the effectiveness of watershed analysis prescriptions in the North Cascades region. TFW Effectiveness Monitoring Report. TFW-MAG1-00-003. http://www.dnr.wa.gov/Publications/fp_tfw_mag1_00_003.pdf**

   Value: 3 for data analysis. Grizzel et al. (2000, unpublished TFW cooperative monitoring report) examined recruitment at 10 buffer sites in the North Cascades of Washington State. The proportion of debris recruited to streams varied as a function of distance from the stream and buffer width. In all three buffer width classes examined (<20m, 20-30 m, >30-38 m) (<66 ft., 66-98 ft., >98 ft.) over 50 percent of debris originated from within 15 meters of the bankfull channel. However, 19 percent and 28 percent of debris pieces were recruited from beyond 20 meters of the streambank in the 20-30 m and >30 m classes, respectively. In the >30 m class, 10 percent of recruitment originated beyond 30 meters from the stream. Thus, indicating that as buffer width increases, the proportion of the total debris load recruited from a particular distance decrease, and with debris being recruited from the outer portions of the wider buffers, it further indicated to the authors that narrower buffers limit recruitment. However, given the large degree of variability in recruitment from site to site the authors opined that recruitment appeared more closely linked to wind-throw levels than to buffer width. In the long-term, however, the authors concluded that wider buffers would produce higher recruitment frequencies simply because there are more trees available to recruit. Study also found non-random fall direction with the pattern reflecting the influence of southerly winds and that trees in buffers oriented perpendicular to the direction of damaging winds had a higher likelihood of being recruited. Stream channels ranged from 2.1 m to 8.1 m (6.9 – 26.6 ft.) wide, including both one- and two-sided buffers. The range of buffer widths tested was 16.4-38.8 m (54-127 ft.) wide.

7. **Johnston, N.T.; S.A. Bird; D.L. Hogan; and E.A. Macisaac. 2011. Mechanisms and source distances for the input of large woody debris to forested streams in British Columbia, Canada. Can. J. For. Res. 41:2231-2246. doi:10.1139/X11-110.**

   Value: 0 for data analysis. Johnston et al. (2011, published) used synoptic surveys to examine LWD recruitment at 51 stream reaches ranging in size from 0.8 to 17 m (2.6-55.8 ft.) bankfull width which spanned 10 biogeoclimatic zones in central and southern British Columbia having mature or old-growth forests. The authors' subsampled the first 30 to 50 pieces (pieces >5cm diameter by 1 m in length; 2 in. by 3.3 ft.) encountered per survey reach (20-30 times bankfull width). Standing dead tree fall was the dominant input mechanism, but bank erosion was important in low gradient riffle-pool channels and large channels (>10-17m; >33-56 ft.). Wind-induced inputs (stem breakage and wind-throw) were relatively more important in small or steep channels. LWD piece size and source distance varied among delivery processes. LWD originated at ground distances up to 65 m (213.3 ft.) from the streams, but 90% of the LWD pieces or volume at a site originated within 15-17 m (49-56 ft. ft.). Statistical models incorporating tree size and stream characteristics (bankfull width, channel type) explained a high proportion of the variation among sites in the distances from which LWD pieces were recruited to the streams, but channel characteristics did not account for variation in the distances from which LWD volume was recruited. Tree mortality accounted for 65% of pieces, bank erosion 18%, stem breakage 12%, windthrow 4%, and landslides 1% of recruitment mechanisms. Classified into small (0-<3.3 m; 0-<11 ft.), medium (3.3-10 m; 11-33 ft.), and large (>10-17 m; >33-56 ft.) categories, the incidence of bank erosion was considerably higher in the large stream category.

8. Johnstone, N.T.; K. Calla; N.E. Down; J.S. Macdonald; E.A. MacIssac; A.N. Witt; and E. Woo. 2007. A review of empirical source distance data for the recruitment of large woody debris to forested streams. British Columbia Ministry of Environment, Fisheries Project Report RD119. Victoria BC. 41pp.

   Value: 0 for data analysis. Johnstone et al. (2007, unpublished B.C. Ministry of the Environment) used published or internet accessible unpublished measurements of large woody debris recruitment to streams to examine the relationship between source distances and stream characteristics associated with the dominant recruitment processes. The authors obtained 137 source distance curves from 13 separate studies, with most coming from coniferous forests along the Pacific coast of the United States. The authors concluded that LWD source distances were variable within similar geographies and vegetation types, with some of this variation attributable to site-level characteristics that influenced the mechanism by with LWD entered the channel. Source distances which accounted for 90% of the cumulative numbers or volumes of LWD pieces increased with increasing tree height. The distance which supplied 90% of the cumulative volume of LWD inputs differed among delivery processes, being greater where tree fall was identified as the dominant input process than for bank erosion and landslides. Authors found that the lateral distance to attain a specified proportion of the cumulative volume of LWD inputs was generally less than that for the same proportion of cumulative of LWD pieces. The authors provided that the median distance within which 90% of the cumulative volumes of LWD originated was 0.36 to 0.85 mean tree heights from the stream. Given this estimated range, and assuming an average mean over-story height of 150 feet for 80–200-year-old conifer stands in western Washington private forests (Schuett-Hames et al., 2005), 90% of the volume would come from 54 to 127.5 ft., with 90% of the pieces coming from farther away (the data set did not allow for a specific estimate of piece contribution). The authors concluded that LWD source distances were variable within similar geographies and vegetation types, with some of this variation attributable to site-level characteristics that influenced the mechanism by with LWD entered the channel. No significant relationship was found between stream width and delivery distance, although the relationship improved with inclusion of stream type in their statistical model. Channel type influenced source distances such that the LWD volume source distances at riffle-pool channels varied little with channel width, but source distances generally increase with channel size at cascade-pool and step-pool channels.

9. Kratz, K.W. 2010. Response to April 1, 2010, Request by the interagency coordinating subgroup for position paper to support the February 23, 2010, elevation of two northwest forest plan issues to the regional executives. Memorandum for Nancy Munn, Ph.D. Co-chair, Interagency Coordinating Subgroup. United States Department of Commerce NOAA. Portland Oregon 97232.

   Value: 0 for data analysis. Kratz (2010, *NOAA unpublished position paper*) provided a position paper for the National Marine Fisheries Service to the USDA Forest Service describing the basis for concerns over riparian thinning proposals by the Forest Service and BLM. The NMFS position is that in large part, thinning cannot be expected to provide greater long-term benefits to large woody debris in streams than leaving the stands uncut, and that in the process the thinning creates a higher risk of causing streams to warm. Of note, the key modeling work used for LWD assessment in this paper was published by Pollock et al. and is represented separately in this bibliography.

10. **May, C.L., and R.E. Gresswell. 2003. Large wood recruitment and redistribution in headwater streams in the southern Oregon Coast Range, U.S.A. Can. J. For. Res. 33:1352-1362.**

    Value: 3 for data analysis- accidentally omitted the wood piece dataset from analysis (and there weren't enough studies reporting wood volume to complete an analysis using the volume data from this study). May and Gresswell (2003, published) examined recruitment distances between 2nd order ephemeral or intermittent colluvial channels (bankfull width 3.3-3.6 ft., 10.8 – 19.7 ft.) and 3rd order perennial alluvial channels (bankfull width 4.8 m, 15.7 ft.) in a 3.9 km2 basin of old growth Douglas fir and western hemlock on the southern coast of Oregon. LWD measured in this study were pieces >20 cm (7.9 in.) in diameter and 2 m (6.6 ft.) in length. Slope instability was a dominant (~52%) recruitment mechanism in the colluvial channels, but a lesser mechanism (~10%) in the alluvial channels. Wind-throw was a dominant process in both channel types but of greater importance in the alluvial channels (~60% compared with ~40%). Delivery distances were significantly different between the two channel types. In colluvial streams, 80% of wood pieces and 80% of the total volume of wood originated from within 50 m (164 ft.) of the channel. In the alluvial channel, 80% of the pieces of wood originated from within 30 m (98.4 ft.) of the channel; however, this accounted for only 50% of the volume of wood. Approximately 90% of the volume of downed wood came from 55 m (180.4 ft.) in the colluvial channels and 63 m (206.7 ft.) in the alluvial channels. Bank erosion was a minor (approximately <7%) process in both channel types, and source distance was poorly correlated with piece length, diameter, and piece volume.

11. **McDade, M.H.; F.J. Swanson; W.A. McKee; J.F. Franklin; and J. Van Sickle. 1990. Source distances for coarse woody debris entering small streams in western Oregon and Washington. Can. J. For. Res. 20:326-330.**

    Value: 3 for data analysis. McDade et al. (1990, published) examined recruitment distance for 39 streams in the Cascade and Coast ranges of Oregon and Washington. Their composite data from the old-growth sites indicate that a 30 m (98.4 ft.) wide strip of streamside forest would produce 85% of the observed debris pieces (10 cm diameter by 1 m length, minimum piece size). This compares with their mature conifer data set wherein 85% of the pieces would come from within approximately 23 meters (75.5 ft.). They also calculated for the old growth data set that 50% of the LWD pieces came from 10 m (32.8 ft.) and 70% within 20m (65.6 ft.). The difference of 7 meters (23 ft.) between the old growth and mature stand 85% recruitment levels likely represents the difference in recruitment that occurs as a stand matures to an old growth stage and height. The study sites varied in channel size (1st to 3rd order) and slope steepness (3-40%); however, they found no significant difference between source distance on steep and gentle streams or between source distance and stream order. Only 11% of wood was assumed to be from bank erosion. The remaining 89% was delivered from wind through and other processes that were not characterized. Research includes alder dominated riparian sites as well, which when examined separately showed 85% delivered within about 13 meters (42.6 ft.).

12. McClure, J.M., R.K. Kolka, A.White. 2004. Effects of forest harvesting best management practices on coarse woody debris distribution in stream and riparian zones in three Appalachian watersheds. Water Air and Soil Pollution: Focus. 4:1:245-261.

    Value: 0 for data analysis. McClure et al. (2004, published) analyzed the distribution of coarse woody debris (CWD) in three Appalachian watersheds in eastern Kentucky, eighteen years after harvest. The three watersheds included an unharvested control (Control), a second watershed with best management practices (BMPs) applied that included a 15.2 m (50 ft.) unharvested zone near the stream (BMP watershed), and a third watershed that was harvested without strict BMPs with harvesting occurring up to the stream edge and slash left within the stream and riparian zones (No BMP watershed). Within both stream and riparian zones, the BMP and No BMP watersheds contained more CWD biomass than in the Control, however, the CWD in the No BMP watershed was in a more advanced state of decay than in either the BMP or Control watersheds. Nitrogen content in CWD was also greater in the No BMP watershed because of the more advanced state of the decay of the slash left behind. Using their decay class data, the authors found that at least some of the CWD in the BMP watershed occurred since harvest, and based on their biomass data, at a much greater rate of recruitment than in the Control watershed. The authors hypothesize that harvest outside of the riparian zone in the BMP watershed may have led to greater windthrow and/or slumping than in the Control watershed. As such, they concluded that riparian zones of 15.2 m (50 ft.) may not be effective in maintaining the short-term integrity of the CWD pool within steep gradient Appalachian systems".

13. **McKinely, M. 1997. Large woody debris source distances for western Washington Cascade streams. Undergraduate Senior Research Project. University of Washington, College of Forestry. October 16, 1997**.

Value: 2 for data analysis- unpublished data, but good rigor. McKinely (1997, unpublished senior research paper) examined recruitment in 50- to 80-year-old forest stands at 17 different stream reaches along the South Fork of the Stillaguamish River in Snohomish County, in the Cascade Mountain foothills of western Washington. The purpose was to determine how LWD source distances are affected by side slope, tree species, and channel gradient and width. Stream bankfull widths range from 5 to 58 feet (1.52 – 17.67 m). The study sampled wood (minimum 4 in. diameter by 4 ft. in length; 10.2 cm by 1.2 m) believed to have originated from the second growth stand and not from the prior old growth forest. Western hemlock comprised the majority of debris pieces sampled, followed by red alder, with the alder occurring predominately in the mainstem reaches. Tributaries sampled were in three groups based on channel gradient: less than 14%, 14-30%, and greater than 44%. About 15% of all samples originated at the bankfull edge. Fifty percent of all recruited LWD originated within the first 10 feet (3 m), and 90% within 35 feet (10.7 m). The greatest source distance was 115 feet (35 m). The mainstem achieved 90% recruitment at about 47 feet (14.32 m) and the tributaries at 30 feet. Recruitment based on hillslope gradient was not significant, and no analysis was found to address the study goal of assessing the role of channel width.

14. Murphy, M., and K.V. Koski. 1989. Input and depletion of woody debris in Alaska streams and implications for streamside management. North American Journal of Fisheries Management 9/427-436.

Value: 0 for data analysis. Murphy and Koski (1989, published) examined LWD input and depletion in seven southeast Alaska watersheds vegetated with undisturbed old-growth forests of western hemlock and Sitka spruce. In each watershed, LWD was inventoried in four to six stream reaches with each reach an example of one of six different channel types. The authors found that 99% of all identified sources of LWD (10 cm diameter by 3 m length) were within 30 m (98 ft.) of the stream bank, 95% were from within 20 m (66 ft.) of the stream, and nearly one-half of the LWD pieces were from trees that had stood on the lower bank (<1 m away). The distance differed between channel types, consistent with the dominant recruitment mechanisms. Bank erosion at three of their six channel types was also very high (52-60%). Neither average or maximum stand heights are provided to help interpret the recruitment curve and table; however, the authors estimate it takes 75 years to grow trees to 24 inches (70 cm) diameter and only 1-6% of LWD were in their maximum size class is >35 inches (90 cm). This stands in contrast to other findings, such as the old growth Douglas fir forest in May and Gresswell (2003) which had mean diameters of 49-69 inches (124.5-175.3 cm)]. This suggests these southeast Alaska stands are unlikely to be of heights comparable to productive timber lands in western Washington. Additionally, channels ranged from 8.2 to 31.4 m (26.9 to 103 ft.) in width, and gradients from 0.8 to 2.9 percent, with braided streams and sites with bedrock and muskeg. These factors considered together suggests the results of the study by Murphy and Koski may not represent the recruitment patterns expected under forest stands on a path to desired future conditions at age 140 in western Washington.

15. Naiman, R.J., Balian, E. V., Bartz, K.K., Robert, E., Latterell, J.J., 2002. Dead Wood Dynamics in Stream. USDA For. Serv. Gen. Tech. Rep. 181, 23–48. http://grwc.info/Assets/Reports/LWD/Dead-wood-Dynamics.pdf

    Value: 0 for data analysis. Naiman et al. (2002, USDA technical report) summarizes the information from the literature on the spatial and temporal variability of LWD abundance, distribution and age; the processes of LWD delivery and elimination; and the influence of LWD on material retention, habitat formation, and productivity of streams. The authors conclude that measures assuring a continued supply of LWD of appropriate size, volume and species composition are essential for maintaining the long-term integrity of stream and river corridors. They provide the following observations based on the literature. LWD abundance peaks in the southern end of the Pacific Coast Ecoregion and decreases toward the north. At one extreme, the LWD biomass in the redwood forested streams of California and at the other extreme, the Sitka spruce-lined streams of southeast Alaska. And as a whole, the Pacific Coastal Ecoregion has higher abundance of LWD than other forested areas in North America. They further observe the abundance of LWD depends in part, on channel size with small channels having more abundant wood than large streams which have a greater capacity to transport wood downstream. LWD is more abundant in unconstrained channels with fine substrate than in constrained channels with bedrock and boulder substrate. Streams in coniferous forests have more LWD than streams in hardwood forests because conifers are usually larger and less easily transported. Similarly streams in mature stands tend to have more LWD than streams in young stands where the riparian forest often is composed of small hardwoods.

16. **Opperman, J.J. 2002. Anadromous fish habitat in California's Mediterranean-climate watersheds: Influences of riparian vegetation, instream large woody debris, and watershed-scale land use. PhD dissertation. University of California, Berkely. Fall, 2002.**

    Value: 3 for data analysis. Opperman (2002, B.S. dissertation) examined LWD function and recruitment from 30 hardwood dominated streams within the Mediterranean Climate of the Russian River basin and San Francisco Bay Area in California. Only 3.8% of the LWD counted was from conifer (Douglas fir and redwood), with California bay, willow, alder, and assorted other hardwoods making up over 96% of the wood pieces delivered to the sample streams. Ninety percent of all hardwood species were estimated to have been delivered from within 10 m (33 ft.) of the channel.

17. Schuett-Hames, D., A. Roorbach, and R. Conrad. 2012. Results of the Westside Type N buffer characteristics, integrity and function study final report. Cooperative Monitoring, Evaluation, and Research Report, CMER 12-1201. Washington Department of Natural Resources, Olympia, WA.

Value: 0 for data analysis. Schuett-Hames et al. (2012, unpublished but peer reviewed) examined the operational application of the state of Washington forestry prescriptions to non-fish-bearing streams in western Washington. Eight sites were clear-cut to the edge of the stream, and thirteen had 50-foot-wide no-cut buffers on both sides of the stream. Comparisons with local reference sites found that one year after harvest, the mean density of live trees in the 50-foot buffers experienced 3.5 times the mortality of that of the reference patches in the first three years. Wind was the dominant mortality agent in the 50-foot buffers, while suppression mortality exceeded wind mortality in the reference reaches. The cumulative percentage of live trees that died over the entire five-year period was 27.3% in the 50-foot buffers compared to 13.6% in the reference reaches. The higher tree falls rates in the 50-ft buffers compared to the reference patches during the first three years after harvest indicate that the newly established buffers were susceptible to wind mortality after the adjacent timber was harvested. However, the data from years 4-5 indicate that during high magnitude wind events the treatment effect is less evident due to increased wind damage in reference stands. The majority of 50-ft buffers (10 of 13) had tree mortality rates less than 33% over the five-year post-harvest period. Mean tree mortality for these buffers was 15%, and the mean density of live trees was 140 trees/acre five years after harvest (range 59-247). Mortality rates exceeded 50% at three of the 50-ft buffers. Mean tree mortality was 68.3% for these buffers over the five-year period and exceeded 90% in one case. During the first five years after harvest, the mean volume of LWD recruited into and over the bankfull channel was 3 times greater in the 50-ft buffers than the reference patches. Only a small percentage of newly recruited pieces initially provided in-channel functions such as sediment storage (8%), debris jam formation (4%), step formation (3%), or pool formation (3%) because most pieces were suspended over or spanning the channel.

18. Spies, T; M. Pollock; G. Reeves; and T. Beechie. 2013. Effects of riparian thinning on wood recruitment: A scientific synthesis. Science Review Team Wood Recruitment Subgroup. January 28, 2013. Unpublished Report by staff the USFWS and NOAA. Pp 1-46. http://www.mediate.com/DSConsulting/docs/FINAL%20wood%20recruitment%20document.pdf

    Value: 0 for data analysis. Spies et al. (2013, unpublished USFS and NOAA science report) used published empirical and theoretical studies, simulation modeling and professional opinion to synthesize the science on the effects of thinning on wood recruitment related to forests in NW Oregon. They provide a number of key points such as: thinning is most beneficial in dense stands, results depend on site stand conditions; conventional thinning with removal of trees generally produces fewer large dead trees, conventional thinning can accelerate development of very large diameter trees, and thinning can increase the amount of pool-forming wood only when thinned trees are smaller in diameter than the average diameter of pool-forming wood. Their growth modeling using the Streamwood model compared thinning to 55 TPA adjacent to no-cut buffers of varying widths. Compared to a

250 foot no-cut buffer, thinning to the bank would provide only 2% of potential wood pieces over 135-year period, a 30-foot no-cut provides only 28% of the wood, a 60-ft no-cut buffer provides 58%, and a 90-ft no-cut buffer provides 88% of the potential wood pieces in the 135 year period. The authors' simulation with the RAIS model for 150 and 170 yr old stands places the 85% recruitment distance for LWD pieces at approximately 25 m and 28 m (82 and 91.9 ft.), respectively. Based on their modeling and the work of McDade et al. 1990; VanSickle and Gregory 1990, Gregory et al. 2003 they concluded that 95% of the total instream wood inputs came from distances that ranged from between about 25 and 45 m (82 to 148 feet) depending on stand conditions (includes hardwood stand modeling).

19. VanSickle, J.; and S.V. Gregory. 1990. Modeling inputs of large woody debris to streams from falling trees. Can. J. For. Res. 20:1593-1601.
    Value: 0 for data analysis. VanSickle and Gregory (1990, published) used probabilistic modelling to predict the total number and volume of large woody debris pieces falling into a stream reach per unit time. Predicted debris inputs from riparian management zones of various widths were compared with the input expected from an unharvested stand. The authors' wood model assumed inputs consist of whole trees falling into the stream channel from an adjacent hillslope or floodplain. Stands of mixed heights (e.g., 73% hardwoods, and 27% conifers of mixed heights) recruited approximately 85% of the potential logs within approximately 18m (59 ft.), while approximately 85% of the logs from a uniform stand of 50 m (164 ft.) conifers recruited within 35 m (114.8 ft). They applied their model to an old-growth conifer stand in the Oregon Cascade Mountains. Debris pieces observed in the stream were generally shorter, with less volume per piece, than those predicted by the model, probably because of bole breakage during tree fall.

Fisheries, Hydrology, Watershed Processes

1. Alexander, D., Macquarrie, K. & Caissie, D. and Butler, K. (2003). The thermal regime of shallow groundwater and a small Atlantic salmon stream bordering a clearcut with a forested streamside buffer. *Proceedings, Annual Conference - Canadian Society for Civil Engineering*. 2003.*

   Location: New Brunswick, Canada. The study compared groundwater temperature in a 60m riparian buffer and a clearcut. The average temperature of the shallow groundwater was 1.0±0.7°C cooler than in the clearcut. The average temperature of the deep groundwater was 0.7± 0.5°C cooler than in the clearcut. The study provides evidence that removal of trees can result in increased groundwater temperature.

2. Allen, Marganne, and Liz Dent. 2001. Shade conditions over forested streams in the Blue Mountains and Coast Range georegions of Oregon. *Oregon Department of Forestry Technical Report #13*, August 2001.

   Location: Coastal Oregon and NE Oregon. In the Coast Range there was a slight positive association of average shade with buffer width, but no such pattern in the Blue Mountains. Comparison of Hemiview with canopy cover showed densiometer tended to over-predict shade in the well vegetated western sites but was in the range on the eastern sites. Shade was generally greater in N-S oriented streams compared with E-W streams in the Blue

Mountains, thus E-W flowing streams may have a greater potential for detectable changes in shade as a result of harvest in the near stream area – particularly on the south bank. In both harvested and unharvested streams in the Blue Mountains the average shade was lower in grazed sites. Along harvested streams, the average shade level for grazed sites was 16% (n=17) lower than non-grazed sites (n=4) (55% vs. 71%). Along unharvested streams the average shade level for grazed sites was 12% lower than grazed sites (n=8) (63% vs. 75%). Shade was 5% and 8% lower on grazed and non-grazed harvested sites, respectively, than grazed and non-grazed unharvested sites; indicating the importance of accounting for multiple uses. Pine dominated stands in the Blue Mountains had lower shade values overall (53%) than other types of coniferous stands, though there was a considerable range of shade conditions (28-80%) for pine stands – no stands were available to represent unharvested pine stands. In the coast range, harvested conifer stands had lower average shade conditions than hardwood stands, though the two types were similar at the harvested sites. The average difference in shade for 3 ft and 10 ft photos ranged from 2.5% to 9.1% across both geo- regions examined, with the percent of shade provided by shrub cover greater at harvested sites. There was no distinct trend between percent of shade contribution from shrubs and bankfull width with narrow channels. However, shrub contribution to shade was less than 8% on channels wider than 25 ft in both georegions. Shade over streams in the Blue Mountains appears to be more sensitive to having additional trees farther away from the stream than the Coast Range. Difference in cumulative basal area are suggested between shade categories in the Blue Mountains within 40 ft of bankfull. In the Coast Range, additional basal area may provide more shade if available 80-100 feet from bankfull, but this was not confirmed statistically. A relationship between shade and tree height was not evident in either georegion or aspect – except slight positive trend between height and shade on N-S flowing streams.

3. Anderson, P, D. Larson, and S. Chan. 2007. Riparian Buffer and Density Management Influences on Microclimate of Young Headwater Forests of Western Oregon. *Forest Science* 53:2:254-269.

   Location: Western Oregon. Anderson et al. (2007) evaluated the impact of variable density thinning and different no-thin buffer configurations on stream and riparian area microclimate of small largely intermittent (average 1.1 m (3.6 ft.) width and <10 cm (3.9 in.) depth) headwater streams in 30–70-year-old Douglas-fir stands in western Oregon. Stands were thinned to from 500-865 tph, (202-250 tpa) to 198 tph, (80 tpa) adjacent to uncut stream-side buffers ranging in width from <5 m (16.4 ft.) up to 150 m (492 ft.) width. The width of the unharvested buffer strips adjacent to the stream channel averaged 69 m (226.4 ft., one site potential tree height, B1), 22 m (54.3 ft, variable width, VB) or 9 m (29.5 ft., streamside retention, SR) width as measured from stream center. Microclimate gradients were strongest within 10 m (32.8 ft.) of stream center, and with thinning adjacent to no-cut buffers of 15 m (49.2 ft.) or greater width, daily maximum air temperature above stream center was less than 1°C greater and daily minimum relative humidity was less than 5% lower than for unthinned stands.

4. Barton, D.R., W.D. Taylor, and R.M. Biette. 1985. Dimensions of Riparian Buffer Strips Required to Maintain Trout Habitat in Southern Ontario Streams. *North American journal of Fisheries Management*. 5:364-378.

Location: Southern Ontario. Barton et al. (1985) examined the relationship between riparian land use and environmental parameters at 40 sites on 38 trout streams in southern Ontario, Canada. The only environmental variable that clearly distinguished between trout and non-trout streams was weekly maximum water temperature: streams with tri-mean weekly maxima less than 22°C had trout; warmer streams at best had only marginal trout populations. Water temperature, concentration of fine particulate matter, and variability of discharge were inversely related to the fraction of the upstream banks covered by forest. Fifty-six percent of the observed variation in weekly maximum water temperature could be explained by the fraction of bank forested within 2.5 km upstream. Data analysis from sites located within buffer strips found that 90% of the observed variation in water temperature could be accounted for using buffer length. Trout streams, on average, were estimated to be more than 80% forested upstream. They used regression to produce an equation that predicts tri-mean weekly maximum temperatures given different buffer lengths and widths: $y = 29.87 - 5.757x_1^{0.333} - 15.42x_2$ where x_1 = buffer strip length in kilometers, and x_2 = buffer strip width in kilometers. The temperature-buffer relationships are too location specific to have applicability to Washington State.

5. Brazier, J.R., and G.W. Brown. 1973. Buffer strips for stream temperature control. Research Paper 15. April 1973. *Forest Research Laboratory, School of Forestry. Oregon State University.* Corvallis, Oregon 97331.

Location: Western Oregon. Brazier and Brown (1973) using data from stands along nine steep V-shaped small mountain streams in western Oregon concluded that the maximum angular canopy density was reached within 80 feet.

6. Bren, L.J. 1998. The geometry of constant buffer-loading design method for humid watersheds. *Forest Ecology and Management*. 110: 113-125.*

Based on modeling a constant pollutant loading (i.e., contributing watershed area) per unit of buffer, the study concluded that fixed width buffers are undersized where hillslopes converge and oversized where hillslopes diverge.

7. Broadmeadow, S.B., Jones, J.G., Langford, T.E.L., Shaw, P.J., and Nisbet, T.R. 2010. The influence of riparian shade on lowland stream water temperatures in southern England and their viability for brown trout. River Research and Applications. 27: 226-237.

Abstract: "Suitable thermal conditions in streams are necessary for fish and predictions of future climate changes infer that water temperatures may regularly exceed tolerable ranges for key species. Riparian woodland is considered as a possible management tool for moderating future thermal conditions in streams for the benefit of fish communities. The spatial and temporal variation of stream water temperature was therefore investigated over 3 years in lowland rivers in the New Forest (southern England) to establish the suitability of the thermal regime for fish in relation to riparian shade in a warm water system. Riparian shade was found to have a marked influence on stream water temperature, particularly in terms of moderating diel temperature variation and limiting the number of days per year that maximum temperatures exceeded published thermal thresholds for brown trout. Expansion of riparian woodland offers potential to prevent water temperature exceeding incipient lethal limits for brown trout and other fish species. A relatively low level of shade (20–40%) was found to be effective in keeping summer temperatures below the incipient lethal limit for brown trout, but ca. 80% shade generally prevented water temperatures exceeding the range reported for optimum growth of brown trout. Higher levels of shade are likely to be necessary to protect temperature-sensitive species from climate warming."

Maximum water temperatures up to 34.5°C (94.1°F) were reported. It seems unlikely that water temperatures would reach this level in streams, especially those in southern England; it seems more likely that some data loggers did not remain continually submerged.

8. Broderson, J.M. 1973. Sizing buffer strips to maintain water quality. *M.S. thesis.* University of Washington, Seattle, Washington.

   Location: Western Washington. As streams become wider, the effectiveness of shading by trees decreases. A stand 200 ft tall at 45°N on flat topography provides shade 89 ft from the trunk in mid-July. In this scenario, trees more than 89 ft from the stream would not be providing any shade to the channel. On a 60% slope the effective shade increases to 120 ft. A stand 250 ft tall on 60% slope has effective shade width of 195 ft. Therefore, recommends a maximum buffer width of 200 ft. States that a width of 50ft has been found to provide 85% of maximum shade for small streams. Recommends a minimum of 50ft for sediment control with a max of 200ft on slopes of 50% and greater but increased to encompass highly unstable and poorly drained areas. Says streams in V-notched valleys should have buffers extended 25ft beyond the change in slope. On highly erosive or unstable areas, the author recommends 200ft buffer to inhibit excessive wind throw.

9. Brosofske, Kimberley, J. Chen, R. Naiman, and J. Franklin. 1997. Harvesting effects on microclimatic gradients from small streams to uplands in western Washington. *Ecological Applications.* 7(4) pp. 1188-1200.

   Location: western Washington. Brosofske et al (1997) evaluated effects the effects of harvesting upon the microclimate of stream buffers. The streams ranged in width from 2 to 4 meters and the riparian buffers ranged in width from 17 to 72 meters. Forest harvesting changed the microclimate in riparian zones. Before harvest, surface temperature and humidity showed a gradient from near-stream conditions to interior forest conditions within 31 to 62 meters of the stream, air and soil temperature had a gradient length of 31 to 47m; after harvest, the temperature gradient increased and the humidity gradient decreased from near-stream into the harvested area. Stations in the buffer showed shifts towards the clear-cut values. Both pre and post-harvest, there were strong correlations between stream temperature and soil temperature 60m beyond the buffer edge. Solar radiation at the stream increased exponentially with decreasing buffer width. The authors concluded that a buffer of 45m or wider (possibly up to 300m) is needed to maintain the natural riparian microclimate against changes induced by forest canopy removal.

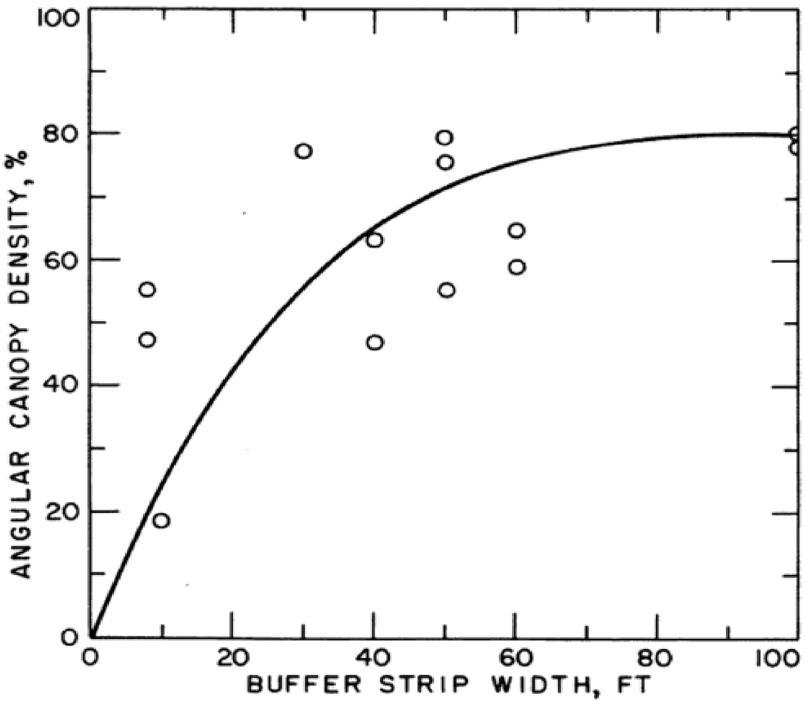
10. Brown, George W. 1969. Predicting Temperatures of Small Streams. *Water Resources Research*. Vol. 5, No 1. February 1969.

    Brown (1969) illustrated how energy budget techniques could be used to create a model to predict temperature changes in small streams. Sections of three small streams in western Oregon were selected for study. Predictions were generally within 1°F of the measured value. Results indicate the necessity of on-site meteorological measurements for accurate temperature prediction on small streams. The data indicate the general nature of the heat-exchange characteristics of these small streams. Net thermal radiation is the predominant source of energy for the stream. Evaporation and convection seem to play a minor role in establishing the temperature of an exposed stream, especially at midday, when most of the net thermal radiation is going into storage. Bottom conduction was important for rock channels but not for gravel bottoms with their much lower thermal conductivities. Rock channels acted as an energy sink during the midday hours and as an energy source later in the day. Authors note that successful prediction of temperature on small streams may require evaluation of energy flow that is insignificant on large rivers given small streams have less capacity for heat storage than large rivers.

11. Brown and Brazier, 1972. Controlling thermal pollution in small streams. EPA-R2-72-083. *U.S. Environmental Protection Agency. Office of Research and Monitoring*. Washington, D.C.

    For the average buffer strip, ACD, and therefore shading potential, reaches a maximum at about 80 feet. 90% of the maximum is reached within 55 feet. Recommends that ACD should be maintained above 80%, or not reduced from natural.

Figure 18: Graph from Brown and Bazier (1972) showing angular canopy density and buffer strip width



12. Brownlee, M.J., B.G. Shepard, and D.R. Bustard. 1988. Some effects of forest harvesting on water quality in the Slim Creek watershed in the central interior of British Columbia. *Can. Tech. Rep. Fish. Aquat. Sci.* 1613: 41p.

    Location: Central British Columbia. Brownlee et al. (1988) examined the effects of forest harvesting on water quality within a watershed 80 km east of Prince George in the central interior of British Columbia between 1971 and 1975. Suspended sediment loading in the study stream, Centennial Creek, increased 4 to 12 times over corresponding levels in an adjacent control stream. Mainline road development was implicated as the main source of increased levels of sediment which persisted for the duration of the three years of study. At associated tributaries, erosion from skid trails, landings, road crossings and streambank damage occurred during and after logging, but in contrast, it did not persist beyond the first summer after logging. Mean water temperatures increased 1 to 3 C following logging to the edge of small tributary streams. Diurnal fluctuations more than doubled. Although maximum water temperatures in these small streams increased up to 9 C they remained within the tolerance levels for salmonids. When instream nutrients were at high levels, logged areas had 1-2 times the orthophosphate concentrations, 2-3 times the total phosphate concentrations, and up to 5 times the nitrate concentrations present in the unlogged watershed. Clear-cutting of 120 ha cutting units was conducted in sequence. Adjacent to main streams (Slim and Centennial) conifer plus deciduous reserve strips of variable width were left standing. Practices near tributary streams, Rosanne and Karolyn creeks, ranged from extensive instream felling and skidding during winter logging in the lower reaches to largely falling and skidding away from channels during the summer in the upper reaches. 16 stations established within the study streams. Cumulative effect of harvesting was compared using data collected at the downstream end of logged Centennial Creek and data from unlogged Slim and Donna creeks. Maximum water temperatures increased during the summer 9C, 4.5C, and 6C respectively over upstream control levels in Hee, Karolyn, and Rosanne creeks. Harvests created openings of 1600 m, 970 m, and 1170 m in these three streams in the first-year post-harvest. Diurnal temperature fluctuations more than doubled in the study streams. [Notes: Paired watershed study that examines effects of a series of harvest and provides a simple control minus treatment response value. Not a well-controlled or described study – use judiciously.]

13. Burkart, M.R., James, D.E., and Tomer, M.D. 2004. Hydrologic and terrain variables to aid strategic location of riparian buffers. *Journal of Soil and Water Conservation*. 59: 216-223.*

    Location: Midwest U.S. Abstract: "Methods for mapping hydrologic variables to locate vegetated riparian buffers were explored using examples from the Deep Loess Region of the Midwest. Elevation and stream-flow data were used to define wetness, baseflow, sediment transport, and discharge indices. Groundwater dominates discharge in very small streams and through riparian areas in the region. All indices showed that riparian areas along first order streams have greater potential to intercept groundwater or runoff than similar areas along larger streams. A wetness index, used to indicate saturated soils, defined a significantly ($p<0.05$) greater probability of saturation along smaller streams, enhancing the potential for groundwater interception. Significantly smaller values of the sediment transport index along smaller streams provide enhanced opportunities for deposition of sediment and associated contaminants. A discharge index shows that buffers along first order streams have orders of magnitude greater opportunities to intercept water passing through riparian areas than along reaches of larger streams."

14. Burns, E. R., Y. Zhu, H. Zhan, M. Manga, C. F. Williams, S. E. Ingebritsen, and J. B. Dunham (2017), Thermal effect of climate change on groundwater-fed ecosystems, *Water Resour. Res*., 53, 3341–3351.

    Location: North-central California. The study indicates that groundwater temperatures are influenced by soil temperatures and that climate warming can result in groundwater temperature increases, which can affect the temperature of receiving surface waters.

15. Chen, J., Saunders, S., Crow, T., Naiman, R., Brosofske, K., Mroz, G., Brookshire, B., and Franklin, J. 1999. Microclimate in Forest Ecosystem and Landscape Ecology – Variations in local climate can be used to monitor and compare the effects of different management regimes. *Bioscience.* 49:4:288-297.

    Based on his prior works and that of Brosofske et al. 1997, Chen et al. conclude that harvesting near the stream results in overall changes in microclimate at the stream, even when buffers are wide (i.e., up to 74 m) and that standardized values show that harvesting at 17 m (42. ft.) or more from the stream results in an increase in air temperature of 2-4 C and a decrease in relative humidity of 2.5-13.8% at the stream. They also argue that the changing microclimate associated with the opening of canopies in riparian zones may result in modification of climate and landscape processes at the coarser scale of the drainage basin. For example, the increased air temperatures in the riparian zone may alter the channeling of air masses through river corridors.

16. Corn, P.S., and Bury, R.B. 1989. Logging in Western Oregon: responses of headwater habitats and stream amphibians. *Forest Ecology and Management*. 29:39-57.

    Location: Western Oregon. Corn and Bury (1989) compared occurrence and abundance of four species of aquatic amphibians in 23 streams flowing through uncut forests to 20 streams flowing through forests logged between 14 and 40 years prior to the study. Species richness was highest in streams in uncut forests. Eleven streams in uncut forests contained all four species and only two of these streams had fewer than three species present. Eleven streams in logged stands had one or no species present and only one contained all for species. Density and biomass of all four species were significantly greater in streams in uncut forests. Physical comparisons between types of streams were similar, except that stream in logged stands had generally smaller substrata, resulting from increased sedimentation. Densities of Pacific giant salamanders and Olympic salamanders were positively correlated with stream gradient in logged stands, but not in uncut forests, suggesting that the disruptive effects of increased sedimentation are greatest in low-gradient streams. Tailed frogs and Dunn's salamanders occurred more often in streams in logged stands when uncut timber was present upstream, but neither density nor biomass of any species were related to either presence of uncut timber upstream or years since logging. Logging upstream from uncut forests also had no effect on the presence, density or biomass of any species. Tailed frogs and Olympic salamanders may be extirpated from headwaters traversing clearcuts; these streams should be afforded some protection in plans for managed forests. Take home message: Denuding vegetation in riparian zones harms amphibians.

17. Cristea, N. C. and Burges, S. J. 2010. An assessment of the current and future thermal regimes of three streams located in the Wenatchee River basin, Washington State: some implications for regional river basin systems. *Climatic Change*. Vol. 102 Iss. 3-4. pp. 493-520.

    Location: Central Washington. Examined summer temperature patterns in the Wenatchee River and two of its major tributaries Icicle and Nason Creeks, located in the Pacific Northwest region of the United States. Through model simulations we evaluate the cooling effects of mature riparian vegetation corridors along the streams and potential increases due to global warming for the 2020s–2080s time horizons. Site potential shade influences are smaller in the mainstream due to its relatively large size and reduced canopy density in the lower reaches, proving a modest reduction of about 0.3°C of the stream length average daily maximum temperature, compared with 1.5°C and 2.8°C in Icicle and Nason Creeks. Assuming no changes in riparian vegetation shade, stream length-average daily maximum temperature could increase in the Wenatchee River from 1–1.2°C by the 2020s to 2°C in the 2040s and 2.5–3.6°C in the 2080s, reaching 27–30°C in the warmest reaches. The cooling effects from the site potential riparian vegetation are likely to be offset by the climate change effects in the Wenatchee River by the 2020s. Buffers of mature riparian vegetation along the banks of the tributaries could prevent additional water temperature increases associated with climate change. By the end of the century, assuming site potential shade, the tributaries could have a thermal condition similar to today's condition which has less shade. In the absence of riparian vegetation restoration, at typical summer low flows, stream length average daily mean temperatures could reach about 16.4–17°C by the 2040s with stream length average daily maxima around 19.5–20.6°C, values that can impair or eliminate salmonid rearing and spawning. Modeled increases in stream temperature due to global warming are determined primarily by the projected reductions in summer stream flows, and to a lesser extent by the increases in air temperature. The findings emphasize the importance of riparian vegetation restoration along the smaller tributaries, to prevent future temperature increases and preserve aquatic habitat. The authors conduct a sensitivity analysis to examine the relative effect on water temperature of the increase in air temperature versus the decrease in water flows associated with climate change. They illustrate in Table 4 that the reduction in flow has a proportionately greater effect on maximum daily water temperatures under the climate scenarios examined (air-change-only resulted in maximum water temperature increases from 0.18-0.62C, while stream-flow-only resulted in changes of 0.66-2.35C in the Wenatchee River (at estimated site potential shade). Take home message: Restoration of riparian vegetation is needed not only to address current temperature problems, but also to offset future climate change induced temperature increases.

18. Curtis, R.O. and Reukema, D.L. 1970. Crown development and site estimates in a Douglas-fir plantation spacing test. *Forest Science*, Vol 16, No. 3. 287-301

    This study evaluated relationships between Doug fr spacing, height, DBH, and crown width in tree plantations with "poor" soil conditions. The trees were planted in 1925. Average heights (for all trees and for largest 100 trees by DBH per acre) of 5yr old trees was greatest in the 4x4 and 5x5 ft spacing, but from 10yrs and after, the average heights were greater for trees with the wider spacing (10x10 and 12x12ft). Tree height at 20yrs old among the spacing configurations ranged from about 15 to 35ft. Tree height at 42yrs old among the spacing configurations ranged from about 20 to 95ft. Trees spaced 12x12 had tree heights ranging from about 50 to about 95ft. At yr 42, crown width for 12x12 spaced trees ranged from about 10ft to about 22ft. At yr 42, crown widths for trees spaced 4x4 ranged from about 6 to 15ft. The study findings indicate that higher tree densities on lower quality soils likely increases competition and results in lower height, diameter and crown dimensions compared to trees of the same age but planted at a lower density. The study could not address whether or not this is also the case for high quality soils.

19. Danehy, R.J., and B.J. Kirpes. 2000. Relative humidity gradients across riparian areas in Eastern Oregon and Washington forests. *Northwest Science*. 74:3:224-233.*

    Location: Eastern Oregon and Washington. Danehy and Kirpes (2000) examined relative humidity gradients within 30 meters of twelve small headwater (second to third order streams with wetted widths of 1.3-5.0 m and stream gradients of 2-9 percent) streams located on the eastern flanks of the Cascade Mountains in Oregon and Washington. They found that mean minimum relative humidity was significantly different between 0 and 5 m at 9 of 12 sites, but was similar beyond 10 m. Small daytime increases in relative humidity close to the stream appeared to be the result of evaporation and transpiration. Authors concluded that local topography controlled the distance to which humidity patterns extended into the adjacent forest, such that shallower side slopes allowed humidity to extend further into the upland; and that this effect was assisted by the generally more open forests of eastern Oregon and Washington. Sites with the most pronounced increase in slope had the most pronounced change in mean minimum relative humidity. Study design consisted of monitoring three stream parallel points at the stream, 5m from the stream, and 10 m from the stream, and a single station at 20 and 30 m from the stream. Authors also measured shade and basal area. Basal areas ranged from 0 to 220 sq ft/acre, and shade from 2 to 100 percent. *(Ecology questions the use of an ANOVA analysis for sites with such highly variable site characteristics; unfortunately, the actual data findings on mmRH were not provided for review.)*

20. Danehy, R.J., Chan, S.S., Lester, G.T., Langshaw, R.B, and Turner, T.R. 2007. Periphyton and Macroinvertebrate Assemblage Structure in Headwaters Bordered by Mature, Thinned, and Clearcut Douglas-Fir Stands. *Forest Science* 53(2).

    Location: Western Oregon. Danehy et al. (2007) examined the structure of periphyton and macroinvertebrate assemblages along with 22 abiotic characteristics in 18 Oregon Coast Range perennial headwater streams bordered by mature (6), clearcut (5), and thinned (7) forest treatments. Basin lithology was dominated by Tyee Sandstone, streams were at the upper end of perennial distribution within 230-289 meters on average from the source. Mature forests consisted of 50-year-old second growth Douglass fir stands, and clearcut treatments had been harvested between 2 to 5 years prior to study. Study notes that study sites were in close proximity to thinned stands, with no further clarification provided. Thinned sites were commercially thinned to a target of 200 tph (81 TPA) from initial densities from 500 to 750 tph (202 to 304 TPA). No tree harvest occurred within a 15 m buffer along streams in the thinned stands. Danehy et al (2007) found mature treatment sites had fewer species of diatoms and less biomass than other treatments. Diatom richness was highest at sites with higher unit area discharge. Diatom assemblages were dominated by a single species. Macroinvertebrate assemblages were rich, with 194 taxa collected across all sites and 42 taxa found at a single site. Macroinvertebrate assemblages differed across treatments with higher abundance, more Chironomidae taxa, and more biomass at clearcut treatment sites. They observed no difference in functional feeding group percentage composition across treatments, with collector-gatherers and shredders composing at least 50% abundance at all treatments. They found little difference in either periphyton or macroinvertebrate assemblages between thinned and mature treatments. Significant abiotic differences occurred for insolation, with thinned and clearcut treatments having 5 and 8 times the insolation as the mature sites; and with total nitrogen significantly different between the mature and clearcut treatments. Temperature was measured 8 cm in the substrate and had treatment site averaged annual maxima occurring during a 15 day period in August of 13.35, 13.37, and 14.6ºC for the mature, thinned, and clearcut treatments, respectively. The study used a post-harvest design, and examined treatments at different time frames post-harvest, which may have increased variability unrelated to the treatments.

21. Davies, P.E. and Nelson, M. 1994. Relationships between riparian buffer widths and the effects of logging on stream habitat, invertebrate community composition and fish abundance. *Aust. J. Mar. Freshwater Res*. 45, 1289-1305.

    Location: Tasmania, Australia. The study compared stream habitat, macroinvertebrate diversity, and fish abundance at 45 paired sites, upstream and downstream of logging areas. Riparian buffers ranged from 0 to 50m in the logged areas and non-logged control areas were included. Water temperature and fine sediment in riffles was significantly higher below logged areas and macroinvertebrate and brown trout abundance was significantly lower. The effects of logging were significant only when buffer widths were less than 30 meters, with the temperature effect being significant only for buffers less than 10m in width.

22. Davies-Colley, R.J. and Quinn, J. 1998. Stream lighting in five regions of North Island, New Zealand: control by channel size and riparian vegetation. New Zealand Journal of Marine and Freshwater Research, 32:4, 591-605.

    Abstract: "Lighting of streams profoundly influences their ecology, particularly through primary production and thermal behaviour. We used paired canopy analysers, instruments with fish-eye lens imaging, to measure sunlight exposure of streams in five regions of North Island, New Zealand. Reach averaged stream lighting, at both water and bank level, was strongly influenced by riparian vegetation type. Pasture streams had comparatively high light exposure (median water level lighting = 45% of ambient), with most shading contributed by banks and overhanging herbs. Lighting was low in small forest streams (median = 1.3% for native forest, 1.2% for pine plantations), but increased sharply as the gap in the canopy widened with increase in channel width above c. 3.5 m. The understorey in pine plantations contributed more shade than the pines themselves: damage to this understorey (e.g., by goat browsing or floods) increased lighting markedly. Harvesting of pine plantations exposed streams to high light levels except where a riparian buffer was maintained. Periphyton biomass, varying over more than four orders of magnitude in the study streams, correlated broadly with lighting."

23. Dent, L., Vick, D., Abraham, K., Schoenholtz S., and Johnson, S. 2008. Summer temperature patterns in headwater streams of the Oregon Coast Range. *Journal of the American Water Resources Association* 44(4):803-813.

    Location: Western Oregon. Dent et al. (2008) examined pre-harvest spatial and temporal patterns in summer stream temperature for small streams of the Oregon Coast Range in forests managed for timber production. Summer stream temperature, channel, and riparian data were collected on 36 headwater streams in 2002, 2003, and 2004. Mean stream temperatures were consistent among summers and generally warmed in a downstream direction. However, longitudinal trends in maximum temperatures were more variable. At the reach scale of 0.5-1.7 km, maximum temperature increased in 17 streams, decreased in seven streams and did not change in three reaches. At the sub-reach scale (0.1-1.5 km), maximum temperatures increased in 28 sub-reaches, decreased in 14, and did not change in 12 sub-reaches. Stream and riparian attributes that correlated with observed temperature patterns included cover, channel gradient, in-stream wood jam volume, riparian stand density, and geology type (but none were significantly correlated in both Subreach 1 and Subreach 2). Twenty-three stream reaches were in sedimentary and 13 in igneous geologic types. Stream reaches were steep, shallow, narrow, confined and well shaded with substrates composed primarily of fines and gravels. Mean conifer basal area increased with distance from stream, while hardwood basal area decreased. Immediate stream edge dominated by deciduous. Thirty percent and 10% of the stream reaches exceeded the ODEQ 7DAYMAX water quality standard at least one day during one of the summers for the 16C and 18C standards, respectively. Author noted the potential importance of conductive heat exchange in small shallow streams; citing Sinokrot and Stefan (1993) as suggesting that conductive transfer be considered in heat budgets for small streams.

24. DeWalle, David R., 2010. Modeling stream shade: riparian buffer height and density as important as buffer width. *Journal of the American Water Resources Association* 46(2):323-333.

    DeWalle (2010) developed a theoretic model to explore the impacts of varying buffer zone characteristics on shading small streams (3 m) using a path length form of Beer's law. DeWalle modeled using a high buffer density of 30 m in height to reach the conclusion that about 80% shading occurred with a buffer of 12m width and 30 m height and LAI of 6 regardless of stream azimuth. DeWalle reached the obvious position that buffer density and buffer height is of equal or greater importance to stream shading. DeWalle uses the geometry of the suns path at 40 degrees latitude and at summer solstice to reach his conclusions. There was a continuous increase in stream shading as the light extinction coefficient (density) increased out to the maximum tested and given a dense buffer an east-west stream azimuth is more protective than a north-south buffer. North sides should not need to be as wide since only 30% of the daily sun energy would come from the north side as the sun rises and falls. Increases in buffer height also steadily increased percent of stream shading, which would level off at a height of about 46m. DeWalle got a maximum shade of 74% at 30 m and reported that 88% of the total 74% shading (65%) occurred in the first 18-20 m of buffer width (so a 9% reduction). Shade appears to have been applied as a single 30m high block along the stream edge. Numbers in text do not match numbers in abstract but are close. 74% shade is not particularly high in comparison to measured data sets.

25. DeWalle, D. 2008. Guidelines for riparian vegetative shade restoration based upon a theoretical shaded-stream model. *JAWRA*. 44(6): 1373-1387.

Abstract: "Guidelines for riparian vegetative shade restoration were developed using a theoretical model of total daily radiation received by a shaded stream. The model assumed stream shading by non-transmitting, vertical or overhanging, solid vegetation planes in infinitely long reaches. Radiation components considered in the model were direct beam shortwave on the stream centerline, diffuse atmospheric shortwave, shortwave reflected by vegetation, atmospheric longwave, and longwave emitted by vegetation. Potential or extraterrestrial shortwave irradiation theory was used to compute beam shortwave radiation received at the stream centerline, and view factor theory was used to compute diffuse radiation exchange among stream, vegetation, and atmospheric planes. Model shade effects under clear skies were dominated by reductions in receipt of direct beam shortwave radiation. Model shade effects with cloudy skies were dominated by the ''view factor effect'' or the decreases in diffuse shortwave and longwave radiation from the atmosphere balanced against increases in longwave radiation from vegetation. Model shade effects on shortwave radiation reflected by vegetation were found to be negligible. The model was used to determine the vegetation height (H) to stream width (W) ratios needed to achieve 50, 75, and 90 % shade restoration for mid-latitude conditions on clear and cloudy days. Ratios of vegetation height to stream width, for dense nontransmitting vegetation, generally ranged from 1.4 to 2.3 for 75% shade restoration at a mid-latitude site (40N). The model was used to show H⁄W needed for E-W vs. N-S stream azimuths, varying stream latitudes between 30and 50N, channels with overhanging vegetation, channels undergoing width changes, as well as the limits to shade restoration on very wide channels."

"Given the natural limits on vegetation height that can be achieved with mature trees, Table 2 for 40N latitude implies that there are some practical limits on the maximum stream width that can be appreciably affected by shade restoration programs. Assuming that if 30 m is the maximum vegetation height that can be achieved, then 50% shade restoration could only be achieved for E-W streams up to about 17-m wide (H⁄W = 1.8 needed) or N-S streams up to 43-m wide (H⁄W = 0.7 needed)."

"Shading on wide streams would be somewhat more effective at higher latitudes and less effective at lower latitudes, at least for E-W stream azimuths. Based upon Figure 3, the maximum E-W stream width for 50% restoration by 30-m tall vegetation would be about 25-m at 50N latitude compared to about 17-m width at 40N latitude."

"On small streams, shade restoration is possible with grass and shrub vegetation for N-S azimuths for some configurations, but taller woody vegetation may be needed for E-W azimuths depending upon stream width."

"On larger streams, opportunities for shade restoration, with or without overhang, are limited to widths less than about 17 m for E-W azimuths and widths less than about 43 m for N-S streams for clear-day, mid-latitude conditions."

26. Dignan, Paul, and L. Bren. 2003. Modelling light penetration edge effects for stream buffer design in mountain ash forest in southeastern Australia. *Forest Ecology and Management* 179:95-106.

Location: Southeast Australia. Dignan and Bren (2003) examined the light environment of a wet sclerophyll forest of south-east Australia before and after clearcut harvesting. The authors used hemispherical photography taken at 1, 3.4, and 6.6 m heights at 10 m intervals along 100 m transects to describe the spatial variation in forest understory light along a gradient from streamside vegetation to the upslope eucalypt-dominated forest. Post logging photographs taken at the same points were used to model the light penetration edge effects. The natural understory light environment was influenced by proximity to the streamline to about 50 m upslope, with light penetration increasing at a relative rate of about 9% for every 10 m from the streamline. Light penetration was influenced by topography and vegetation characteristics. Creation of a sharp edge by logging of the upslope forest resulted in major changes in light penetration.

27. Dong, J, Chen, J., Brosofske, K., and Naiman, R. 1998. Modeling Air Temperature Gradients Across Managed Small Streams in Western Washington. *Journal of Environmental Management*. 53. pp 309-321.

    Dong et al. (1998) used the data reported by Brosofske et al. (1997) to develop empirical models and quantitatively describe air temperature responses to harvesting. Buffer width was not a significant variable in predicting stream air temperature, suggesting that even a 72 m (178 ft.) buffer was not sufficient to maintain stream environment because of greater depth of edge influences. The results are suggested to indicate that even a 70 m (173 ft.) forest buffer did not protect against the increase in air temperature associated with harvesting.

28. Dosskey, M.G., Neelakantan, S., Mueller, T.G., Kellerman, T., Helmers, M.J., and Rienzi, E. 2015. AgBufferBuilder: a geographic informations system (GIS) tool for precision design and performance assessment of filter strips. *Journal of Soil and Water Conservation*. Vol. 70, No. 4.

    Abstract: "Spatially non-uniform runoff reduces the water quality performance of constant-width filter strips. A geographic information system (GIS)-based tool was developed and tested that employs terrain analysis to account for spatially non-uniform runoff and produce more effective filter strip designs. The computer program, AgBufferBuilder, runs with ARCGIS versions 10.0 and 10.1 (Esri, Redlands, California) and uses digital elevation models to identify detailed spatial patterns of overland runoff to field margins. The tool then sizes filter dimensions according to those patterns using buffer area ratio relationships. The resulting design is larger along segments where more runoff flows and smaller along segments where runoff is less and delivers a constant level of trapping efficiency around the field margin for sediment and sediment-bound pollutants. The tool also can estimate trapping efficiency of existing filter strips or hypothetical configurations. In a validation test, estimates of sediment trapping efficiency using the tool's assessment function compared closely to measurements taken on large field plots in central Iowa. Using AgBufferBuilder, designs developed for a sample of fields in the mid-western United States were estimated to trap nearly double the sediment, on average, during a design storm than constant-width configurations having equivalent total filter area. AgBufferBuilder can be used to bolster environmental performance of filter strips where runoff is spatially non-uniform. The

AgBufferBuilder tool is publicly available on the websites http://www2.ca.uky.edu/BuflerBuilder and http://nac.un1.edu/too1s/AgBufferBuilder."

29. Dosskey, M.G., Helmers, M.J., and Eisenhauer, D.E. 2011. A design aid for sizing filter strips using buffer area ratio. *Journal of Soil and Water Conservation.* Vol. 66, No 1.

    The authors used modeling to develop graphs with a family of curves that can be used to estimate an appropriate buffer width for sediment and sediment-bound and dissolved pollutants where runoff across a parcel is not uniform. The field length must be known to use the curves. The simulations were based on a grass filter strip with runoff uniformly distributed (for a given scenario, i.e. part of a farm, not from the parcel overall) in the buffer area. The design aid addresses buffer area ratio as well as site slope, soil texture, and soil cover management. The curves are limited for some scenarios in that the graph does not extend to buffer area ratios above 0.16, so an equivalent pollutant trapping efficiency (e.g. 80%) is not shown for all curves. However, the equations for the lines are presented and can be used to calculate trapping efficiencies for greater buffer area ratios. The runoff used in simulations was based on a rainfall event 2.4 in (61mm) in one hour, which is a 10yr event in the Central Plains, Corn Belt, and northern Piedmont. A 10-year frequency is commonly used for designing conservation practices. (Notes: from NOAA: in most of WA the 10yr, 1hr precip intensity ranges from 0.4 to 0.8 inches (from old 1973 reference I think). a 10yr 2-day precip. intensity in WA ranges from 1.5 inches on the Columbia Plateau to 10 inches in the Olympic Mtns. Most of the agricultural areas in the state range from 2.5 to 6 inches for this return interval; the 2yr 2-day intensity in ag areas in WA generally ranges from 1.25 to 4 inches. https://www.nws.noaa.gov/oh/hdsc/PF_documents/TechnicalPaper_No49.pdf)

30. Dosskey, M.G., Helmers, M.J., and Eisenhauer, D.E. 2008. A design aid for determining width of filter strips. *Journal of Soil and Water Conservation.* Vol. 63, No 4.

    The authors used modeling to develop graphs with a family of curves that can be used to estimate an appropriate buffer width for sediment and sediment-bound and dissolved pollutants where non-uniform runoff from farmland occurs. The simulations were based on a grass filter strip with runoff uniformly distributed. The graphs are based on buffer width as opposed to buffer area ratio as in Dosskey et al. (2011). The same rainfall intensity as in Dosskey et al. (2011) was used but four of the seven simulation conditions are different (i.e. different combinations of slope, soil texture, material type, and field length).

31. Dosskey, M.G., Helmers, M.J., and Eisenhauer, D.E. 2006. An approach for using soil surveys to guide the placement of water quality buffers. *Journal of Soil and Water Conservation*. Vol. 61, No 6.

    Location: northwestern Missouri. The study developed a model which was used to compare the ability of buffers on different soil map units to remove pollutants from crop fields. The focus was upon sediment trapping, capture of dissolved pollutants in surface runoff, and transport of pollutants in groundwater. Pollutant capture is affected by soil type, slope, and hydrologic conditions. Pollutant removal from subsurface water in a buffer is generally limited to water that is within six feet of the soil surface, as this is the approximate rooting depth limit for deep-rooted plants. Denitrification in the soils requires hydric conditions-riparian areas or upland areas of poorly drained soils. Denitrification in groundwater at deeper depths probably occurs whether or not a riparian buffer is in place. Lower values of sediment and dissolved pollutant capture efficiency occurred on soil units "where runoff loads were higher and where a buffer will trap greater loads of sediment, but smaller loads of dissolved pollutants." Translation: buffers trap sediment better where slopes are flatter, allow greater water infiltration, and do not promote concentrated flow formation.

32. Druille, M., Cabello, M.N., Omacini, M., and Golluscio R.A (2013) Glyphosate reduces spore viability and root colonization of arbuscular mycorrhizal fungi, Applied Soil Ecology, 64, pp.99–103. 44*

    Abstract: "Our aim was to study the effects of glyphosate, tilling practice and cultivation history on mycorrhizal colonization and growth of target (weeds) and non-target (crops) plants. Glyphosate, the world's most widely used pesticide, inhibits an enzyme found in plants but also in microbes. We examined the effects of glyphosate treatment applied in the preceding fall on growth of a perennial weed, Elymus repens (target plant) and a forage grass, Festuca pratensis (non-target plant) and their arbuscular mycorrhizal fungal (AMF) root colonization in a field pot experiment. Non-target plants were sown in the following spring. Furthermore, we tested if glyphosate effects depend on tillage or soil properties modulated by long cultivation history of endophyte symbiotic grass (E+ grass). AMF root colonization, plant establishment and growth, glyphosate residues in plants, and soil chemistry were measured. Glyphosate reduced the mycorrhizal colonization and growth of both target and non-target grasses. The magnitude of reduction depended on tillage and soil properties due to cultivation history of E+ grass. We detected glyphosate residues in weeds and crop plants in the growing season following the glyphosate treatment. Residues were higher in plants growing in no-till pots compared to conspecifics in tilled pots. These results demonstrate negative effects of glyphosate on non-target organisms in agricultural environments and grassland ecosystems."

33. Duda, A.M., and Johnson, R.J. 1985. Cost-effective targeting of agricultural nonpoint-source pollution controls. *Journal of Soil and Water Conservation.* 40: 108-111.*

    Location: southern Ontario. *Abstract:* "The identification of runoff generating areas (RGAs) within a watershed is a difficult task because of their temporal and spatial behavior. A watershed was selected to investigate the RGAs to determine the factors affecting spatio-temporally in southern Ontario. The watershed was divided into 8 fields having a Wireless System Network (WSN) and a V-notch weir for flow and soil moisture measurements. The results show that surface runoff is generated by the infiltration excess mechanism in summer and fall, and the saturation excess mechanism in spring. The statistical analysis suggested that the amount of rainfall and rainfall intensity for summer (R2 = 0.63, 0.82) and fall (R2 = 0.74, 0.80), respectively, affected the RGAs. The analysis showed that 15% area generated 85% of surface runoff in summer, 100% of runoff in fall, and 40% of runoff in spring. The methodology developed has potential for identifying RGAs for protecting Ontario's water resources."

34. Dugdale, S.J., Malcolm, I.A., Kantola, K., and Hannah, D.M. 2018. Stream temperature under contrasting riparian forest cover: understanding thermal dynamics and heat exchange processes. *Science of the Total Environment*. 610-611.

Abstract: "Climate change is likely to increase summer temperatures in many river environments, raising concerns that this will reduce their thermal suitability for a range of freshwater fish species. As a result, river managers have pursued riparian tree planting due to its ability to moderate stream temperatures by providing shading. However, little is known about the relative ability of different riparian forest types to moderate stream temperatures. Further research is therefore necessary to inform best-practice riparian tree planting strategies. This article contrasts stream temperature and energy fluxes under three riparian vegetation types common to Europe: open grassland terrain (OS), semi-natural deciduous woodland (SNS), and commercial conifer plantation (CS). Data was recorded over the course of a year by weather stations installed in each of the vegetation types. Mean daily stream temperature was generally warmest at OS and coolest at CS. Energy gains at all sites were dominated by shortwave radiation, whereas losses where principally due to longwave and latent heat flux. The magnitude of shortwave radiation received at the water surface was strongly dependent upon vegetation type, with OS and SNS woodland sites receiving approximately 6× and 4× (respectively) the incoming solar radiation of CS. Although CS lost less energy through longwave or latent fluxes than the other sites, net surface heat flux was ordered OS > SNS > CS, mirroring the stream temperature results. These findings demonstrate that energy fluxes at the air-water interface vary substantially between different riparian forest types and that stream temperature response to bankside vegetation depends upon the type of vegetation present. These results present new insights into the conditions under which riparian vegetation shading is optimal for the reduction of surface heat fluxes and have important implications for the development of 'best-practice' tree planting strategies to moderate summer temperature extremes in rivers."

35. Ebersole, J.L., Liss, W.J., and Frissell, C.A. 2003. Cold water patches in warm streams: Physicochemical characteristics and the influence of shading. *Journal of the American Water Resources Association*, 39: 355–367*

Location: NE Oregon. ABSTRACT: "Discrete cold-water patches within the surface waters of summer warm streams afford potential thermal refuge for cold water fishes during periods of heat stress. This analysis focused on reach scale heterogeneity in water temperatures as influenced by local influx of cooler subsurface waters. Using field thermal probes and recording thermistors, we identified and characterized cold water patches (at least 3°C colder than ambient streamflow temperatures) potentially serving as thermal refugia for cold water fishes. Among 37 study sites within alluvial valleys of the Grande Ronde basin in northeastern Oregon, we identified cold water patches associated with side channels, alcoves, lateral seeps, and floodplain spring brooks. These types differed with regard to within floodplain position, area, spatial thermal range, substrate, and availability of cover for fish. Experimental shading cooled daily maximum temperatures of surface waters within cold water patches 2 to 4°C, indicating a strong influence of riparian vegetation on the expression of cold-water patch thermal characteristics. Strong vertical temperature gradients associated with heating of surface layers of cold-water patches exposed to solar radiation, superimposed upon vertical gradients in dissolved oxygen, can partially restrict suitable refuge volumes for stream salmonids within cold water patches."

36. Ebersole, J.L., Wigington, Jr., P. J., Leibowitz, S. G., Comeleo, R. L., and Van Sickle, J. 2014. Predicting the occurrence of cold-water patches at intermittent and ephemeral tributary confluences with warm rivers. *Freshwater Science.* 34(1): Published online 22 August 2014.*

    Location: Oregon. The study demonstrated that cold, subsurface water beneath dry channels can result in the formation of ecologically significant thermal refugia in downstream waterbodies.

37. Edwards, D.R., Daniel, T.C. and Moore Jr., P.A. 1996. Vegetative filter strip design for grassed areas treated with animal manures. *Trans. Am. Soc. Agric. Engin*. 12(1):31-38.

    The article presents an algorithm that can be used to determine vegetated filter strip length for areas treated with animal manures. The article is not particularly useful for developing riparian buffer guidelines because the equations require inputs that are not readily available.

38. Erman, D.C., J.D. Newbold, and K.B. Roby. 1977. Evaluation of streamside bufferstrips for protecting aquatic organisms. *University of California, Davis*. Contribution No. 165. September 1977.

    Location: northern California. Studied the effects of logging with and without riparian buffers upon aquatic macroinvertebrate communities. Narrow or absent buffers were associated with a significant decrease in diversity. The effect was distinguishable for sites with buffers less than 30 meters wide. Channel stability was also reduced at sites with narrow or no buffer. Concluded that the degree of stream protection probably increased up to a 30m buffer width, after the aquatic biota was no different than at non-logged sites.

39. Forster, C. and Smith, L. 1989. The influence of groundwater flow on thermal regimes in mountainous terrain: A model study. *J. Geophys. Res.,* 94(B7), 9439–9451.

    The article presents a groundwater thermal modelling technique that is not particularly relevant for the riparian buffer guidance. The most relevant information gleaned from the article is that heat can be transferred to water as it percolates through the soil profile. This suggests that for a given location, a soil that is not shaded will transfer more heat to shallow subsurface water than if the soil is well vegetated.

40. Fox, D.M., Bryan, R.B., and Price, A.G. 1997. The influence of slope angle on final infiltration rate for interrill conditions. *Geoderma* 80 (1997) 181-194.

    As slope increases, infiltration rate declines non-linearly.

41. Fullerton, A.H., Torgerson, C.E., Lawler, J.J., Faux, R.N., Steel, E.A., Beechie, T.J., Ebersole, J.L., and Leibowitz, S.G. 2015. Rethinking the longitudinal stream temperature paradigm: region-wide comparison of thermal infrared imagery reveals unexpected complexity of river temperatures. *Hydrol. Process.* 29, 4719-4737.

Type: Observational. This paper discusses an evaluation of longitudinal temperature profiles for rivers in the Pacific Northwest and classified the observations into one of five general patterns. These five patterns are asymptotic (increasing then flattening), linear (increasing steadily), uniform (not changing), parabolic (increasing then decreasing), or complex (not fitting other classes). Patterns did not appear to be associated with a geographic pattern. The authors also examined how different environmental factors correlated with the temperature patterns. The factors the evaluated included: August air temperature, August precipitation, tributary temperature, water velocity, elevation, river, gradient and distance upstream. Different factors may cause thermal discontinuities at different places along a river. The authors cite Poole and Berman (2001) as proposing that riparian shade may have a greater influence upon thermal patterns in headwaters reaches, while surface and subsurface inflows may have a stronger influence upon thermal patterns in downstream reaches. The authors suggest that the observed thermal diversity (and cold water refugia at multiple spatial scales) among rivers may facilitate biological resilience to climate change and that climate change may differing effects upon rivers. Models that predict thermal changes associated with climate change should not assume that rivers display an asympototic profile.

42. Gresswell, R.E., Barton, B.A., and Kershner, J.L. eds. 1989. Practical approaches to riparian resource management. An educational workshop. May 8-11, 1989. *U.S. Bureau of Land Management*. Billings, MT

    (Relevance/Value: 0 out of 3)

    The reference contains multiple articles that address various riparian resource management strategies. The articles are interesting and informative, but none are particularly relevant/useful for addressing the effectiveness of riparian buffers at reducing nonpoint source pollution.

43. Grizzel, J., McGowan, M., Smith, D., and Beechie, T. 2000. Streamside buffers and large woody debris recruitment: evaluating the effectiveness of watershed analysis prescriptions in the North Cascades region. TFW Effectiveness Monitoring Report. TFW-MAGI-00-003.

    Location: western WA. Type: Observational. This study evaluated the effectiveness of riparian buffers at 10 sites along seconds to fourth order streams in forested areas with recent timber harvest. Average buffer widths were either <20m, 20 to 30m, or >30m. Sites lengths ranged from 385 to 700m and coincided with timber harvest boundaries. Average bankfull channel widths ranged from 2.1 to 8.1m. All sites were below 400m in elevation. Half of the sites had buffers on one-side of the stream, half on both sides. Of the five sites with only one-sided buffers, four had intact second growth on the opposite bank, while one had a buffer established under previous forest practices regulations. Average one-sided buffer widths ranged from 16.4 to 38.8m. Mean tree diameter (DBH) in the buffers ranged from 25.1 to 34.8cm (9.9in to 13.7in). Large wood that was apparently recruited prior to the timber harvest was not included in the count since the purpose was to evaluate effectiveness of the timber harvest buffer. Post-harvest tree mortality was mostly attributed to wind throw (but included standing dead and down trees) and ranged from 2.9 to 56.8% (average of 18.3%) of stand basal area and 4.8 to 60.5% (23.8% average) of stem density. Older wood was larger and more frequent in the channel than wood recruited from the second-growth buffers. For all three buffer width classes, over 50% of wood was recruited from within 15m of the channel. For 20-30m buffers, 19% was recruited from beyond 20m from the channel. For 30+m buffers, 28% of wood was recruited beyond 20m form the channel, and 10% from beyond 30m. As buffer width increased the proportion of broken wood pieces reaching channels decreased, but buffer width had no effect on the proportion of downed trees reaching the channel. 73% of trees fell in a northerly direction. Trees in buffers oriented perpendicular to and on the windward side of a stream (tending to be the south side in western WA) have a higher recruitment likelihood than trees in perpendicular buffers on the leeward side, or trees in buffers oriented parallel to the prevailing storm paths.

The study findings are somewhat complicated by the fact that the buffers included both one and two-sided buffers, since recruitment cannot be attributed solely to one bank or the other; also, the findings showed that buffer position relative to stream orientation matters for wood recruitment, but the study did not separate sites based on position. For example, if all of the sites were east-west channels, then we would expect wood recruitment to be much higher if buffers were on the south side than if the buffers were on the north side of the channels. Channel orientation was not reported in this document.

44. Guenther, S.M., Gomi, T., and Moore, R.D. 2014. Stream and bed temperature variability in a coastal headwater catchment: influences of surface-subsurface interactions and partial-retention forest harvesting. *Hydrological Processes*. Volume 28, Issue 3, 30 January 2014, Pages 1238–1249*

    Location: coastal British Columbia. Abstract: "Stream temperature was recorded between 2002 and 2005 at four sites in a coastal headwater catchment in British Columbia, Canada. Shallow groundwater temperatures, along with bed temperature profiles at depths of 1 to 30 cm, were recorded at 10-min intervals in two hydrologically distinct reaches beginning in 2003 or 2004, depending on the site. The lower reach had smaller discharge contributions via lateral inflow from the hillslopes and fewer areas with upwelling (UW) and/or neutral flow across the stream bed compared to the middle reach. Bed temperatures were greater than those of shallow groundwater during summer, with higher temperatures in areas of downwelling (DW) flow compared to areas of neutral and UW flow. A paired-catchment analysis revealed that partial-retention forest harvesting in autumn 2004 resulted in higher daily maximum stream and bed temperatures but smaller changes in daily minima. Changes in daily maximum stream temperature, averaged over July and August of the post-harvest year, ranged from 1.6 to 3 °C at different locations within the cut block. Post-harvest changes in bed temperature in the lower reach were smaller than the changes in stream temperature, greater at sites with DW flow, and decreased with depth at both UW and DW sites, dropping to about 1 °C at a depth of 30 cm. In the middle reach, changes in daily maximum bed temperature, averaged over July and August, were generally about 1 °C and did not vary significantly with depth. The pre-harvest regression models for shallow groundwater were not suitable for applying the paired-catchment analysis to estimate the effects of harvesting. However, shallow groundwater was warmer at the lower reach following harvesting, despite generally cooler weather compared to the pre-harvest year."

45. Haberstock, A.E., Nichols, H.G., DesMeules, M.D., Wright, J., Christensen, J.M., and Hudnut, D.H. 2000. Method to identify effective riparian buffer widths for Atlantic salmon. *JAWRA*. Vol. 36, No. 6.

Location: Maine. The article presents a modelling method for deriving riparian buffer widths based on site specific slope, soil, and vegetation attributes. The article asserts that riparian buffers should not be reduced for smaller streams since they are commonly more sensitive to changes in water quantity and quality. States that beyond 2/3 to 3/4 of a site potential tree height, the incremental gain in providing LWD rapidly decreases, so the effective widths for LWD can be considered to be less than one tree height. 100ft fixed width setbacks are very common in the eastern U.S, but setbacks as low as 35ft are also common. The authors assert that variable width buffers with multiple zones have more flexibility which better addresses site specific factors and can prevent overprotection. The three primary attributes for determining the prescribed buffer width are slope, soil hydrologic group, and percent canopy closure. A linear relationship between buffer attributes and buffer effectiveness. The method includes a key for determining the unadjusted buffer width prescription. Unfortunately, only an excerpt from the keys is provided. The unadjusted buffer widths range from 70ft for flat slopes (0-8%), highly permeable soils, and near to full canopy closure, to 230ft for steep slopes (>25%), low permeability soils, and limited canopy. The authors state that these unadjusted widths are based on the scientific literature from forested locations in the northern U.S. and Canada. If only one of the three primary attributes is known, then that one is used to derive the unadjusted buffer width. The width measurement begins at the ordinary high-water mark, or upland edge of the floodplain or open wetlands if present. The prescription can be modified based on field survey information on factors including surface water features, groundwater seepage/springs, surface roughness, understory vegetation, land use, stream size, sand/gravel aquifer presence, and wetlands. The authors note that the specific width adjustments based on field observed factors are arbitrary and based mostly on BPJ (i.e., not based on scientifically derived mathematical relationship). A given parcel site would be delineated into units, such that each unit may be given a different buffer width, resulting in a variable width buffer on a parcel. The method also divides the buffer into two zones. Zone one is to have no soil or vegetation disturbing land use. Zone two can have limited tree removal and light recreation, but all perennial water features in zone two should have a 35ft no harvest strip. The method acknowledges that a conflicting land use may be occurring in the prescribed buffer and should be discontinued in the buffer as practicality allows. The authors state that this method is for identified critical habitat reaches and was not designed to be applied throughout a watershed, including headwaters areas because it does not account for watershed scale land use.

46. Hatten, J., and R. Conrad. 1995. A comparison of summer stream temperatures in unmanaged and managed sub-basins of Washington's Olympic Peninsula. *Northwest Indian Fisheries Commission.* Olympia, WA. 59 pp.

Location: western Washington. Water temperatures were compared for low elevation sites on 26 streams with differing levels of timber management. Managed sites were those having a contributing sub-basin in which ≥15% of the mature forest had been harvested or harvesting occurred within the 600m reach containing the temperature monitoring site. Unmanaged sites were those having <15% of the mature forest harvested in the sub-basin and no harvest of trees in the riparian zone of the reach containing the temperature monitoring site. The authors concluded that maximum water temperatures exceeded the Washington State temperature criterion of 16.0^{o}C ten times more frequently at sites in managed sub-basins than at sites in unmanaged sub-basins. The average number of days during the 39-day monitoring period with peak water temperatures exceeding 16.0^{o}C was 1.8 days for unmanaged sites and 18.3 days for managed sites. Note that four of the unmanaged sites had a t least one day in which temperatures exceeded 16^{o}C. Elevation and shade for the monitoring reaches were not significantly different between the two groups and did not affect the temperature differences between managed and unmanaged sites; however, due to small sample sizes the tests had low power (<0.5). The ANOVAWC indicated that the difference between temperatures at managed and unmanaged sites was due to the percentage of mature forest in the contributing sub-basins. The authors assert that their findings demonstrate that "managing for stream temperature at the reach level will not be successful unless logging activity throughout a basin in considered." Take home message: there is evidence that increased water temperatures occur when the mature forest cover is removed from a significant proportion (e.g., ≥15%) of a watershed.

47. Hedman, E.R., Osterkamp, W.R., 1982. Stream flow characteristics related to channel geometry of streams in western United States. USGS Water-Supply Paper 2193, 17 pp.

    Used for defining perennial, intermittent, and ephemeral stream flow characteristics.

48. Hendrick, R., and J. Monahan. 2003. An assessment of water temperatures of the Entiat River, Washington using the Stream Network Temperature Model (SNTEMP). Washington Department of Ecology and the Entiat WRIA Planning Unit. Yakima and Entiat, WA. 85 pp. (http://www.cascadiacd.org/files/documents/SNTEMP_FinalDraft_Sept03.pdf).

    Value: 0 for temperature-buffer data analysis, 2 for information regarding thermal loading factors. Location: central WA. Type: Observational, Modeling. This study of the Entiat River shows how changes in stream temperatures are more strongly influenced by changes in shading than changes in flow.

49. Henriksen, A. and Kirkhusmo, L. A. 2000. Effects of clear-cutting of forest on the chemistry of a shallow groundwater aquifer in southern Norway. *Hydrol. Earth. Syst. Sci.*, 4, 323–331.

    Value: 0 for temperature-buffer data analysis, 2 for thermal process info. Location: Norway. The authors studied how clearcutting affected groundwater quality. Groundwater temperature increased following clearcutting and remained elevated for at least 11 years afterward.

50. Hetrick, N. J., M. A. Brusven, W. R. Meehan, and T. C. Bjornn. 1998. Changes in solar input, water temperature, periphyton accumulation, and allochthonous input and storage after canopy removal along two small salmon streams in southeast Alaska, *Transactions of the American Fisheries Society.* 127:6, 859-875.

Value: 0 for temperature-buffer data analysis, 1 for thermal process info. Location: SE Alaska. Hetrick et al. (1998) alternated removal and retention of 40 m to 70 m (131ft to 229.7ft) patches of deciduous (red alder), riparian vegetation along two small (1-3 m) (3.3-9.8 ft) anadromous salmon streams on Prince of Wales Island in southeast Alaska. Seasonal average daily water temperature and diel fluctuations were similar in the two canopy types in 1988 when the weather was predominantly overcast and rainy was but was significantly higher in the open canopy section in 1989 when the summer weather was mostly sunny with infrequent rain. Periphyton biomass was significantly higher in open-canopy sections of the two streams in the summer of 1988 and in the one stream sampled in 1989. Using a model (Beschta et al. 1987), and setting 11°C as a baseline, they predicted no increase in seasonal average water temperature under any weather condition at high flows (0.020 m^3/s) in a 160 m (525 ft) open reach, a 3°C increase in seasonal average stream temperature during moderate flows (0.010 m^3/s) over a 150 m (492 ft) reach, under sunny weather, and 3°C to 15°C in about 50 m (164 ft) of open canopy at low flows (0.001 m^3/s) during overcast and sunny weather respectively.

51. Holtby, L.B. 1988. Effects of logging on stream temperatures in Carnation Creek, British Columbia, and associated impacts on the coho salmon (*Onchorhynchus kisutch*). *Can. J. Fish. Aquat. Sci.* 45:502-515.

    Value: 0 for temperature-buffer data analysis, 2 for linking land use to aquatic biota effects. Location British Columbia. Holtby (1988) found that clear-cut logging of 41% of the basin of Carnation Creek, British Columbia, resulted in increased stream temperatures in all months of the year. Increases above prelogging monthly mean temperatures ranged from 0.7C in December to 3.2C in August. Earlier emergence of coho salmon fry associated with the temperature increases lengthened their summer growing season by up to 6 wk. Fingerlings were significantly larger by the fall in the years after logging compared with the years before logging. The increased size of fingerlings was associated with improved overwinter survival. Following logging, yearling smolt numbers doubled, although 2-yr-old smolt numbers decreased. Warmer spring temperatures were also associated with earlier seaward migration of smolts, probably resulting in decreased smolt-to-adult survivals. The authors develop life history models to further examine and compare these apparent contradictory responses of the coho population to temperature increases. Prior to logging stream temperatures were cool with monthly mean temperatures ranging from about 2.5C in February to only 10C in August. Multiple regression was used to partition the observed variability in stream temperatures between climatic and logging effects. High winter discharge coupled with early smoltification was associated with poor survival. Modeling resulted in a predicted 9% increase in adult coho numbers – considerably less than the observed 47% increase in smolt numbers. (Note: Monthly mean stream temperatures in Carnation Creek remained at or below 15C after harvest based on Figures 4 and 5. Author cites Thedinga and Koski, 1984 as demonstrating that migrating 1-2 weeks earlier or later than the median day can result in 45-60% the survival of smolts leaving during the middle of the smolt run.) The author noted the habitat perturbations such as the observed temperature increase can affect more than one life state simultaneously and in opposite direction and that the effects at one state can persist throughout the remainder of the life cycle and for salmonids, into the marine phase. The author also noted that summer temperatures in coastal streams like Carnation Creek are typically cool and adverse effects of moderate summer warming would not be expected. The effects of warming in systems where summer temperatures are much higher could be expected to differ from those in this study.

52. Johnson, M. and Wilby, R. L. 2015. Seeing the landscape for the trees: Metrics to guide riparian shade management in river catchments. *Water Resour. Res*., 51, 3754-3769.

    Location: United Kingdom. New: Johnson and Wilby (2015) measured and modeled two upland rivers in the Dove and Manifold Rivers in the United Kingdom to assess the relative significance of landscape and riparian shade to thermal behavior of river reaches. For the two rivers studied, they found that approximately 0.5 km of complete shade is necessary to off-set a 1C increase in water temperature during July at the headwater site, whereas 1.1 km of shade is required 25 km downstream. (*Note: study is not very transferable to Washington since it is from a system largely devoid of trees where the existing trees are relatively short but does provide some good discussion of heating processes and illustrations on the relationship between solar altitude and cumulative solar loading as well as length of shade per tree height and solar angle. Notes studies showing rates of warming: Rutherford et al. 1997 daily maximum in summer can change by 3-4C in 600 m for a river in Hamilton, New Zealand (38S; ave width 1.2 m). Hopkins 1971 found 3-4C in 500 m for second order streams in Wellington, New Zealand (41S; 1.5-2.0 m wide). Rutherford et al 2004 found higher rates (10C/km) in Western Australia and south-east Queensland (26-35S; 1.3-3.3 m wide). Since these sites are closer to the equator than the rivers Dove and Manifold, they would receive more intense solar radiation.)*

53. Jones, K. L., Poole, G. C., Meyer, J.L., Bumback, W., and Kramer, E. A. 2006. Quantifying expected ecological response to natural resource legislation: a case study of riparian buffers, aquatic habitat, and trout populations. Ecology and Society 11(2):15.

    Location: Georgia. Jones et al. (2006) established and quantified relationships among riparian forests, aquatic habitat (stream temperature and riffle embeddedness), and trout reproductive success (biomass of young trout). They used these relationships to determine the expected impacts of the buffer width reduction on aquatic habitat and trout reproductive success at the stream segment and stream network scales and assessed associated uncertainty. When compared with stream segments having 30-m wide buffers, their analysis indicated that individual stream segments with 15-m wide buffers have: 1) higher peak temperatures (average peak stream temperatures during the warmest week of the year increase by □2.0 ± 0.3°C, depending on summertime climate conditions); and 2) more fine sediments (fines in riffle habitats increase by approximately 25% of the observed inter-study-site range). The data show that trout populations will respond markedly to these habitat changes. Linear regression models and an associated Monte Carlo uncertainty assessment document an expected 87% reduction in young trout biomass, with a 95% confidence interval ranging from a 66% reduction to a 97% reduction. A landscape assessment showed that 63% of Georgia's 2nd- to 5th-order trout stream segments could maintain stream temperatures likely (>50% probability) to support young trout in streams bordered by 30-m wide forested riparian buffers. Less than 9% of those streams (only those at the highest elevations) would maintain such temperatures with 15-m wide riparian buffers. As young trout are indicative of trout reproductive success, our results portend substantial reductions or elimination of trout populations in northern Georgia streams where vegetated riparian buffer widths are reduced to 15 m. (Note: buffer width estimated using percent cover within 30 m of the stream as supported by a pilot sample of 18 sites with r2=0.83 p<0.01. Care must be exercised with this study since this is testing association as much as causation. For example, the method may be identifying intact forests in places where it is assumed to represent 30 m buffers).

54. Kaylor, M.J., Warren, D.R., and Kiffney, P.M. 2017. Long-term effects of riparian forest harvest on light in Pacific Northwest (USA) streams. *Freshwater Science*. 36:1:1-13.

    Location: W. Oregon. Kaylor et al. (2017) measured light and canopy cover along in a 4th order stream basin dominated by late-successional riparian forests that included 7 streamside harvest units 50 to 60 years old in Western Oregon. Bankfull widths at the harvest sites ranged from 2.8 to 10.12 m (median approximately 8 m). Estimated light fluxes were lower in harvest units than in up- and downstream sections bordered by old-growth forests. The authors also conducted a space for time analysis based on a literature review of Douglas fir-dominated forests of the US Pacific Northwest. Canopy closure generally occurred without 30 years of harvest and was followed by a period of maximum canopy cover that lasted from 30 to 100 years. Data were limited for stand in the 100- to 300-year-old range, but openness and variability were greater in late-successional forests (dominant canopy trees >300 years old) than in stands that were 30 to 100 years old (18% versus 8.7%). Suggesting that streams with mid-successional riparian forests probably are in a period of minimal summer light flux. (*Notes: Only about 30-45% of the differences were significant, leaving to question the strength of the reported trends. Only two sites were in the 100–300-year-old range, which when considered along with their use of a mean to represent all >300-year-old age class stands makes asserting a trend difficult to accept. I did not see where they present the results from their use of the photo-decay rate of fluorescein dye. Within sampled sites: Canopy openness explained 36% of the variation in PAR. When streams were evaluated separately canopy openness explained 0.44 in McRae and 0.02 in MCTE. See page 6-7 for comparisons. Percent openness was 6.1% greater on average (range -2.2-14.5%) in old growth sections than in adjacent harvest units with 5 of 14 comparisons being statistically significant. Recorded reach-average canopy openness values ranged from 6.5-22.4% with a general trend of greater openness for wider stream channels (3.1 - 10 m bankfull width)).*

55. Klos, P.Z. and Link, T.E. 2018. Quantifying shortwave and longwave radiation inputs to headwater streams under differing canopy structures. *Forest Ecology and Management* 407:116-124.

    Location: northern Idaho. Klos and Link (2018) examined the radiative heating of small streams having 5-year-old riparian buffers that differed substantially in their structure but had similar levels of shade. The partial over story cut and dense understory clear-cut reaches had similar radiative regimes as intact forested reaches; the sparsely vegetated understory only canopy reach had higher levels of short-wave radiation. The data support the hypothesis that increases in stream temperature after harvesting is due to "increases in turbulent and advected energy fluxes from the nearby cleared areas and lower canopies post-harvest." However, the authors note that "Any sensible flux increases, may however be balanced or enhanced by latent energy fluxes, hence the magnitude of this effect will depend strongly on ambient humidity conditions and diurnal temperature cycles that control the amount and direction of vapor transfer to or from the stream surface." In other words, a stream with only an understory canopy may receive the same radiative flux but can have temperature increases due to increased sensible heat from turbulent transfer. "Stream temperature increases may however be buffered by (1) large latent heat losses if vapor pressure deficits are relatively high, (2) suppression of turbulent energy transfer if water temperatures are much colder than air and strong inversions are present over the water surface, or (3) by large groundwater gains and/or hyporheic flows within a given reach."Clear-cut reaches had 9.1 m (30 ft) equipment exclusion buffers.

56. Kuglerova, L., Agren, A., Jansson, R., and Laudon, H. 2014. Towards optimizing riparian buffer zones: Ecological and biogeochemical implications for forest management. *Forest Ecology and Management* 334 (2014) 74-84.

    Kuglerova et al. (2014) provide an argument for why ground water areas connected with riparian forest provide unique services that warrant protection and argue that instead of providing uniform buffers along streams that more variable buffers that capture these ground water discharge areas would be better overall. (Note: Overall this is a poorly supported hypotheses, but it does provide some useful summary and reference information on some of the ecosystem functions provided by ground water discharge areas.)

57. Kurylyk, B. L., MacQuarrie, K. T. B., Linnansaari, T., Cunjak, R. A., and Curry, R. A. 2015b. Preserving, augmenting, and creating coldwater thermal refugia in rivers: concepts derived from research on the Miramichi River, New Brunswick (Canada). *Ecohydrology*. Vol 8, Iss. 6.

    Location: New Brunswick, Canada. The article focuses on the identification, protection, and enhancement of cold water refugia in streams and rivers. The authors state that forest canopies influence shallow groundwater temperatures by reducing the amount of solar radiation that reaches the ground surface and by modifying convective processes between the ground surface and atmosphere. They further assert that where vegetation removal in the uplands leads to increased groundwater temperatures, warmer water can be discharged to streams even if adequate riparian buffers are in place.

58. Kurylyk, B.L., Bourque, C.P.-A., and MacQuarrie, K.T.B., 2013. Potential surface temperature and shallow groundwater temperature response to climate change: an example from a small, forested catchment in east-central New Brunswick (Canada). *Hydrol. Earth Syst. Sci.*, 17, 2701-2716.

    Location: New Brunswick, Canada. Kurylyk et al. (2013) model changes in groundwater temperature due to climate change. Groundwater thermal regimes are driven by water and energy transfers through the ground surface and geothermal energy. The results indicate that shallow groundwater (1.5m deep) temperature will show seasonality, while at deeper depths (8.75m), the temperature will be constant and roughly equal to the mean annual ground surface temperature. Shallow groundwater temperatures are more sensitive to changes in atmospheric and ground surface temperatures and during the summer were projected to increase by 3^{o}C. Changes in temperature for deeper groundwater were projected to show a lag and change on the scale of decadal climate changes. Streams whose baseflow is dominated by groundwater inputs may be more sensitive to climate change than previously thought.

59. Kurylyk, B.L., MacQuarrie, K.T.B., Caissie, D., and McKenzie, J.M., 2015a. Shallow groundwater thermal sensitivity to climate change and land cover disturbance: derivation of analytical expressions and implications for stream temperature modeling. *Hydrol. Earth Syst. Sci.*, 19, 2469-2489.

    Location: N/A. Kurylyk et al. (2015) model changes in groundwater temperature due to climate change and other land cover disturbances such as logging. The thermal sensitivity of a stream is defined as the slope of the regression line between water and air temperatures measured over short periods. However, the high correlation between air and stream temperatures is because both are strongly influenced by solar radiation. This method may not be appropriate for groundwater dominated streams whose groundwater temperatures are determined by multi-decadal thermal responses. Studies have shown increases in groundwater temperature caused by deforestation and wildfires. "In all cases (i.e., climate change, deforestation, and wildfires), the surface disturbance warms shallow aquifers by increasing the downward heat flux from the warming land surface. For example, climate change can influence surface thermal regimes and subsurface heat fluxes by altering convective energy fluxes from the lower atmosphere and causing increased net radiation at the ground surface." When vegetation is removed, the decrease in transpiration is associated with an increase in the potential amount of energy that can be transferred to the land surface and cause heating. In response to deforestation, headwater streams can warm more quickly than larger streams because relative amount of shading lost is typically greater for smaller streams. Stream temperature models often exclude considerations of groundwater warming based on the rationale that groundwater temperatures are constant; however, this assumption only holds true for annual or short term inter-annual time scales.

60. Lekberg, Y., Wagner, V., Rummel, A., McLeod, M., and Ramsey, P.W. 2017. Strong indirect herbicide effects on mycorrhizal associations through plant community shifts and secondary invasions. *Ecol. App.* 27(8): 2359-2368.

    Abstract: "Millions of acres of U.S. wildlands are sprayed with herbicides to control invasive species, but relatively little is known about non-target effects of herbicide use. We combined greenhouse, field, and laboratory experiments involving the invasive forb spotted knapweed (Centaurea stoebe) and native bunchgrasses to assess direct and indirect effects of the forbspecific herbicide picloram on arbuscular mycorrhizal fungi (AMF), which are beneficial soil fungi that colonize most plants. Picloram had no effect on bunchgrass viability and their associated AMF in the greenhouse but killed spotted knapweed and reduced AMF colonization of a subsequent host grown. Results were similar in the field where AMF abundance in bunchgrass-dominated plots was unaffected by herbicides one year after spraying based on 16:1x5 phospholipid fatty acid (PLFA) and neutral lipid fatty acid (NLFA) concentrations. In spotted-knapweed-dominated plots, however, picloram application shifted dominance from spotted knapweed, a good AMF host, to bulbous bluegrass (Poa bulbosa), a poor AMF host. This coincided with a 63% reduction in soil 16:1x5 NLFA concentrations but no reduction of 16:1x5 PLFA. Because 16:1x5 NLFA quantifies AMF storage lipids and 16:1x5 PLFA occurs in AMF membrane lipids, we speculate that the herbicide-mediated reduction in host quality reduced fungal carbon storage, but not necessarily fungal abundance after one year in the field. Overall, in greenhouse and field experiments, AMF were only affected when picloram altered host quantity and quality. This apparent lack of direct effect was supported by our in-vitro trial where picloram applied to AMF mycelia did not reduce fungal biomass and viability. We show that the herbicide picloram can have profound, indirect effects on AMF within one year. Depending on herbicide-mediated shifts in host quality, rapid interventions may be necessary post herbicide applications to prevent loss of AMF abundance. Future research should assess consequences of these potential shifts for the restoration of native plants that differ in mycorrhizal dependency."

AMF are known to enhance phosphorus uptake by plants that they are associated with. Different plants have different suitability for hosting AMF. The use of herbicides in a buffer can shift the plant community towards a community that is less suitable for hosting AMF, thereby potentially decreasing the ability of the buffer vegetation to absorb phosphorus delivered by surface and subsurface flow generated on agricultural uplands. This may be a trade-off of broad leaf weed control in buffers.

61. Li, H.W., Lamberti, G.A., Pearsons, T.N., Tait, C.K., Li, J.L., and Buckhouse, J. C. 1994. Cumulative effects of riparian disturbances along high desert trout streams of the John Day Basin, Oregon. *Transactions of the American Fisheries Society.* 123:627-640.

Location: North-central Oregon. Li et al. (1994) in a study of the cumulative effects of riparian disturbance by grazing on the trophic structure of high desert trout streams, watersheds with greater riparian canopy had higher standing crops of rainbow trout, lower daily maximum temperatures (range 16-23C compared with 26-31C), and perennial flow. Standing crops of rainbow trout were negatively correlated with solar radiation and maximum temperature in watersheds flowing northward. In watersheds flowing southward, trout biomass was negatively correlated with solar radiation whereas positive relationships were found for discharge and depth. Algal biomass was positively correlated with solar insolation (r=0.91), total invertebrate biomass (r-0.77), and herbivorous invertebrate biomass (r=0.79) in all watersheds. Invertebrate biomass was not significantly correlated with rainbow trout standing crop. High irradiance apparently resulted in increased algal biomass and invertebrate abundance. However, temperature elevations to levels close to lethal may impose high metabolic costs on rainbow trout, which may offset higher food availability and affect the availability of prey. Authors note that their results differ from those of other studies done to examine clear- cuts may be due to their examination of stream reaches extending several kilometers rather and hundreds of meters, and the clear-cut sites may have received the benefits of cold, high-quality water from the old growth reaches upstream and the increased primary productivity from greater solar input in the clear-cut areas. Waters flowing into the authors study sites were degraded by elevated temperatures, physiologically stressful to trout, and changed prey composition to a less favorable mix.

62. Licht, L.A. and J.L. Schnoor, J.L. 1993. Poplar tree buffer strips grown in riparian corridors for non-point source pollution control and biomass production, Leopold Cent. Sustain. Agric. Pap. 31.
    Type: Observational. Location: Iowa. This study evaluated the removal of nitrate from soils and shallow groundwater. Four rows of poplars were planted in a 3.6m buffer, and a 4.6m fallow strip was maintained between the trees and the creek. Shallow groundwater below the buffer had roughly 95% lower nitrate concentrations than below the corn field. The trees also appeared to reduce soil nitrate content. The authors did not examine nitrate removal in groundwater through bacterial denitrification but attributed all the reductions to uptake by poplar.

63. Liquori, M.K. 2006. Post-harvest riparian buffer response: implications for wood recruitment modeling and buffer design. *JAWRA.* 42(1).

    Abstract: "Despite the importance of riparian buffers in providing aquatic functions to forested streams, few studies have sought to capture key differences in ecological and geomorphic processes between buffered sites and forested conditions. This study examines post-harvest buffer conditions from 20 randomly selected harvest sites within a managed tree farm in the Cascade Mountains of western Washington. Post-harvest wind derived treefall rates in buffers up to three years post-harvest averaged 268 trees/km/year, 26 times greater than competition-induced mortality rate estimates. Treefall rates and stem breakage were strongly tied to tree species and relatively unaffected by stream direction. Observed treefall direction is strongly biased toward the channel, irrespective of channel or buffer orientation. Fall direction bias can deliver significantly more wood recruitment relative to randomly directed treefall, suggesting that models that utilize the random fall assumption will significantly under predict recruitment. A simple estimate of post-harvest wood recruitment from buffers can be obtained from species specific treefall and breakage rates, combined with bias corrected recruitment probability as a function of source distance from the channel. Post-harvest wind effects may reduce the standing density of trees enough to significantly reduce or eliminate competition mortality and thus indirectly alter bank erosion rates, resulting in substantially different wood recruitment dynamics from buffers as compared to unmanaged forests."

    Buffer widths ranged from 17 to 78m. Treefall rates were much greater for hemlock and silver fir than they were for alder, cedar, and doug fir. Median treefall was 15% and ranged from 1 to 57%. Trees tended to fall in a northerly direction, yet there was also a bias of falling towards the channel regardless of stream orientation. The bias was greater closer to the channel. Buffer design can be modified to promote wood recruitment to trees, e.g. thinning to allow winds to penetrate further into buffers can increase short-term wood recruitment. The data was limited, but there was no conclusive pattern in the magnitude of treefall in inner buffer zones relative to buffer characteristics.

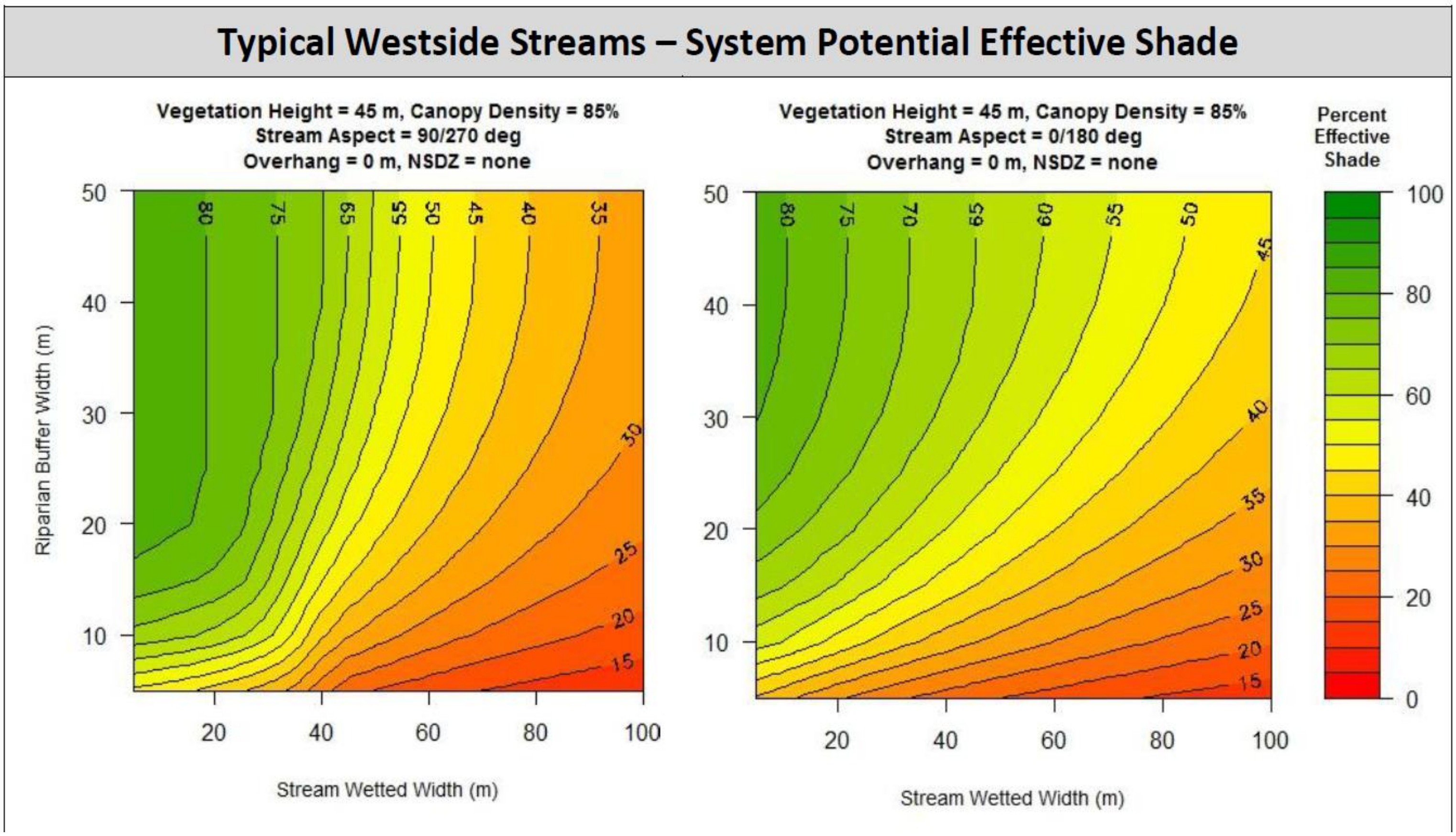
64. Mander, Ü., Kuusemets, V., Lõhums, K., Mauring, T. 1997. Efficiency and dimensioning of riparian buffer zones in agricultural catchments. *Ecological Engineering*. 8: 299-324.

    Location: Estonia. The authors perform a meta-analysis of nutrient retention in riparian zones and also present an efficiency assessment for nutrient retention for sites in Estonia and the U.S. Biological processes removing nitrogen from runoff in riparian ecosystems include: vegetation uptake and storage; microbial transformation of inorganic nitrogen into organic nitrogen and storage in soils; and microbial mediated denitrification into nitrogen gas. A table is presented with published rates of nitrogen removal for different processes and ecosystems. Denitrification rates in riparian areas have been found to range from <1 to 1600kg per hectare per year. Vegetation uptake of nitrogen in riparian areas has been found to range from <10 to 350 kg per hectare per year, with the highest amount in riparian meadows. Processes resulting in the capture of phosphorus in riparian zones include: 1) soil adsorption; 2) plant uptake of dissolved organic phosphorus; 3) microbial uptake; and organic phosphorus incorporation into peat. A table is presented with published rates of phosphorus removal for different processes and ecosystems. Soil adsorption has been found to range from 0.1 to 236 kg P per hectare per year and vegetation uptake from <10 to 350 kg per hectare per year. Between the Estonian two sites (Porijogi- 20m buffer and Viiratsi- 28m buffer) the buffer removal efficiency ranged from 2.9 to 4.1% per meter for nitrogen and 2.9 to 3.5% for phosphorus; for the Porijogi site N and P retention were 81 and 67% respectively, while for the Viiratsi site it was 80 and 81% for N and P respectively. These rates translate to a theoretical 100% retention for a buffer width between approximately 24 and 34.5 m The 50 to 60m buffer that included a grass strip, wet meadow, and alder stand retained most of the nitrogen and phosphorus that entered the buffer. Shrub stands, young forests, and wet grasslands showed the most intensive nutrient removal. *Note: this paper is somewhat difficult to follow.*

65. Mohamedali, T. 2014. A potential approach for developing prescriptive buffer widths for temperature TMDLs. Technical Memo. April 17, 2014. WA State Dept. of Ecology.

    This document uses models to evaluate relationships among stream wetted width, channel orientation buffer width, and effective shade. In general, as channel width increases potential effective shade decreases. Overhanging branches significantly increase potential effective shade for small to mid-size channels. For modelling purposes, TMDLs were reviewed to select tree height and canopy density inputs to the model for eastern and western WA. The values selected were a 45m tree height and 85% canopy density for western WA, and a 30m tree height and 75% canopy density for eastern WA. Below are two examples of contour plots that are presented in the document. These plots display the maximum modelled potential effective shade that can be achieved for a given buffer width and channel wetted width. Note that shading can never achieve 100% effective shade and that for a given stream width there is a threshold buffer width beyond which no further increase in potential shading can be achieved- this threshold occurs on the plot where a contour line becomes vertical. Note also that north-south channels greater than 60m wide and east-west channels greater than about 80m wide have a maximum potential shading of less than 50%. Accounting for a near-shore disturbance zone (e.g., exposed gravel bars) significantly reduces potential channel shading. The document also suggests that a 100ft buffer (for the specific vegetation and stream characteristics represented - 10 or 30m channel width, 0- or 90-degree azimuth) provide 70 to 80% effective shade (previous studies suggest that old-growth forests provide 80 to 90% effective shade - Brazier and Brown, 1973, Steinblums, 1984).

Table 39: From Mohamedali (2014) showing Westside streams – System potential effectiveness shade



66. Mohseni, O. and Stefan, H. 1999. Stream Temperature/Air Temperature Relationship: a Physical Interpretation. *Journal of Hydrology*. 218:128-141.

Location: N/A. Mohseni and Stefan (1999) examined the heat exchange process that contributes to surface water temperature as it relates to air temperature. The authors concluded that in stream reaches with large drainage areas stream temperature can be approximated by equilibrium temperature. Equilibrium temperature is described as a hypothetical temperature that water reaches under constant atmospheric heating/cooling where no more heat is transferred at the air/water interface and the bulk coefficient of heat transfer is a function of air temperature, dew point temperature, and wind velocity. After

long travel time (from ground water input) the memory of the upstream temperature is lost and only weather determines the water temperature. Therefore, equilibrium temperature is solely weather dependent, whereas upstream temperature depends upon geology, climate and man-made reservoirs and discharges.

67. Moore, R.D. 2007. Headwater stream temperature response to alternative riparian management strategies: An experimental and modeling approach. *Final report for Forest Science Program Project FP-Y061049*. Department of Geography and Department of Forest Resources Management, The University of British Columbia, 1984 West Mall, Vancouver, B.C. V6T 1Z2.

Location: western British Columbia. Moore (2007) used a paired-catchment BACI design to examine the effects of harvesting on stream temperature. Buffer widths were not reported. Three sets of sites located in western British Columbia, Canada were examined: 1) Malcolm Knapp Research Forest Streams – first phase was clearcut harvesting with and without riparian buffers and the second phase was logging about 40% of the catchment of three treatment streams to remove 50% of the basal area. 2) Moakwa Creek and Lewis Lake Streams - harvesting with different portions of the stream length covered by forest patches (0, 15, and 50%). Stream discharge and groundwater input were measured using constant rate salt injection. Canopy cover measured using Angular Canopy Density as well as using hemispherical canopy photographs. Neither dispersed nor patch retention treatments were fully effective at protecting against stream temperature increases since significant post-harvest temperature increases occurred spring through summer at almost all of the treatment streams. The temperature increase at Griffith and Mirror Creeks were as high as 6°C and were on the same scale as streams in the MKRF that had been exposed to clear-cut harvesting with no riparian buffer (5-8°C Gomi et al., 2006). The author opined that the smaller catchment areas and less incised streams may have contributed to making these streams more sensitive to losses in shade.

68. Nagel, D.E., Buffington, J.M., Parkes, S.L., Wenger, S., and Goode, J.R. A 2014. A landscape scale valley confinement algorithm: delineating unconfined valley bottoms for geomorphic, aquatic, and riparian applications. *Gen. Tech. Rep. RMRS-GTR-321*. USDA, Forest Service. Rocky Mountain Research Station.

Location: Idaho. The authors describe a GIS-based approach for delineating stream valley confinement. The method has applications for aquatic and riparian management, since valley confinement determines the potential width of riparian zones, thereby influencing riparian chemical, physical, and biological attributes and processes; for example, a wide valley allows a stream to migrate and deposit alluvium, which influences hyporheic and groundwater hydrology and typically results in a different riparian ecotone, whereas a narrow v-shaped valley has much less potential to develop a riparian ecotone with strong alluvial groundwater influence. The approach in this study used four primary variables: 1) cost-weighted distance; 2) flood height; 3) ground slope; and 4) maximum valley width. Channels were classified as confined if the valley was <4.0 times the bankfull channel width and unconfined if the ratio was ≥4.0.

69. NOAA precipitation frequency atlas 1973.

Provides information on storm intensity/frequencies for Washington State.

70. O'Briain, R., S. Shephard, B. Coghlan. 2017. River reaches with impaired riparian tree cover and channel morphology have reduced thermal resilience. *Ecohydrology*, Vol. 10 Issue 8.

Location: Ireland. O'Briain et al. (2017) evaluated the effects of riparian tree cover and channel morphology on the thermal regimes of 3 adjacent rivers in different years in Dublin, Ireland. The effects of tree cover changed among years such that greater cover was required to maintain a given water temperature regime in the warmer summer of 2013 than in 2014 or 2015. Water temperature was also related to mean depth in some years; shallower sites, typically associated with artificial channel widening, showed greater temperature extremes. Results suggest that the thermal resilience of modified streams can be improved by restoration of riparian tree cover and restored channel morphology. Though study shows a positive effect of greater mean depth in moderating higher temperatures, in warmer years, the effect of increasing mean depth is diminished. And it is noted that in this regard the need for substantial tree cover to buffer thermal extremes may be greater in modified rivers. Hyporheic and groundwater exchange buffer stream temperatures from the heat inputs from air temperature and solar radiation. Riparian shade typically exerts the primary control over the heating of small to medium sized streams (1^{st} - 3^{rd} order) and is of lesser importance for larger streams.

71. Paine, D. P., and Hann, D.W. 1982. Maximum crown-width equations for southwestern Oregon tree species. Forest Research Laboratory, Oregon State University, Corvallis. Research Paper 46. 20 p.

Abstract: "Maximum crown width (MCW) equations were developed for 16 tree species found in southwest Oregon. MCW equations are required to compute the crown competition factor, a stand density variable, for the mixed coniferous stands of the area. For all species, MCW was found to be related to diameter at breast height (D). For 11 species, additional equations were developed that related MCW to D and to geographic position variables. The later equations are limited to specific geographic areas."

Crown widths generally correspond to the distance of root spread.

The general equation for Douglas fir yielded the following approximate results for maximum crown widths:

Table 40: Maximum crown width estimates for Douglas fir in feet and meters

Diameter at breast height (in (ft))	Maximum crown width (ft)	Maximum crown width (m)
10 (0.8)	15	4.6
20 (1.7)	32	9.8

30 (2.5)	44	13.4
40 (3.3)	53	16.2
50 (4.2)	60	18.3
60 (5)	65	19.8
70 (5.8)	67	20.4

72. Parkyn, S.M., Davies-Colley, R.J., Halliday, N.J., Costley, K.J., and Croker, G.F. 2003. Planted riparian buffer zones in New Zealand: do they live up to expectations? *Restoration Ecology* Vol. 11, No. 4, pp. 436-447.

    Location: New Zealand. The authors evaluated chemical, physical, and biological variables at nine sites where fenced riparian buffers had been established 2 to 24 years prior. Buffer widths ranged from 3.5 to 75 m (median = 12.7m) and lengths ranged from 100 to 4200m (median 664m); mean channel widths ranged from 1.6 to 8.1m. Each fenced and planted buffer was compared to an unfenced, grazed reach upstream (except for 2 sites that had to be compared to sites on nearby streams of similar character). There were few clear differences between buffered and non-buffered sites. Note: The obvious major flaw in the study design is that the non-buffered sites were upstream of the buffered sites such that chemical, physical, and biological conditions in the degraded reaches were transmitted downstream into the reaches with rehabilitated riparian zones.

73. Phillips, J.D. 1989. Evaluation of the factors determining the effectiveness of water quality buffer zones. *Journal of Hydrology*. 107: 133-145.

    Location: eastern NC. Philips used two models to explore the importance of slope length, slope gradient, soil surface roughness, and soil hydraulic attributes to the effectiveness of buffers. For sediment or pollutants adsorbed to sediments in overland flow, slope gradient, followed by soil hydraulic conductivity were the most important factors for determining pollutant capture. For dissolved pollutants in surface or subsurface flow, buffer width was the most important factor and soil moisture storage capacity was also a factor; storage capacity applies only to the soil profile above a seasonal high-water table.

74. Pilgrim, J., Xing, F., and Stefan, H. 1998. Stream Temperature Correlations with Air Temperatures in Minnesota: Implications for Climate Warming. *Journal of the American Water Resources Association*. 34:5:1109-1121.*

    Location: Minnesota. Pilgrim et al. (1998) examined water and air temperatures for 39 Minnesota streams estimated that if atmospheric CO_2 doubles in the future, air temperatures in Minnesota are projected to rise by 4.3ºC in the warm season, and this would translate into an average 4.1°C stream temperature rise, provided that stream shading would remain unaltered.

75. Pollock, M.M., T.J. Beechie, M. Liermann, and R.E. Bigley. 2009. Stream Temperature Relationships to Forest Harvest in Western Washington. *Journal of the American Water Resource Association*. 45:1:141-156.

Location: western WA. Pollock et al. (2009) compared summer stream temperature patterns in 40 small, forested watersheds in the Hoh and Clearwater basins in the western Olympic Peninsula, Washington. The authors examined correlations between previous riparian and basin-wide harvest and stream temperatures. Seven watersheds were unharvested while the remaining 33 had between 25% and 100% of the total basin harvested, mostly within the last 40 years. Mean daily maximum temperatures were significantly different between the harvested and unharvested basins, averaging 14.5°C and 12.1°C, respectively. Diurnal fluctuations were also significantly different with 1.7°C and 0.9°C respectively. Total basin harvest was correlated with average daily maximum temperature (r2=0.39), as was total riparian harvest (r2=0.32). The probability of a stream exceeding the states surface water quality criteria (16°C as a 7-DADMax) increased with timber harvest activity. All unharvested sites and five of six sites that had 25-50% harvest met the criteria. In contrast, only nine of eighteen sites with 50-75% harvest and two of nine sites with >75% harvest met the criteria. The authors opined that the impact of past forest harvest activities on stream temperatures cannot be entirely mitigated through the reestablishment of riparian buffers. Study was focused on subbasins (1-10 km^2 in size) underlain by sedimentary rock known to have perennial flows and at elevations between 75-400 m.

76. Qui, Z. 2003. A vsa-based strategy for placing conservation buffers in agricultural watersheds. *Environmental Management*. 32: 299-311.*

Location: N/A. Abstract: Conservation buffers have the potential to reduce agricultural nonpoint source pollution and improve terrestrial wildlife habitat, landscape biodiversity, flood control, recreation, and aesthetics. Conservation buffers, streamside areas and riparian wetlands are being used or have been proposed to control agricultural nonpoint source pollution. This paper proposes an innovative strategy for placing conservation buffers based on the variable source area (VSA) hydrology. VSAs are small, variable but predictable portion of a watershed that regularly contributes to runoff generation. The VSA-based strategy involves the following three steps: first, identifying VSAs in landscapes based on natural characteristics such as hydrology, land use/cover, topography and soils; second, targeting areas within VSAs for conservation buffers; third, refining the size and location of conservation buffers based on other factors such as weather, environmental objectives, available funding and other best management practices. Building conservation buffers in VSAs allows agricultural runoff to more uniformly enter buffers and stay there longer, which increases the buffer's capacity to remove sediments and nutrients. A field-scale example is presented to demonstrate the effectiveness and cost-effectiveness of the within-VSA conservation buffer scenario relative to a typical edge-of-field buffer scenario. The results enhance the understanding of hydrological processes and interactions between agricultural lands and conservation buffers in agricultural landscapes and provide practical guidance for land resource managers and conservationists who use conservation buffers to improve water quality and amenity values of agricultural landscape.

77. Qui, Z. and Prato, T. 1998. Economic evaluation of riparian buffers in an agricultural watershed. *J. Amer. Water Resourc. Assoc*. 34:877-890.

Location: Missouri. The study presents a method for estimating the economic value of implementing riparian buffers in order to reduce nonpoint source pollution to stream using the SWAT model and an indirect valuation method. According to the authors, when selecting effective farming systems for reducing nonpoint source pollution in a stream, the farm scale is not the appropriate scale; the watershed or landscape scale is appropriate. The method included the valuation of crop production with and without buffers, the land opportunity cost, and government costs for CRP. 32.2-meter buffers were assumed. Multiple farming systems were evaluated and adjusted in scenarios with and without riparian buffers in order to achieve the target pollutant concentration for Atrazine at the watershed outlet (since Atrazine was the limiting factor for farming systems that achieved the target concentrations over sediment and nutrients). In other words, the method evaluates how much land would have to be put into CRP to reduce a pollutant to a given level and what would be the net cost vs. the net cost of achieving the pollutant reductions through riparian buffers. The baseline (no change) in Atrazine reductions without buffers requires 58% of the land to be put into CRP, while reducing Atrazine by 46% through riparian buffers requires no land to be in CRP. However, because the existing concentration of Atrazine is so high, increasingly lower targets resulted in increased acres of land needed to be in CRP both with and without buffers, and therefore more stringent targets steadily decrease the net economic value and government cost savings of buffers. Achieving a 93% reduction in order to meet the drinking water standard begins to approach a zero net economic value for buffers in this scenario. Without buffers, 97% of the watershed would need to be in CRP to meet the Atrazine DW standard and with buffers, 83% would need to be in CRP. (*Note: unfortunately, this study highlights that application of atrazine at agronomic rates results in severely polluted water that would require almost all land to be taken out of production in order to protect water quality.)*

78. Rahel, F.J., Keleher, C.J., and Anderson, J.L. 1996. Potential habitat loss and population fragmentation for cold water fish in the North Platte River drainage of the Rocky Mountains: response to climate warming. *Limnol. Oceanogr*. 42 (5).

Abstract: "We used three approaches to examine potential habitat loss in relation to climate warming for cold water species of fish in the North Platte River drainage in Wyoming. The projected loss of habitat varied among approaches, but all methods indicated a noticeable loss of habitat for even minor increases in temperature. An approach based on the use of summer air temperatures to define the thermal limits of cold water species estimated a loss of 9-76% of the present geographic range for temperature increases of l-5°C. A second approach, also based on air temperature limits, projected a loss of 7-64% of the stream distance currently having thermally suitable habitat for cold water fish for temperature increases of I-5°C. A third approach, based on the use of summer water temperatures to define the thermal limits of cold water species, projected a loss of 16-69% of the stream distance currently having thermally suitable habitat for temperature increases of l-5°C. In addition to habitat loss, population fragmentation would occur as remaining enclaves of cold-water fish are forced to retreat to increasingly isolated headwater stream reaches."

79. Rex, J.F., Maloney, D.A., Krauskopf, P.N., Beaudry, P.G., and Beaudry, L.J. 2012. Variable-retention riparian harvesting effects on riparian air and water temperature of sub-boreal headwater streams in British Columbia. *Forest Ecology and Management*. 269 (2012) 259-270.

    Location: central British Columbia. Rex et al. (2012) used a (BACI) study design to examine the effect of applying variable retention harvests on at four sites within three watersheds of the British Columbia central interior (53-54° Latitude). The policy retention level resulted in 16, 20 and 14 stems per 100 m of merchantable trees being retained (reducing to 6, 16, and 10 after blowing down) along five small fish-bearing streams (0.9-1.48 m wide). Harvesting resulted in a significant decrease in shade (ACD) as well as an increase in air and stream temperature at all treatment sites. Shade was reduced by 30-50% from pre-harvest levels and mean weekly average and mean weekly maximum stream temperatures increased by as much as 5 and 6°C, respectively. Despite substantial recovery of ACD-shade measured at the water surface within 2 years (due to growth of streamside deciduous vegetation), mean and maximum water temperatures remained significantly higher at treatment sites than control sites. Rather than decreasing with increased shade levels, water temperature in the study streams continued to experience heating by 1–2°C in the treatment reach (length 320-670 m). The authors determined that shade from over-story may be more effective at maintaining riparian air and stream temperatures than understory vegetation because it can limit energy transfer to the stream. The increase in air temperature at the 0.5 m elevation identified a change in the microclimate above treatment streams. The authors concluded this suggested greater energy exchange was occurring by long wave, conductive, and advective heat transfer mechanisms as facilitated by higher cut block wind speeds. The discrepancy between shade recovery and temperature response indicates that vegetative surface height receiving radiation must be considered along with shade (recovery of shade was primarily from the growth of a deciduous understory). Water Temperatures: MWMT in treatment streams increased generally less than 3°C in one stream, up to 4°C and one, and up to 6°C in the third. (*Note: Maintained 5 m machine free zone. Actual buffer widths left were not described. Table 3 gives pre and post shade by year and it isn't clear how they reach the conclusion that shade was recovering towards pre-harvest levels when it was quite variable and incomplete*.)

80. Richardson, J.S. and Béraud, S. 2014. Effects of riparian forest harvest on streams: a meta-analysis. *Journal of Applied Ecology*. 51, (1712-1721).

    Summary from article:

    > "1. Riparian forest harvesting impacts streams in many ways, from altering temperature regimes, shifting geomorphic structure, increasing sediment fluxes and affecting fish populations. However, we have noted considerable variation in the results between studies that led us to ask whether the effects of forest harvesting on streams were consistent between studies. We used meta-analysis of 34 replicated studies to address

the effects of riparian logging on biological and chemical components of streams in contrast to control sites.

2. We found that the overall effect sizes of several response variables in replicated studies were significantly higher than zero, especially benthic invertebrates, and nitrogen and potassium concentrations. However, there was a very large amount of variation in the effect sizes between studies, and for many measures, the effect sizes from different studies were positive or negative, indicating site-specific responses.

3. We explored whether stream size, stream gradient and regional potential evapotranspiration could explain some of the effect size variation between studies. Relations with these environmental variables were weak, but suggestive that some of the context-specific, individual outcomes might be due to underlying environmental differences between sites.

4. Synthesis and applications. Despite relatively low numbers of replicated studies, we found significant overall effects of riparian forest harvesting although the magnitude and direction of responses within individual studies were site specific. This lack of consistency in the direction of effect sizes suggests we need a more context-dependent approach to the protection of freshwaters from forest management."

81. Ryan, D.K., Yearsley, J.M., and Kelly-Quinn, M. 2013. Quantifying the effect of semi-natural riparian cover on stream temperatures: implications for salmonid habitat management. *Fisheries Management and Ecology*, 20:494-507.

Relevance/value: 0 out of 3 due to location and lack of rigor.

Location: Ireland. Ryan et al. (2013) used upstream-downstream monitoring to examine the relationship between stream temperature variability and local climatic conditions for 17 sites over discrete 300-m sections of a watercourse. Seventeen stream sections were chosen within the Slaney catchment in Ireland on the basis of cover and size. Continuous monitoring over a 2-year period found that riparian cover had a measurable cooling effect on water temperatures at small spatial scales. The magnitude of the effect was dependent on-stream size and local climatic conditions. The analysis focused on months from June to August. The 300 m long stream sections were grouped by size (large or small) and riparian cover (shaded or unshaded) giving a total of nine shaded sections (flour large and five small) and eight unshaded sections (four large, four small). Large stream sections had a mean wetted width of ≥8 m (range 8-11 m) and a mean pool depth of ≥0.6 m. Small stream sections had a mean wetted width ≤4 m (range 3-4 m) and a mean pool depth ≤0.4 m. Temperature collected every 30 minutes. All study sites were adjacent to improved agricultural grassland. Riparian corridor widths rarely exceeded 1-2 trees deep and were made up predominantly of alder and willow with typical tree heights varying from 8-15 m. Temperature differential across all 300-m stream sections varied significantly with year, sunshine, flow, and upstream water temperatures. Increasing sunshine generally increased the temperature differential, but this effect was weakened by increasing flow and increasing upstream temperature. Decreasing flow also increased temperature differentials in small stream sections but not in large stream sections. No effect of air temperature could be detected once the effects of upstream temperature, sunshine, flow and year had been accounted for. After taking account of all confounding variables, a significant effect of riparian cover remained. The effect of sunshine in increasing temperature differential was weaker, but still significant for shaded stream sections. Based on text and discussion summary the authors found that short strips (300 m) of semi-natural riparian buffer can cool small (wetted ≤4 m, range 3-4 m) nursery streams by up to 1C, and cool large streams (wetted ≥8 m, range 8-11 m) by approximately 0.5C. (*Notes: Did not address groundwater inputs which may be the cause of the observed cooling, rather than shade. They did not measure shade, nor do they give statistically based results describing the difference in cooling for buffered versus unbuffered large and small streams (so I used Figure 2 and some of the text statements summarizing the results). When authors describe small spatial scales, this is meant as a comparison to catchment wide studies. Noted confounding by macrophytes in some unshaded streams.*)

82. Rykken, J., Chan, S., and Moldenke, A. 2007. Headwater Riparian Microclimate Patterns under Alternative Forest Management Treatments. *Forest Science* 53:2:270-280.

    Location: western Oregon. Rykken et al. (2007) measured the magnitude and extent of microclimatic gradients associated with headwater streams in mature unmanaged forests and determined whether these patterns were maintained in clearcut harvested units with and without a 30-m (98.4 ft.) wide riparian buffer on each side of the stream. Streams had a strong effect on afternoon air temperature and relative humidity to a distance of 10m from the channel. The results indicated that the riparian microclimate gradient was protected by a 30m buffer.

83. Salemi, L.F., Groppo, J.D., Trevisan, R., Marcos de Moraes, J., de Paula Lima, W., and Martinelli, L.A., 2012. Riparian vegetation and water yield: a synthesis. *Journal of Hydrology*. 454-455.

    Abstract: "Forested riparian zones perform numerous ecosystem functions, including the following: storing and fixing carbon; serving as wildlife habitats and ecological corridors; stabilizing streambanks; providing shade, organic matter, and food for streams and their biota; retaining sediments and filtering chemicals applied on cultivated/agricultural sites on upslope regions of the catchments. In this paper, we report a synthesis of a different feature of this type of vegetation, which is its effect on water yield. By synthesizing results from studies that used (i) the nested catchment and (ii) the paired catchment approaches, we show that riparian forests decrease water yield on a daily to annual basis. In terms of the treated area increases on average were 1.32 ± 0.85 mm day^{-1} and 483 ± 309 mm yr^{-1}, respectively; n = 9. Similarly, riparian forest plantation or regeneration promoted reduced water yield (on average 1.25 ± 0.34 mm day^{-1} and 456 ± 125 mm yr^{-1} on daily and annual basis, respectively, when prorated to the catchment area subjected to treatment; n = 5). Although there are substantially fewer paired catchment studies assessing the effect of this vegetation type compared to classical paired catchment studies that manipulate the entire vegetation of small catchments, our results indicate the same trend. Despite the occurrence of many current restoration programs, measurements of the effect on water yield under natural forest restoration conditions are still lacking. We hope that presenting these gaps

will encourage the scientific community to enhance the number of observations in these situations as well as produce more data from tropical regions."

84. Schlosser, I.J. and Karr, J.R. 1981. Riparian vegetation and channel morphology impact on spatial patterns of water quality in agricultural watersheds. *Environ. Management* 5:233-243.

Location: Illinois. The authors used modeling based on the Universal Soil Loss Equation to predict levels of suspended solids, turbidity, and phosphorus in two agricultural watersheds with varying levels of riparian protection. The USLE based model does not adequately predict the influence of agricultural practices and upland erosion on suspended sediment and turbidity in streams with unstable bed and banks lacking riparian vegetation because runoff vs. sediment relationships are muddied by resuspension of deposited sediment and bank erosion. The authors suggest that BMP planning in agricultural watersheds needs to focus on identifying critical erosive and depositional areas in the aquatic and terrestrial ecosystems.

85. **Schuett-Hames, D. and Stewart, G. 2019. Changes in Stand Structure, Buffer Tree Mortality and Riparian-Associated Functions 10 Years After Timber Harvest Adjacent to Non-Fish-Bearing Perennial Streams in Western Washington. Draft Report. Cooperative Monitoring, Evaluation, and Research Report. Washington Department of Natural Resources, Olympia, WA.**

From WA DNR CMER report summary: This report presents the 10-year post-harvest results from the Westside Type N Buffer Characteristics, Integrity and Function (BCIF) study conducted by Washington's Cooperative Monitoring, Evaluation and Research Committee (CMER). The study documents the magnitude of change in stand structure, tree mortality, wood recruitment, shade, wood cover and soil disturbance when the riparian prescriptions for Westside Type Np (perennial non-fish-bearing) streams were applied in an operational setting.

Treatment sites were randomly selected from approved forest practice applications. Three components (treatments) of the Westside Type Np Riparian Prescriptions were evaluated: non-buffered clear-cut harvest to the channel edge (CC treatment), 50-foot-wide no-cut buffers (BUF treatment), and 56-foot radius no-cut buffers around the perennial initiation points (PIP treatment). Unharvested second-growth reference (REF) reaches were located in proximity of the treatment sites. Statistical tests were done to compare the CC, BUF and REF results.

Change in Stand Structure. During the first five years after harvest, density and basal area decreased in BUF, PIP and REF stands because tree mortality exceeded ingrowth of young trees. Mean mortality and associated change in stand structure were greatest in PIP stands, less in BUF stands and least in REF stands. Cumulative mortality as a percentage of live basal area was 48.1% in PIP stands, 27.2% in BUF stands and 9.4% in REF stands. Between years five and ten, stand structure stabilized in PIP and BUF stands due to a marked reduction in mortality rates. Over the entire 10-year post-harvest period, cumulative change in live basal area (trees >4" DBH) was positive in REF stands (+2.7%) and negative in BUF (-14.1%) and

PIP (-38.9%) stands, however the BUF-REF contrast was not statistically significant. Wind was the dominant mortality agent in PIP and BUF stands. Mortality in REF stands were dominated by other factors (e.g., suppression); however, there was an increase in wind mortality in REF stands during year 4–5 due to a storm with hurricane-force winds. Substantial conifer regeneration (seedling and saplings) was observed in BUF and PIP stands, including buffers with high mortality (see Figure 9). Almost no trees remained in the CC reaches after harvest, but regeneration with planted trees appeared to be successful.

Tree fall and Wood Input to Streams. Tree fall and wood recruitment was driven by mortality; consequently rates were highest during the first five years post-harvest. Cumulative recruited wood pieces/100 feet in the PIP reaches (includes Ns portion of stream above PIP) (11.2 pieces) was nearly double that in the REF (6.2 pieces) and BUF (7.0 pieces) reaches over the entire IPH-YR10 period. Cumulative recruited wood volume in the (BUF) and (PIP) reaches was double and four times the REF volume, respectively. Most recruiting fallen trees came to rest above the channel where they provided cover but did not interact with flowing water. Consequently, few newly recruited pieces provided sediment storage or formed pools, steps or debris jams. Wood recruitment was minimal in CC reaches during the IPH-YR10 period due to lack of trees, following slash input (primarily branches and tops) during harvest.

Shade/Cover. One year after harvest, canopy closure, an indicator of shade from trees and tall shrubs, was lower in the BUF (76%) and PIP (52%) reaches compared to the REF reaches (89%). By year 10, canopy closure in the BUF and PIP reaches increased to over 85%, similar to the REF reaches, apparently due to growth of shrubs and saplings adjacent to the stream. Mean canopy closure in the CC reaches was only 12% one year after harvest of trees but increased to 37% by year 5 and 72% by year 10 in response to growth of shrubs and saplings. Buffers in the BUF and PIP reaches prevented slash input from the adjacent harvest unit. Consequently, wood cover was higher in CC reaches due to logging debris input but decreased over the post-harvest period.

Soil Disturbance. On average, harvest-related soil disturbance occurred on 6.2% of the area within the 30-foot-wide equipment limitation zones (ELZ) in the CC reaches. All BUF and PIP reaches met the performance target (<10% of the ELZ area with soil disturbance) but one of eight CC reaches exceeded the target. The average distance to the stream for erosion features that delivered sediment was 1.0 foot and the maximum was 7.7 feet. Soil disturbance from uprooted trees was twice as frequent in BUF reaches as REF reaches, but the percentage of root-pits with evidence of sediment delivery was greater in the REF reaches (26%) than the BUF reaches (19.8%). Mean horizontal distance to the stream for root-pits that delivered sediment was 8.2 feet compared to 28.0 feet for those that did not deliver.

Effectiveness in Meeting Forest Practices Habitat Conservation Plan Resource Objectives
The unbuffered CC treatment was least effective in meeting the Forest Practices Habitat Conservation Plan (FPHCP) resource objectives. Clear-cut harvest to the edge of the stream resulted in greater initial disturbance during harvest compared to reaches where buffers were provided. There was substantial input of logging slash in clear-cut reaches, but almost

no additional post-harvest wood input occurred and cover from woody debris decreased during the first ten years after harvest. Clear-cut harvest resulted in the initial loss of canopy shade, but shade from growth of streamside herbs, shrubs and saplings increased over time. We predict that clear-cut harvest on a typical rotation schedule of 40–50 years will result in a continuous cycle of disturbance and rapid changes in stand structure and shade and long-term reductions in large wood loading due to lack of input from large trees.

The RMZ and PIP buffers (the BUF and PIP treatments) were more effective in providing shade and wood recruitment after harvest than the unbuffered CC treatment. Although there was an incremental loss of shade and wood recruitment potential associate with harvest of the adjacent stand beyond the buffer, 50-foot RMZ buffers provided the majority of the shade and wood recruitment potential found in unharvested second-growth reference sites. More shade and wood recruitment potential would be provided by wider buffers or by variable width buffers that leave additional trees in areas where benefits to shade and potential wood recruitment would be greatest.

Mortality from wind is a complicating factor in evaluating the effectiveness of the RMZ and PIP buffers. Mortality was variable, but extensive mortality occurred at some sites. About one-quarter of the RMZ buffers and two-thirds of the PIP buffers had substantial mortality (>5%/year), resulting in reduction of density, canopy shade and wood recruitment potential, but tree fall from wind supports the resource objectives by providing a pulse of large wood. Most fallen trees came to rest suspended or spanning above the channel where they provide cover but will not immediately influence channel conditions and processes. The majority of fallen trees were uprooted, but sediment input from soil disturbance was limited to trees in close proximity to the channel. Conifer regeneration was observed in sites with elevated mortality, so development of multi-age conifer stands is likely in disturbed sites over time.

86. Schuett-Hames, D., Roorbach, A., and Conrad, R. 2012. Results of the Westside Type N buffer characteristics, integrity and function study final report. *Cooperative Monitoring, Evaluation, and Research Report, CMER 12-1201*. Washington Department of Natural Resources, Olympia, WA.

    Location: western WA. Schuett-Hames et al. (2012) examined the operational application of the State of Washington forestry prescriptions to non-fish-bearing streams in western Washington. Eight sites were clear-cut to the edge of the stream, and thirteen had 50-foot-wide no-cut buffers on both sides of the stream. Comparisons with local reference sites found that one year after harvest, mean overhead shade was lower in the 50-foot buffer streams (76%) than in the reference patches (89%). Mean overhead shade in the clear-cut streams was 12% one year after harvest but increased to 37% five years after harvest in response to growth of shrubs and saplings. The mean density of live trees in the 50-foot buffers experienced 3.5 times the mortality of that of the reference patches in the first three years. Wind was the dominant mortality agent in the 50-foot buffers, while suppression mortality exceeded wind mortality in the reference reaches. The cumulative percentage of live trees that died over the entire five-year period was 27.3% in the 50-foot buffers compared to 13.6% in the reference reaches. Large woody debris recruitment

generally followed the pattern of tree mortality with mean volume recruited into and over the bankfull channel 3 times greater in the 50-foot buffers then the reference patches.

87. Schultz, R., Colletti, J., Mize, C., Skadberg, A., Christian, M., Simpkins, W., Thompson, M. and Menzel, B. 1991. Sustainable tree-shrub- grass buffer strips along midwestern-waterways. Pp. 312-326, In: *Proc. 2nd Conference on Agroforestry in North America*, H.E.G. Garrett (Ed.). Columbia, MO.: Univ. Missouri.

Location: Iowa. The authors describe why a constructed multi-species riparian buffer strips are beneficial for water quality and advocate for a 20m width. This reference appears to be a mid-project report as it contains little useful data/information on the actual functioning of the buffers. It does note, however, that where tile drains are present, buffers are not going to reduce pollutants from such discharges.

88. Simmons, J.A., Anderson, M., Dress, W., Hanna, C., Hornbach, D.J., Janmaat, A., Kuserk, F., March, J.G., Murray, T., Zwieniecki, J., Panvini, D., Pohlad, B., Thomas, C., and Vasseur, L. 2015. A comparison of the temperature regime of short stream segments under forested and non-forested riparian zones at eleven sites across North America. *River Res. Applic*. 31: 964-974.

Location: North America. The study compared summer temperature in paired stream sites at eleven locations in North America. In general, forested reaches had lower daily mean and daily maximum temperatures as well as lower rates of warming. *This study is not very useful due to a lack of control over variables influencing thermal flux.*

89. Smith, J.H.G. 1964. Rootspread can be estimated from crown width of Douglas fir, Lodgepole pine, and other British Columbia tree species. Research Paper No. 65. *The Forestry Chronicle*. University of British Columbia.

Root length for Douglas fir roughly extended to the width of the crown. Root length for Lodgepole pine on peat or poor soils roughly extended 2.4 times wider than the crown width. For Western hemlock the ratio of root spread to crown width was roughly 0.8. For Western red cedar the ratio was about 0.65. For Red alder the ratio was about 0.6. Poorly drained sand and sandy gravel soils have a low site productivity, with Doug fir growing to a height of 100ft at 100yrs. Hemlock had the widest root spread on well-drained soils. Cedar had the widest root spread on poorly drained soils. Only about 20% of the total root spread area was occupied by roots. The author suggests using a root spread to crown width ratio of 1.0 for planning purposes but keeping in mind that species such as spruce and lodgepole have relatively wide spreading roots on poorly drained soils.

90. Steeves, M. D. 2004. Pre- and post-harvest groundwater temperatures, and levels, in upland forest catchments in northern New Brunswick, *MSc Thesis*, University of New Brunswick, Fredericton, NB, Canada, 222 pp.

Location: New Brunswick, Canada. The author studied groundwater temperatures before and after forest harvesting in 10 small catchments and found that they increased following harvesting. Daily average temperatures increased by as much as 2.5°C and the annual thermograph was shifted by up to 3 months earlier.

91. Steinblums, I.J., Froehlich, H.A., and Lyons, J.K. 1984. Designing stable buffer strips for stream protection. *Journal of Forestry*. Pp.49-52.

Location: western Cascades, Oregon. Steinblums et al. (1984) measured angular canopy density associated with 1–15-year-old buffer strips of varying widths left along streams in the Cascade Mountains of western Oregon that did not display indications of prior significant blowdown. In the 12 strips bounded on the south by uncut forest, ACD ranged from 26 to 83 percent. ACD of the 28 shade-providing strips ranged from 15 to 87 percent. When regressed against width a significant relationship was found: ACD = 100-109.3(e-0.01382*width) with r2=0.51. Notes: Using the shade prediction equations developed by Steinblums et al. (1984) at 40 sites in the Western Oregon Cascades, buffers of 33 ft. (10 m) provide 17% less Angular Canopy Density (ACD) than 50 ft. (15.2 m) buffers, and 65% less than a 98 ft. buffer (30 m). The actual data was not provided, so suggest using original thesis from Steinblums which appears to be these same sites.)

92. Sweeney, B.W., Bott, T.L., Jackson, J.K., Kaplan, L.A., Newbold, J.D., Standley, L.J., Hession, W. C., and Horowitz, R.J. 2004. Riparian deforestation, stream narrowing, and loss of stream ecosystem services. *PNAS*. Vol. 101. No. 39. 14132-14137.

Location: SE Pennsylvania, northern Maryland. The authors studied chemical, physical, and biological attributes of 16 streams (1st to 5th order), with paired reaches of forested and deforested riparian zones. Riparian deforestation lead to narrowing of stream channels (*likely in unconfined valleys*). Wider channels have greater in-stream processing of pollutants due to greater contact of the water column with substrates. The authors cite Hession et al (2003) as finding that forested stream reaches have channel migration rates that are 20 to 33% less than deforested channels. There was a greater abundance of benthic macroinvertebrates per unit channel in the forested reaches.

93. Taniguchi, M., Williamson, D. R., and Peck, A. J. 1998: Estimations of surface temperature and subsurface heat flux following forest removal in the south-west of Western Australia, *Hydrol. Process*., 12, 2205–2216*.

Location: western Australia. Abstract: "Ground surface temperature and subsurface heat flux following forest removal for agricultural development have been estimated using temperature–depth profiles measured in the Collie River Basin, Western Australia. Temperature measurements have been done in water filled piezometer tubes to depths of 30–50 m, 19 years after forest removal and the establishment of annual pasture and cereal crops in areas of about 100 ha. Two parameters, change in average surface temperature and thermal diffusivity of the strata, were estimated by optimization to minimize the deviation of predicted from observed temperature–depth profiles. The increases in average annual temperatures for the ground surface 19 years after tree removal were estimated to be 3.4, 3.8 and 4.1 °C in Wights, Dons and Lemon catchments with average rainfall of 1120, 800 and 820 mm yr^{-1}, respectively. The estimated increase in ground surface temperature in a 1 ha area where forest was partially removed in Wights catchment was 2·2 °C, and in 15 ha of agriculturally developed area cleared to parkland (trees at 20 m spacing) in Dons catchment the increase was 1·6 °C. Subsurface heat fluxes between the ground surface and

1 m depth are predicted to become positive (upward) again 208 years after forest removal in Wights catchment and 46 years after parkland forest removal in Dons catchment."

94. Teply, M., McGreer, D., and Ceder, K. 2014. Using simulation models to develop riparian buffer strip prescriptions. *Journal of Forestry*. 112(3):302-311

    Location: Idaho. Teply et al. (2014) developed a model to simulate prescriptions for use as prescriptions in the state of Idaho. They found that thinning throughout the buffer (i.e. up to the stream bank) and very narrow buffers (e.g. 50 ft or less) led to unacceptable decreased in shade (>10%). They also found that the portion of the stand immediately adjacent to the stream was disproportionately important for allowing greater overall management flexibility. Given the state's desire to operate throughout the buffer the authors tested prescriptions to look for an overall best balance and found that thinning lightly in the inner 25 ft buffer zone, with heavier thinning in an outer 50 ft zone would satisfy their multiple objectives. Stating: "An inner no-harvest zone is an important consideration for formulating effective riparian management prescriptions." Notes: Authors only tested to a maximum width of 100 feet and varied prescriptions in 25-foot increments. The authors used relative stocking (Relative Stocking = RDsum/maximum RDsum. Simulations were of uncut stands with relative stocking >55%. The authors note Idaho FPAAC wanted to limit shade loss to 10%, and LWD had to increase. The shade criterion was used as a surrogate for a temperature limit of a 1.8C increase. They determined they could not limit shade loss to 10% except in very light (and silviculturally insufficient) thinnings in these 75-foot RMZs.

95. Teti, P. 2006. Stream shade as a function of channel width and riparian vegetation in the BC Southern interior. *Streamline Watershed Management Bulletin*. Spring 2006. 9:2:10-15

    Location: South-central British Columbia, Canada. Teti (2006) found that clear-cutting the riparian areas of small streams in south central British Columbia, Canada, tended to reduce average shade (based on ACD) from 75% to 47%. Natural shade levels decrease steadily as wetted channel width increases to about 30 m, at which point the seral stage of riparian vegetation may have little effect on average shade on a reach. However, late-seral riparian vegetation tends to ensure consistently high reach average ACD levels on small streams (e.g. bkf width <7m).

96. Tolzman, S.A. 2001. GIS based riparian area management plans: recommendations to local governments of the Columbia River Estuary Study Taskforce. *MSc Thesis*. Oregon State University, Corvallis, OR. 69pp.

    Location: Seaside, Oregon. A GIS project using a water detention model was undertaken to develop riparian buffer recommendations. The paper provides a review of some riparian buffer research in terms of pollutant removal as well as a review of factors influencing riparian buffer effectiveness. Key effectiveness factors include: riparian zone slope, which affects surface and subsurface water velocity; soil attributes, specifically infiltration and saturated hydraulic conductivity; vegetation type, which influences surface roughness and therefore water velocity, and assimilation of nutrients from runoff. Tables are included relating: average soil slope to run-off rate classes; soil hydrologic groups and infiltration

rates; soil permeability classes and flow rates; vegetation type and Manning's Roughness Coefficient. The author recommends a riparian buffer of 75 to 100ft based on the riparian buffer literature review and the study area having flat slopes, infiltration rates that would produce rapid runoff, moderate soil permeability, and surface roughness provided by grass, brush, and trees.

97. Trimble, S.W. 1997. Stream channel erosion and change resulting from riparian forests. *Geology*. Vol. 25, No. 5; pp 467-469.

    Location: Wisconsin. Type: Observational. This study evaluates channel widths and depths for adjacent reaches with grassed vs. forested riparian areas. Grassed riparian areas were associated with narrower channels than forested areas. The article does not do well at reasoning why this may be the case.

98. South Dakota tree species fact sheets. undated

    Cottonwood crown height ranges from 50 to 100 ft, crown width from 40 to 75 ft, and roots are shallow, and spreading a greater distance than the tree height. Rocky Mountain Douglas fir crown height ranges from 40 to 70ft, crown width from 20 to 30ft. Ponderosa pine crown height ranges from 50 to 70ft, crown width from 25 to 30ft.

99. U.S. Forest Service and Bureau of Land Management, 2012. Northwest Forest Plan Temperature TMDL Implementation Strategy. Evaluation of the Northwest Forest Plan aquatic conservation strategy. May 25th, 2012. 35pp.

    This document describes the science behind how the USFS and BLM intend to use riparian buffers to provide shade and meet water temperature criteria in streams flowing through 25 million acres of public lands under their jurisdiction. The document states that: "The document is multipurpose in that it affirms the adequacy of existing direction to protect and maintain stream shade and demonstrates how management within Riparian Reserves can occur while maintaining stream shade through time. The scientific approach outlined in this Strategy is to be used if it has been determined that management of even-aged stands within Riparian Reserves will benefit the attainment of one or more ACS objectives." The document presents nine goals which are used to guide protection of watershed processes and water quality. The 1994 Record of Decision for The Northwest Forest Plan (NWFP) identified that the width of the "Riparian Reserve (which allows mgmt to protect and restore aquatic and riparian ecosystems) on perennial and intermittent streams will be equal to one site-potential tree height. States that this width of riparian buffers should protect key riparian functions including shading, large wood recruitment, litter input, nutrient regulation, and sediment control. The document mentions that the USFS and BLM are required to identify BMPs to protect water quality under the Clean Water Act and states the following about these BMPs. "The Forest Service Regional BMP handbook entitled "General Water Quality Best Management Practices, Pacific Northwest Region, November 1988" provides the core BMPs from which adjustment is made to accommodate site specific conditions. The 1988 handbook is being revised based on a National BMP program."

    The document provides a summary of the physics of stream heating. Document states that the amount of solar radiation directly upon the stream is the primary source of water temperature increases. A figure is provided showing that the heat energy flux from solar radiation is vastly larger than energy flux from convection or conduction. "The effect of riparian vegetation on stream shading decreases with increasing distance from the stream bank, the degree of channel constraint and floodplain development. Effectiveness of streamside vegetation to provide shade varies with geomorphology, topography, orientation, extent of canopy opening above the channel, and forest structure. The most significant shade is derived from near stream riparian vegetation (FEMAT 1993). Just as the width of the riparian area vegetation shading the stream varies, the effective shade diminishes beyond a point where the incremental benefit of a wider riparian buffer is either negligible or immeasurable." A narrow stream may reach site potential shade from trees that have not reached maturity while a wide stream may require trees at their mature height to reach site potential shading. Effective shade is controlled by slope, plant species composition, plant height, plant density, plant distance from stream banks, and stream width. Effective shade is provided by only a portion of the riparian canopy. Effective shade decreases as stream channels become wider and the site potential vegetation is not tall enough for shadows to span the channel. When the sun is near solar noon, trees nearest the channel provide shade and when the sun is lower in the sky, trees farther form the channel provide shade. As slope steepness increases, the width of riparian trees providing stream shade increases. Angular canopy density (ACD) changes as the location of the sun in the sky changes. ACD never reaches 100%. Two main factors influencing ACD are tree density and solar angles.

A diagram is presented relating the tree height to riparian width on 70% slope. The document states that a 150ft tall tree that is 145ft from a stream on a 70% slope can provide 1% effective shading to the stream; in this example, the tip of the tree provides a shadow that touches the stream at some point during the day. The document indicates that a buffer width equal to one site-potential tree height "overestimates the width of trees in the riparian area that could potentially provide meaningful shade to the stream." **"Based on FEMAT science and Spence 1996, as concluded in Part 2, one site potential tree height is more than adequate to provide for the ecological and hydrologic processes in riparian areas."**

In regard to "shade zones": "The period of greatest solar loading typically occurs between 1000 and 1400 hours (Figure 12) that includes the period during which approximately 60% of the total daily solar radiation is cast. Vegetation that intercepts solar radiation between 1000 and 1400 hours is critical for providing stream shade and maintaining stream temperature. This vegetation constitutes the primary shade zone. The primary shade zone provides stream shade throughout the entire day and is the only vegetation that provides shade between 1000 and 1400 hours. During the morning and afternoon hours (e.g., 0600 to 1000 hours and 1400 to 1800 hours, respectively), in stands with lower tree density, trees outside of the primary shade zone can also provide stream shade by increasing ACD. This area is referred to as the secondary shade zone. An important concept to remember is that trees in the primary shade zone provide shade throughout the entire day. If the tree density is high in the primary shade zone, then trees in the secondary shade zone become "trees behind trees" and add little to no additional stream shade." The width of the primary shade zone can be estimated using three equations provided in the text based on tree height, slope, and solar angles between 1000 and 1400 hours.

“A study was conducted on the Rogue River Siskiyou National Forest in 2006 in cooperation with BLM, DEQ and EPA, measuring changes in ACD as a result of thinning. The study established varying widths of no treatment buffers and measured ACD before and after thinning. The intent of the study was to add to the 1972 Brazier and Brown ACD data set and to apply Table 4 of the Strategy, to verify that ACD remains unchanged after thinning by applying the specified “no treatment” width. Digital photography was used to generate light histograms to measure ACD. The study site was clearcut in the early 1960s and was replanted with Douglas-fir. At the time of the study, the second-growth trees were 40 years old, 95 feet tall and on a slope less than 30 percent and in need of thinning. Given these characteristics and referring to Table 4, the primary shade zone and no cut buffer is 50 feet. Figure 13 compares the changes in ACD before and after thinning with no-treatment buffer widths of 20, 40, 60 and 80 feet. Figure 13 shows **there was no change in ACD before and after the thinning treatment with a minimum no treatment buffer of 50 feet.**”

The document provides a rationale that no cumulative increase in stream temperature can be expected when no tree harvesting occurs within the primary shade zone and only thinning occurs in the secondary shade zone.

Regarding microclimate: Microclimate is the gradient of influence of the stream upon the air temperature, humidity, etc. upon the adjacent uplands. The riparian area in turn influences the air temperature, humidity, wind speed, precipitation interception, soil temperature, etc. near the stream. Evaporation and convection release heat energy from streams and are influenced by riparian microclimate. The amount of heat transferred between air and a stream through convection is relatively low. Microclimate gradients tend to be strongest within roughly 50ft of a stream. Headwater streams tend to have less diurnal variability in temperatures than streams downstream and have a cooler microclimate because they tend to be at higher elevations. There is evidence that for buffers in old-growth douglas fir stands, air temperatures for thinned stands with variable width buffers were similar to intact old growth stands within 30m of the stream. The same has been found for buffers with a width equal to one-site potential tree height- within 30m of the stream temperatures were similar to intact stands. For the latter, temperatures increased with distance from the stream if the buffer was adjacent to patch cuts but did not increase if adjacent to thinned stands.

“For the purposes of employing the Strategy for forest treatments in Riparian Reserves, research indicates that the following microclimate elements are of relevance: 1) microclimate gradients over streams are the strongest and diminish rapidly moving upslope; especially when a 15m retention buffer is applied, 2) near-stream microclimate appears to be topographically controlled, and therefore considerations should be made for buffer widths utilizing slope breaks, 3) thinning beyond 15m is does not measurably affect microclimate, 4) stream thin-through treatments may have slight microclimate effects, 5) small patch openings greater than 15m from streams affects microclimate moderately, 6)

where regeneration harvest is planned at the boundary of Riparian Reserves; edge effects may extend up to 15m into the buffer with subtle effects on microclimate gradients."

100. Vadas, R.L. Jr. 2000. Instream-flow needs for anadromous salmonids and lamprey on the Pacific coast, with special reference to the Pacific Southwest. Environmental Monitoring and Assessment 64: 331-358

Unshaded streams may show reduced base flows b/c of higher evaporation.

101. Vuori, K-M. and Joensuu, I. 1996. Impact of forest drainage on the macroinvertebrates of a small boreal headwater stream: do buffer zones protect lotic biodiversity? *Biological Conservation*. 77. 87-95.

Location: western Finland. The authors studied the effects of logging and forest drainage ditches upon benthic macroinvertebrate communities. Drainage ditches resulted in elevated turbidity, suspended solids, aluminum, iron, and chemical oxygen demand, and a decrease in pH. Substrates that were originally stones with moss cover became dominated by an unstable sand substrate. The reduction in moss habitat resulted in severe degradation of the macroinvertebrate community and dominance by pollution tolerant organisms. The stream and ditches had buffer zones ranging from 10 to 30m.

102. Williams, R.D. and Nicks, A.D. 1988. Using CREAMS to simulate filter strip effectiveness in erosion control. *J. Soil & Water Conserv*. 43:108-112.*

Location: Oklahoma. Abstract: "The CREAMS (Chemical, Runoff, and Erosion from Agricultural Management Systems) field-scale model is used to evaluate the effectiveness of grass filter strips for erosion control. Simulations are presented for filter strips of several widths (3–15 m), slopes (2.4–10%), and grass stand qualities (Manning's n, 0.023–0.46) on a 1.6 ha wheatland watershed in the Reddish Prairie land resource area. Filter strip effectiveness is dependent upon strip width, Manning's n, slope and slope configuration, and storm intensity. For 2.4% slopes with a concave-convex, concave, or uniform configuration, a filter strip 15 m (50 feet) wide with a good grass stand (Manning's n of 0.46) reduced soil loss 29%, 26%, and 33 %, respectively. A 2.4% convex slope presented the worst general condition for filter strip use, although a 15-m wide filter strip with a good grass stand could reduce soil loss as much as 46%. Results indicate that CREAMS can be a useful tool for evaluating filter strip effectiveness in reducing sediment yield."

103. Xiang, W.-N. 1993. Application of a GIS-based stream buffer generation model to environmental policy evaluation. *Environ. Manage.* 17(6):817- 827

Location: eastern North Carolina. The author presents a GIS-based method for riparian buffer delineation. The author notes three basic strategies for setting buffer widths. The first is a fixed width minimum buffer. The second is a minimum buffer width that can be extended based on slope, soil, and land cover. The third delineates variable buffers based on site specific physical conditions. States that a fixed minimum buffer width cannot take into account geographic differences in physical, ecological, and social-economic conditions and cites Phillips (1989) as stating that the majority of the time minimum buffer widths are

"based on educated guesses at best, and arbitrarily or politically at worst." The author states that the third strategy is infeasible due to the intensive data requirements, unless a GIS is used. The buffer model is derived from a detention time model from Phillips (1989). The buffer delineation equation is based on comparison to a reference buffer, where the ratio of a buffer's effectiveness to the reference buffer effectiveness (a ratio below 1 indicates the buffer is less effective than the reference) is set equal to the ratio between the buffer's water detention and the reference buffer's detention time. This latter ratio is set equal to the product of buffer to reference buffer ratios for Manning's roughness coefficient, buffer width, soil saturated hydraulic conductivity, slope, soil moisture capacity. This equation can be rearranged to solve for buffer width. In deriving the parameters for the reference buffer, the author states that a 36.27m grass buffer under typical soil conditions would effectively filter agricultural runoff, urban runoff, or septic overflow in the study area. The estimated effectiveness for surface flow into the reference buffer was 65% for biochemical oxygen demand, 33% for nitrogen, and 40% for total phosphorus; subsurface flow efficiencies were estimated to be 97%, 89%, and 95% for the three parameters. The GIS buffer delineation method was hindered by uncertainty in soil parameters (i.e., soil surveys report ranges for parameter values). This lead to the calculation of prescribed buffer ranges for individual parcels. The minimum and maximum buffer width in local regulations based on the model were 15.24 and 36.58m. An additional step was used to evaluate whether buffers in Cabarrus County, NC were adequate or excessive based on best, median, or worst soil properties. This process estimated that the 15.24m regulation was inadequate for 87.1% of the parcels; this width was adequate for less than 10% of the parcels. The 36.58m buffer was determined to be excessive for 35.3 to 41.9% of the parcels, but inadequate for 40.7 to 50.6% of the parcels; this buffer width was adequate for less than 18% of parcels. The author states that the GIS method was unable to determine optimal buffer widths due to data uncertainties.

104. Young, K. A., Hinch, S.G. and Northcote, T. G. 1999. Status of Resident Coastal Cutthroat Trout and their Habitat Twenty-Five years after Riparian Logging. *North American Journal of Fisheries Management*. 19:4, 901-911.

Location: western British Columbia, Canada. Abstract: "In 1973 two sections of a small headwater stream containing allopatric non-anadromous coastal cutthroat trout Oncorhynchus clarki were subjected to two types of streamside logging: (1) clear-cut to the streambank with all existing wood and logging debris left in the channel and on adjacent hill slopes (section B; 4.2% gradient), and (2) clear-cut to the streambank with all logging debris and existing instream wood removed from the channel and adjacent hill slopes (section A; 0.8% gradient; termed scarified). A third upstream reference section was undisturbed (section C; 4.8% gradient)."

Notes: The authors noted the much greater warming associated with the scarification treatment which caused summer maximum temperatures post-harvest to reach 30C and increase 15C or more as water moved through the treatment block. The authors found the cutthroat density was substantially reduced in the scarification block with re-establishment related to the amount of large wood-associated pool habitat. Note that the scarification treatment reach was much lower gradient than the reference and non-scarification treatment.

105. Zaller, J. G., Heigl, F., Ruess, L. & Grabmaier, A. (2014) Glyphosate herbicide affects belowground interactions between earthworms and symbiotic mycorrhizal fungi in a model ecosystem. Scientific Reports, 4, 5634. DOI: 5610.1038/srep05634*

Abstract: "Herbicides containing glyphosate are widely used in agriculture and private gardens, however, surprisingly little is known on potential side effects on non-target soil organisms. In a greenhouse experiment with white clover we investigated, to what extent a globally used glyphosate herbicide affects interactions between essential soil organisms such as earthworms and arbuscular mycorrhizal fungi (AMF). We found that herbicides significantly decreased root mycorrhization, soil AMF spore biomass, vesicles and propagules. Herbicide application and earthworms increased soil hyphal biomass and tended to reduce soil water infiltration after a simulated heavy rainfall. Herbicide application in interaction with AMF led to slightly heavier but less active earthworms. Leaching of glyphosate after a simulated rainfall was substantial and altered by earthworms and AMF. These sizeable changes provide impetus for more general attention to side-effects of glyphosate-based herbicides on key soil organisms and their associated ecosystem services."

Section 3: Secondary Sources (literature reviews) Relevant to Riparian Management Zones

1. Allan, J.D. and Castillo, M.M. (2007) *Stream Ecology: Structure and Function of Running Waters*. 2nd Edition, Chapman and Hall, New York.

   This is a book addressing multiple aspects of stream ecology.

2. Anchor QEA, LLC. 2013. Final draft semi-arid riparian functions and associated regulatory protections to support shoreline master program updates. Prepared for: Grant County, WA.

   This is a consultant report providing recommendations for riparian buffers as part of Shoreline Master Program updates for Grant County, WA. The document cites some of the same references in the primary literature annotated bibliography for Ecology's riparian buffer BMP evaluation. For water quality functions, the report states that "a vegetative buffer of 65 feet "should provide adequate protection of stream water quality for slopes up to 15 percent." For erosion control functions, 40 to 50ft is recommended. The recommendation for protecting fish and wildlife habitat functions is 50 to 70ft. For shade and cover functions, the recommendation is 20ft maximum since this is stated as the typical riparian area width in this semi-arid region. For organic inputs, up to 125ft is recommended for reaches with cottonwoods, up to 30ft for reaches without trees, but supporting mature willow, and up to 10ft for reaches that only support herbaceous plants.

   For all functions combined: small incised streams with narrow riparian corridors are recommended to have a 50ft buffer; river deltas with wider riparian corridors and active floodplains are recommended to have a 100ft buffer; large rivers with narrow riparian and steep slopes/cliffs recommended to have 65ft buffer; small river or large stream with narrow riparian/limited floodplain recommended to have 65ft buffer; lakes with narrow riparian corridor and mix of open and developed shoreline recommended to have 50ft buffer.

3. Arora, K., Mickelson, S.K., Helmers, M.J., and Baker, J.L. 2010. Review of pesticide retention processes occurring in buffer strips receiving agricultural runoff. *JAWRA*. Vol. 46, No. 3.*

   Abstract: "Review of the published results shows that the retention of the two pesticide carrier phases (runoff volume and sediment mass) influences pesticide mass transport through buffer strips. Data averaged across different studies showed that the buffer strips retained 45% of runoff volume (ranging between 0 and 100%) and 76% of sediment mass (ranging between 2 and 100%). Sorption (soil sorption coefficient, Koc) is one key pesticide property affecting its transport with the two carrier phases through buffer strips. Data from different studies for pesticide mass retention for weakly (Koc < 100), moderately (100 < Koc < 1,000), and strongly sorbed pesticides (Koc > 1,000) averaged (with ranges) 61 (0-100), 63 (0-100), and 76 (53-100) %, respectively. Because there are more data for runoff volume and sediment mass retention, the average retentions of both carrier phases were used to calculate that the buffer strips would retain 45% of weakly to moderately sorbed and 70% of strongly sorbed pesticides on an average basis. As pesticide mass retention presented is only an average across several studies with different experimental setups, the application of these results to actual field conditions should be carefully examined."

4. Belt, G.H., O' Laughlin, J., and Merrill, T. 1992. Design of forest riparian buffer strips for the protection of water quality: analysis of the scientific literature. *Report No. 8.* Idaho Forest, Fish, and Range Policy Analysis Group. 40 pp.

   This reference summarizes the effects of timber harvesting upon streams and the effectiveness of buffers at attenuating those effects in the context of forest practices rules in Pacific NW states. The information in this document is by and large redundant to information gleaned from other sources.

5. Beschta. R.L. 1997. Riparian Shade and Stream Temperature: An Alternative Perspective. *Rangelands* 19:25-28.

   This is a general discussion about the importance of riparian vegetation for moderating stream temperatures in rangeland streams.

6. Beschta, R. L., Bilby, R. E., Brown, G. W., Holtby, L. B., and Hofstra, T. D. 1987. Stream temperature and aquatic habitat: fisheries and forestry Interactions. In: *Streamside Management: Forestry and Fisheries Interactions*. E. 0. Salo and T. W. Cundy (Editors). Contribution No. 57, University of Washington, Institute of Forest Resources, 471 pp.*

   This is a book chapter addressing influences upon and influences of water temperature in forested streams.

   Abstract: "The temperature of water entering a forest stream system typically resembles that of the watershed's subsoil environment. As this water continues to flow down the stream system, seasonal and diurnal water temperatures are strongly influenced by solar radiation. Pronounced differences in stream temperature patterns are evident for streams draining watersheds throughout the Pacific Northwest. Seasonal and diurnal patterns of stream temperature influence a wide range of responses by instream biota. Furthermore, logging activities can initiate pronounced temperature changes by the removal of forest vegetation along channels. Buffer strips of forest vegetation are an effective means of minimizing stream temperature impacts associated with logging. Although direct mortality of fish is probably not a major concern throughout the Pacific Northwest when stream temperatures are altered by management activities, temperature changes can influence rates of egg development, rearing success, species competition, and other factors."

7. Bolton, S. and Monohan, C. 2001. A review of the literature and assessment of research needs in agricultural streams in the Pacific Northwest as it pertains to freshwater habitat for salmonids. Center for Streamside Studies. University of Washington. Seattle, WA.

   This report reviews riparian and aquatic ecology in the PNW and discusses effects of agriculture on streams and identifies associated gaps in knowledge. It also collected comments from regional scientists and managers on what they considered to be pertinent areas of potential research. It does not evaluate buffer effectiveness or provide buffer recommendations.

8. Broadmeadow, S. and Nisbet, T.R. 2004. The effects of riparian forest management on the freshwater environment: a literature review of best management practice. *Hydrology and Earth System Sciences*, 8(3) 286-305.

This is a review of forested riparian buffer management, with particular reference to Britain. The recommended average width of buffers to prevent sedimentation is 5m for channels 1m wide or less, 10m for channels 1 to 2 m wide, and 20m for channels greater than 2m wide. States that the Russian ministry of Reclamation and Water Management requires a riparian buffer of 22 to 100m on forest land with a slope greater than 5.2%. Cites a Scottish study finding that 50% of suspended sediment load was removed through a 60 to 70m buffer on mineral soils and that this effectiveness was likely to be lower on slopes greater than 7% and higher on less erodible soils, such as peat soils. Cites a study in Maryland finding that effective buffer width was related to sediment particle size, slope, surface roughness, and runoff flow rate (study predicted that on a 3.5% slope, buffer width would need to increase from 30m to 60m in order to remove 90 to 95% of sediment). Cites studies finding that a high level of nitrate removal can occur within buffers ranging from 5 to 30m wide, with the lower end of the range occurring where subsurface denitrification activity was high. States that the risk of pesticide reaching surface waters can be reduced by prohibiting its usage in riparian buffers, but that it also partially depends on the ability of riparian soils and vegetation to inhibit pesticide transport form upland sources. States that clearing a 10m strip of conifers along a river in Wales caused a mean daily winter temperature to decrease and mean daily spring/summer increase by 0.5 to 1.0^{o}C. Cites a study in Japan finding that the magnitude of temperature increases as a result of riparian tree removal varies by stream width. Cites several studies finding that forested buffer widths ranging from 12m to 30m resulted in minimal changes to stream temperature regimes. Suggests that 50% of the stream surface should be under dappled shade and cites a review finding that about half of forestry guidelines call for leaving 50% of the riparian canopy or tree basal area intact; states that in colder climates heavy shade is undesirable because it inhibits stream productivity. Cites a study finding an increase in trout and aquatic macroinvertebrate production following riparian conifer harvest, one in which the conifers were partially replaced by hardwoods. Suggests that buffer widths should be varied based on variation in hillslope gradient, canopy density, and ground cover density. Cites the role of instream large wood at helping control sediment transport and influencing channel morphology, such as pool formation. Riparian conifers have been shown to have a minimal effect upon stream-water acidity. Alder can contribute to stream acidification through leaching of nitrogen associated with its ability to fix atmospheric nitrogen.

9. Brown, G.W. and Krygier, J.T. 1970. Effects of clear-cutting on stream temperature. *Water Resources Research*. 6:4:1133-1139.

Brown and Krygier (1970) found that the clear cut harvesting, stream clearing, and burning of one small watershed (Needle Branch) in the Alsea drainage of western Oregon increased average monthly maximum temperatures by 14°F (7.8^{o}C) annual maximum temperatures from 13.9 to 29.4°C, but patch cutting 25% of a neighboring watershed with 100 ft buffers along perennial streams was reported to not be associated with any significant increase in the mean monthly maximum temperature of the mainstem downstream. (Note: Not well done or documented. Suggest using Harris (1977) which extends the analysis for 7 years post-harvest and uses modeled predictions to assess treatment rather than a heavy reliance on graphical comparisons. Two of the three patch cuts were in the upper basin on portions of apparently non-perennial tributary streams, only one was included the 100 ft buffer along the perennial mainstem stream – appears likely to be at the bottom of the treatment watershed. Study uses graphical comparisons for the clear-cut treatment and a time series statistical comparison pre to post with some undisclosed consideration to factoring out the effects of climate – probably using the control watershed. Also: Checked to see if Brown and Krygier 1967 noted that as a stream passed 1300 feet through a clearcut, its temperature increased as much as 16F. Could not find data or reference to support this finding cited by another author. There is no data on reach length.)

10. Buffler, S. 2005. Synthesis of design guidelines and experimental data for water quality function in agricultural landscapes in the Intermountain West. *Msc. Thesis*. Utah State University Logan, UT. 48p.

    This report contains a review of buffer research and guidelines for implementing buffers on agricultural lands in arid regions- and so is most relevant to eastern WA. The focus is upon identifying buffer width needed to retain sediment, nitrogen, phosphorus, pesticides, and pathogens. Primary landscape attributes influencing buffer effectiveness are reviewed, including: buffer width, slope gradient, soil infiltration, surface roughness, slope length, and adjacent land use. Secondary landscape attributes that influence effectiveness and are often used to modify preliminary buffer widths include: surface water features, sand/gravel aquifers, seeps/springs, floodplains, and wetlands. In arid regions, more water is contributed to streams from overland flow due to less vegetative biomass (and lower plant density) and less consistent precipitation. "Vegetation type and hydrologic and geological considerations of the site should be taken into consideration in order to appropriately assess conditions appropriate for removal of dissolved nutrients." This is because there is wide variation in the removal of dissolved N and P among sites with differing environmental characteristics. Recommended buffer widths for individual pollutants, based on a 90% removal objective, are as follows: 20 to >40m for nitrogen (but may be narrower under ideal site conditions); 3 to >10m for sediment; >20m for phosphorus; 3 to >6m for pathogens; >9m for pesticides.

    "The minimum buffer width recommended in the Riparian Buffer Handbook (Johnson and Buffler, 2005) based on the literature review and assessment of Intermountain conditions is 70' (21.3m) or top of stream bank plus 35'(10.7m), whichever is greater, thus slope length was not considered a primary attribute for determining buffer width because attenuation occurs within the minimum length recommended. "Implementing NRCS in-field and range conservation practices such as terraces, in-field buffers, grassed waterways, and rotational grazing have proved effective at reducing contaminants before they reach riparian buffers (Buffler 2005)."

11. Castelle, A.J., and Johnson, A.W. 2000. Riparian vegetation effectiveness. *Technical Bulletin No. 799*. National Council for Air and Stream Improvement.

    This report provides a review of vegetated buffer effectiveness. It concluded that vegetated areas within the first 5 to 25m of a streambank provide at least 50%, and frequently 75% or greater effectiveness at stabilizing streambanks, reducing sediment, removing chemicals, producing large organic debris, producing particulate organic matter, and producing stream shading. Buffer width was not found to have a strong effect upon streambank stability, but rather was more affected by fine root density and soil properties. Flood-prone areas, soil properties, and sideslope gradient were cited as factors that may be better correlated with stream protection than vegetation metrics such as tree numbers, size, and vigor. Their analysis found that 40 to 60% of large wood comes from approximately the first 10m of a buffer and that 80 to 100% comes from within 20 to 30m. Points out that may study of buffer width did not look at multiple increments, which may lead to erroneous interpretations. For example, a study that looked only at a 30m width and found it to be effective may suggest that this width is the minimum width necessary, yet the study did not examine narrower widths which may or may not have been just as effective.

12. Castelle, A.J., Johnson, A.W., and Conolly, C. 1994. Wetland and Stream Buffer Size Requirements – A review. *Environ. Qual.* 23:878-882.

    This paper reviews buffer literature and examines buffer width in terms of effectiveness. In most scenarios buffers 15 to 30m wide were determined to protect streams and wetlands, with widths closer to 30m being more likely to protect biological communities. Site specific factors lead to a range in the effective buffer width estimate from 3m to 200m, but buffers less than 10m generally provide insufficient protection.

13. Castelle, A.J., Conolly, C., Emers, M., Metz, E.D., Meyer, S., Witter, W., Mauermann, S., Erickson, T. and Cooke, S.S. 1992. Wetland buffers: use and effectiveness. *Publication No. 92-10.* Washington State Dept. of Ecology.

    This report is a review of wetland buffer effectiveness. The report concluded that a buffer of 100ft will generally protect water quality, but that degraded wetlands could have a buffer narrower than 100ft while sensitive wetlands require a buffer wider than 100ft.

14. CH2MHill. 2000. Review of the Scientific Foundations of the Forests and Fish Plan. Prepared for the Washington Forest Practices Association. Olympia, WA.

    This report summarizes the science underlying Washington State's Forest Practices Rules. The report states that more than 70 percent of the large wood delivered to streams comes from within 50 feet of the channel, 7% comes from over 100ft from streams, and 1% from more than 150ft away. For western Cascades mature and old-growth forests, the average distance providing 95% of the large wood supply among three studies was 96ft (78.5ft for mature stands only). For eastern WA, 95% of the supply from mature forest stands was provided at 91ft (1 study). Cite Brazier and Brown (1973) as finding that 70% of potential stream shade in an old growth stand comes from within 50ft of the channel, 10% from more than 50ft; 80% was the maximum shading potential in this study. The report concluded that "the Forests and Fish plan contains biologically sound and economically practical solutions that will improve and protect riparian habitat on non-federal forestlands in Washington."

    Notable quotes:

    "Tree height for 100-year-old trees on the Eastside at may range from 60 to 130 feet for Douglas-fir; from 70 to 130 feet for grand fir; and is somewhat lower for red cedar where it occurs in riparian areas (Hegyi et al. 1981)."

"The influence of shade appears to be negligible at stream widths observed at distances of 31 to 37 miles (50 to 60 km) from the watershed divide (Sullivan et al. 1990)." "The cumulative effectiveness of riparian vegetation to shade streams approaches its maximum at tree retention widths of 60 to 120 feet from the channel, depending on the stand height and condition (Figure 2.2-2)." "Smaller streams in old-growth stands typically range from 75 to 90 percent shaded (Brazier and Brown 1973; Erman et al. 1977; Steinblums et al. 1984; Beschta et al. 1987)."

"Steinblums et al. (1984) identified that shade could be delivered to streams from beyond 75 feet and potentially out to 140 feet. In some site-specific cases, forest practices between 75 and 140 feet from the channel have the potential to reduce shade delivery by up to 25 percent of maximum. However, any reduction in shade beyond 75 feet would be relatively low on the horizon, and the impact on stream heating would be low or none because direct-beam radiation declines in effectiveness as the angle approaches the horizon, according to Lambert's Law."

15. Christensen, D. 2000. Protection of riparian ecosystems. A review of best available science. Final draft. Jefferson County Environmental Health Division. Jefferson County, WA.

    This is a brief review of riparian buffer effectiveness. Buffers of 150ft were recommended for shorelines of the state and waters with high fish, wildlife, or human use. Buffers of 100ft were recommended for perennial or intermittent streams with insignificant to moderate fish, wildlife, or human use. Buffers of 0 to 50ft were recommended for waters that are basically ephemeral.

16. City of Boulder. 2007. Wetland and stream buffers: a review of the science and regulatory approaches to protection. City of Boulder Planning and Development Services. Boulder, CO.

    This is a review of buffer effectiveness and a discussion of regulatory approaches for implementing buffers. Contains a table of minimum buffer widths recommended by EPA for wetlands. The recommended width for addressing water quality is 50ft for pathogens and pesticides, and for sediment and phosphorus where hillslopes are <5%, to 100 feet for sediment and phosphorus on slopes 5-15% (and an increment (e.g. 10ft) for each 1% of slope above 15%), and 100ft for nitrate.

17. Czarnomski, N. and Hale, C., 2013. Effectiveness of riparian buffers at protecting stream temperature and shade in Pacific Northwest Forests: A systematic review. Final Report to the Oregon Forest Practices Board. Sept. 2013.

    This is a systematic review of available research on the effects of riparian forest management upon stream shading and temperature relative to Oregon Forest Practices rules and rule alternatives. Many of the references reviewed are included in the Ecology evaluation of literature on the effectiveness of buffers at addressing thermal pollution. Specific findings are detailed, specific to riparian mgmt. prescriptions, and are not presented here.

18. Dabney, S.M., Moore, M.T., Locke, M.A. 2006. Integrated management of in-field, edge-of-field, and after-field buffers. *Journal of American Water Resources Association*. 42: 15-24.

This article reviews the effectiveness of implementing multiple runoff and erosion control BMPs in concert on a farm. It addresses the combination of in-field and edge-of-field BMPs along with other practices such as residue management and after-field BMPs such as vegetated ditches and constructed wetlands. The three in-field BMPs discussed are grassed waterways, contour buffer strips, and alley cropping. The three edge-of-field BMPs discussed are field borders, filter strips and riparian forest buffers. Vegetative barriers may be used in-field and edge-of-field. In a properly integrated BMP system, multiple buffers act to protect each other from excessive runoff and erosion.

The front edge of a buffer has a disproportionate effect upon trapping sediment as well as disrupting transport of soluble chemicals depending upon the infiltration rate. “Buffers treat surface runoff best with slow, shallow, diffuse flows and least well for rapid, deep, concentrated flows.” Runoff flow rate into a buffer is strongly affects pollutant removal effectiveness. Shallow soils are generally more vulnerable to runoff generation and erosion than deeper soils. In-field buffers provide an effective way to reduce runoff and erosion near the source.

“Where flow concentrates in tilled agricultural fields, ephemeral gullies may form in the same place year after year due to topographic or seepage (Principle 4) properties, only to be filled in again by tillage. When a farmer converts to no-tillage farming, these ephemeral gullies may grow into classic gullies that are too large to be crossed or filled with conventional farm equipment (Figure 2a). Stabilization can be achieved with a grassed waterway or, for small contributing areas, by a series of vegetative barriers (Figure 2b).”

Contour buffers must be periodically maintained to prevent berms from forming at the upslope edge because such berms can concentrate and re-direct runoff. The hydraulic roughness of a buffer depends upon soil roughness at very shallow runoff flows and vegetation density and stiffness at deeper flows; Manning’s n, the roughness parameter, at first increases with increasing water depth (assuming constant velocity) but then decreases as vegetation becomes more and more submerged.

Edge-of-field buffers are more practical than in-field buffers on flat lands. The NRCS standard for filter strips specifies that the gradient along the front edge of the strip should be less than 0.5% and the upslope field gradient should be between 1 and 10%. The articles discuss the usage of grade control pipe systems on flatter lands to slow runoff and capture sediment.

Irrigation return flows can bypass edge-of-field and grade control structures, but may be addressed by riparian buffers, constructed wetlands, or even vegetated ditches.

19. Davies, P., Cook, B., Rutherford, K., and Walshe, T. 2004. Managing high in-stream temperatures using riparian vegetation. *River Management Technical Guideline No. 5*. Land & Water Australia, Canberra.

This publication provides guidance on the use of riparian buffers to protect water temperatures. “Priority areas for restoration aimed at relieving in-stream thermal stress are to: restore lower order streams before higher order streams; restore streams with woody vegetation before seeking to improve lower density or degraded vegetation.

restore streams on north-west aspects before south-east aspects [note: in northern hemisphere this would be the southeast and northwest aspects, respectively]; and preferentially restore reaches where soil properties are most favourable for successful vegetation establishment.” Most of the document is too specific to Australia to be useful for other areas.

20. DeGasperi, C.L., R.W. Sheibley, B. Lubliner, C.A. Larson, K. Song, and L.S. Fore. 2018. Stormwater Action Monitoring Status and Trends Study of Puget Lowland Ecoregion Streams: Evaluation of the First Year (2015) of Monitoring Data. Prepared for Washington Department of Ecology Stormwater Action Monitoring program. Prepared by King County in collaboration with the Washington Department of Ecology, U.S. Geological Survey, and the Puget Sound Partnership. Science and Technical Support Section, Water and Land Resources Division, Seattle, Washington.

    This is a stormwater status and trends evaluation and is not relevant for evaluating BMP effectiveness.

21. Desbonnet, A., Pogue, P., Lee, V., and Wolff, N. 1994. Vegetated buffers in the coastal zone - a summary review and bibliography. *Coastal Resources Center Technical Report No. 2064.* University of Rhode Island Graduate School of Oceanography. Narragansett, RI. 72pp.

    This publication reviews the effectiveness of buffers at reducing nonpoint source pollution. Tables and graphs are presented that provide literature values for pollutant mass removed per unit buffer area as well as % pollutant removed for buffers of varying widths. The graphs treat all data points as being equal even though Ecology’s primary literature review found that for most, if not all pollutants, this is not an appropriate treatment of the data since removal often varies according to other factors more important than buffer width. As such, there is a weak basis for the pollutant removal and wildlife habitat value ascribed to buffers of specific widths that are provided by the authors. The second half of the publication reviews buffer policies for coastal areas.

22. Desbonnet, A., Pogue, P., Lee, V., Reis, D., Boyd, J., Willis, J., and Imperial, M. 1995. Development of Coastal Vegetated Buffer Programs. *Coastal Management*. Vol. 23 pp 91-109.

    This journal article summarizes the information presented in Desbonnet et al. (1994).

23. Dillaha, T.A., Sherrard, J.H., and Lee, D. 1989. Long-term effectiveness and maintenance of vegetative filter strips. *Water Environment and Technology*. 1: 418-421.*

    Abstract: “Vegetative filter strips (VFS) on 33 Virginia farms were visited and observed over a 13-month period to evaluate their long-term effectiveness for water quality improvement. Operational problems observed during the site visits were documented and design or maintenance procedures to alleviate the problems were evaluated. Of the VFS observed, 36% were judged to be totally ineffective, were no longer in existence, or were simply extensions of pastures - although all were, or had been, part of the state cost-share program. Most of the sites visited had topographic limitations which severely limited VFS

performance. Accumulation of surface runoff in natural drainageways within fields before it reached the VFS was the most common and critical problem. Runoff from the drainageways crossed the VFS in a few narrow areas, totally inundating the filters and rendering them ineffective for sediment and nutrient reduction. This situation is difficult to control and VFS are probably not appropriate for fields with extensive internal drainageways unless the VFS extend up into the fields and parallel the drainageways forming wide grassed waterways.

Vegetative filter strips were judged to be beneficial even when they could not filter sediment and nutrients from runoff because they provided localized erosion protection in critical areas along streambanks. They did not act as filters, however, and should therefore be referred to as vegetative buffer strips or critical area plantings.

From Summary and Conclusions: The most significant factor affecting VFS performance was the flow regime of runoff. For runoff flowing shallowly and uniformly distributed across the VFS, the strips were highly effective for sediment removal and presumably moderately effective for nutrient removal. Under concentrated flow conditions, however, deeper flows tended to inundate the VFS, bending the vegetation over and greatly reducing VFS effectiveness. It was estimated from the fields observed that 60% of the runoff concentrated in natural and man-made drainageways within the fields before reaching the VFS at the edges of the fields. The water concentrated in the drainageways, then flowed across the VFS at a few narrow points and only minor pollutant reduction was achieved.

Since it is difficult to economically change flow patterns in fields to improve VFS performance, it is suggested that cost shared VFS be limited to topographic situations for which they are suited, namely, fields with fairly uniform slopes and poorly developed drainage patterns. Overall, the observed VFS had adequate cover, but many had weed problems which reduced grass thickness and cover. Mowing for weed control and to promote thicker grass growth is highly recommended (2 to 3 mowings per year):

Wildlife habitat filter strips were judged to be totally ineffective as filter strips. They may provide valuable food and habitat for wildlife but cover and vegetative conditions at ground level are too sparce for effective filtering or flow retardance. Because the factors controlling VFS effectiveness are highly site specific, it is recommended that a conservation professional with a knowledge of VFS and hydrology visit each field before it is approved for VFS cost-sharing to determine if the site is acceptable. Sites in which more than 40% to 50% of the runoff crosses the VFS as concentrated flow should probably be excluded. Other BMPs, such as reduced tillage, would be much more effective for these fields unless the

VFS extend up into the field and filter the runoff before it concentrates in the natural drainageways."

24. Dorioz, J.M., Wang, D., Poulenard, J., and Trévisan, D. 2006. The effect of grass buffer strips on phosphorus dynamics – a critical review and synthesis as a basis for application in agricultural landscapes in France. *Agriculture, Ecosystems and Environment*. 117: 4-21.

    This paper provides a comprehensive overview of the processes and factors affecting the ability of buffers to remove phosphorus from runoff. Particulate phosphorus tends to adsorb more so with the clay fraction of soils, and thus a high rate of removal requires preventing clay in runoff from reaching waterways. Dissolved P is not the dominant form in runoff but has a much wider range of capture by buffers (cited as ranging from -83 to +95%, with retention of 20 to 30% being frequent) because it is more mobile. "According to Schmitt et al. (1999) the percentage retention of bioavailable P is always less than that of total-P and is only significant (>60%) in the case of buffers that are sufficiently wide (>15 m) to influence the transfer of the fine and dissolved fractions, which closely constitute the pool of bioavailable P." The paper suggests that a good general estimate is for a buffer to remove 50% of the P load in runoff, with 5m (ranging from 5 to 10m) being a general minimum for slopes 1 to 10%. Some evidence indicates that perennial, herbaceous vegetation leads to higher P retention than other types of vegetation such as trees, shrubs, or newly planted grasses. This is thought to be due to higher soil permeability in established stands of grass. Soil texture also plays an important role due to its influence on infiltration rates. The Soil Conservation Service 1997 standard is noted, which prescribes a minimum grass buffer strip of 11-22m for slopes of 0.5 to 5% and 36 to 71m for slopes >5%. It is thought that over the long term, the retention of P in buffers reaches a saturation point and dissolved P is released from previous storage unless some sort of maintenance occurs to remove P (such as periodic buffer vegetation removal).

25. Dosskey, M.G.G. 2001. Toward quantifying water pollution abatement in response to installing buffers on crop land. *Environmental Management*. 28: 577-598.

    This is a review of buffer effectiveness that addresses many of the references contained in ECY's annotated bibliography of primary literature. It also identifies large gaps knowledge related to stream/lake response to buffers, buffers that reduce field runoff, loads of pollution reduced by buffers, filtering of groundwater runoff from fields, effect of buffers on bank erosion, and the effect of buffers upon instream pollutant processing. Information on watershed scale effects of buffers is also lacking and likely requires sophisticated modelling to address.

26. Dosskey, M.G.G., Helmers, M.J., Eisenhauer, D.E. [and others]. 2003. Hydrologic routing of farm runoff and implications for riparian buffers. In: Williams, J.D., Kolpin, D., eds. *Agricultural hydrology and water quality: Proceedings of the American Water Resources Association 2003 spring specialty conference*. Middleburg, VA. TPS-03-1. CD-ROM.

    This is a summary of a study on multiple farms in Nebraska which found that significant and widely variable amounts of runoff bypass riparian areas through conveyances such as grassed waterways and subsurface pipes. It was concluded that source control BMPs would be needed to reduce runoff and pollutant loads and that runoff would need to be routed to buffers to increase pollutant trapping.

27. Dosskey, M.G.G., Eisenhauer, D.E., and Helmers, M.J. 2005. Establishing conservation buffers using precision information. *Journal of Soil and Water Conservation*. 60: 349-354

    This article presents methodology for using a GIS to model site specific runoff patterns in order to develop variable width buffers at the field scale as an alternative to fixed width buffers.

28. Dosskey, M. G., Vidon, P., Gurwick, N. P., Allan, C. J., Duval, T. P., and Lowrance, R. 2010. The Role of Riparian Vegetation in Protecting and Improving Chemical Water Quality in Streams. *Journal of the American Water Resources Association* 1-18.

This is a literature review focusing on the role of riparian vegetation in pollutant removal from runoff. The focus is on processes that affect pollutant transport and capture. There's good information in this reference that is too extensive to summarize here.

29. Durst, J.D. and Ferguson, J.M. 2000. Buffer Strip Function and Design: an annotated bibliography. Compiled for the Region 3 Forest Practices Riparian Management Committee. Alaska Dept. of Fish and Game.

This is an annotated bibliography that focuses on the role of riparian buffers in protecting water quality and fish habitat with an emphasis on managed forests. This bibliography is less than comprehensive.

30. Ellis, J.H. 2008. Scientific Recommendations on the Size of Stream Vegetated Buffers Needed to Protect Water Quality, Part One, The Need for Stream Vegetated Buffers: What Does the Science Say? Report to Montana Department of Environmental Quality, EPA/DEQ Wetland Development Grant. Montana Audubon, Helena, MT. 24 pp.

Part One addresses the general role and benefits of riparian buffers at protecting water quality. The general conclusion was that an average stream buffer width of 132ft would remove approximately 80% of multiple pollutant types. Stream temperature is not addressed. The general recommendations of the evaluation are: 100ft buffers to protect for removal of nitrate, sediments, and bacteria; site specific factors, such as steep slopes, may be cause for implementing wider buffers.

31. Ellis, J.H. 2008. Scientific Recommendations on the Size of Stream Vegetated Buffers Needed to Protect Fish and Aquatic Habitat, Part Two, The Need for Stream Vegetated Buffers: What Does the Science Say? Report to Montana Department of Environmental Quality, EPA/DEQ Wetland Development Grant. Montana Audubon, Helena, MT. 20 pp.

Part Two addresses the general role and benefits of riparian buffers at protecting fish and aquatic habitat. The recommendations are: buffers should be at least 100ft wide; a 150ft buffer should be implemented in forested areas to maintain large wood recruitment; 300ft buffers are recommended for streams with native salmonids; 150ft buffers recommended for non-fish bearing streams and reservoirs; 100ft buffers for intermittent and ephemeral streams. A table is provided that summarizes/recommends mean buffers widths to provide certain protections: for erosion control, 100yr floodplain, but at least 100ft; for flood control- 100yr floodplain; for road construction- 150ft; for large wood- 155ft; for water temp- 77ft; for fish habitat and invertebrates- 110ft; for fish and aquatic habitat- 155ft or 100yr floodplain, whichever is greater.

32. EDAW, Inc. and Mason, Bruce, and Girard, Inc. 2002. CMER/RSAG Temperature Workshop-2001. Summary Report. Prepared for the Riparian Scientific and Advisory Group and the Cooperative Monitoring, Evaluation, and Research Committee. Olympia, WA.

This report summarizes presentations and discussions from a 2001 workshop sponsored by WA State's Forest Practices Adaptive Mgmt Program. Topics included physics of stream heating, riparian vegetation influence on stream temperature, microclimate, temperature modelling, physics of groundwater heating.

33. Feld, C.K., Rosário Fernandes, M., Ferreira, M.T., Hering, D., Ormerod, S.J., Venohr, M., and Gutiérrez-Cánovas, C. 2018. Evaluating riparian solutions to multiple stressor problems in river ecosystems. A conceptual study. *Water Research* 139, 381-394.

    The authors developed a conceptual model that links human stressors upon riparian areas and effects upon streams. Unfortunately, this reference is of little use because it doesn't provide any new knowledge on the topic- it basically just says that riparian areas are important for protecting streams.

34. Fennessy, M.S. and Cronk, J.K. 1997. The effectiveness and restoration potential of riparian ecotones for the management of nonpoint source pollution, particularly nitrate. *Critical Reviews in Environmental Science and Technology*. 27: 285-317.

    This is a lengthy review of nitrogen removal by riparian buffers. Most of the references examined regarding buffer width and nitrogen removal are included in Ecology's bibliography of primary riparian buffer literature. The assert that nitrate removal is greater in forested riparian areas with subsurface flow relative to grassed buffers with surface flow. They identify denitrification as the primary process responsible for nitrate removal in buffers. Denitrification is driven by subsurface carbon availability, subsurface saturation and dissolved oxygen levels, vegetation type and hydrologic processes. The authors suggest that a buffer of 20 to 30m can remove up to 100% of nitrate.

35. Flanagan, S. E., Patrick, D. A., Leonard, D. J., and Stacey, P. 2017. Buffer Options for the Bay: Exploring the Trends, the Science, and the Options of Buffer Management in the Great Bay Watershed Key Findings from Available Literature. *PREP Reports & Publications*. 380.

    This is a buffer literature review with applications to the Great Bay Estuary in NH. Suggested buffer widths for protection of water quality, hydrology, and wildlife habitat are presented.

36. GEI Consultants, Inc. 2005. Efficacy and economics of riparian buffers on agricultural lands. Phases I (2002) and II (2005). Submitted to: Washington Agricultural Caucus. Moxee, WA.

    This document evaluates buffer effectiveness and the economic effects of buffers. It is apparent that an intended purpose of the document is to justify the use of variable width buffers over fixed width buffers- so not an unbiased reference. Buffers ranging from 5 to 30m are asserted to be adequate for protecting water quality and stabilizing streambanks. In the end, they recommend the following on farms implementing upslope BMPs: minimum 25ft buffer of native vegetation on each side of stream for lands with <7% slope in areas with less than 18" precip; minimum 35ft buffer of native vegetation on each side of stream for lands >7% slope or in areas with more than 18" precip. On farms not implementing upslope BMPs: minimum 60ft buffer of native vegetation on each side of stream.

37. Gold, A.J., Groffman, P.F., Addy, K., Kellogg, D.Q., Stolt, M., and Rosenblatt, A.E. 2001. Landscape attributes as controls on ground water nitrate removal capacity of riparian zones. *Journal of American Water Resources Association*. 37: 1457-1464.

This article discusses the effects of geomorphology and groundwater flow paths upon subsurface nitrate removal in riparian zones. There is considerable spatial variability in the potential for denitrification to occur in riparian areas. Areas with glacial outwash or organic/alluvial deposits have a relatively greater potential for denitrification. Areas with glacial till tend to have surface seeps, and therefore less denitrification, which tends to occur subsurface. Shallow subsurface flow tends to have more denitrification than deeper flow. Croplands with artificial drainage cause nitrate laden water to bypass areas where denitrification would occur.

38. Granger, T., T. Hruby, A. McMillan, D. Peters, J. Rubey, D. Sheldon, S. Stanley, E. Stockdale. April 2005. Wetlands in Washington State - Volume 2: Guidance for Protecting and Managing Wetlands. Washington State Department of Ecology. Publication #05-06-008. Olympia, WA.

This guidance contains Ecology's recommendations for wetland buffers.

39. Gray, J. R. et al., 2000. Comparability of suspended-sediment concentration and total suspended solids data. Water-Resources Investigations Report 00-4191. U.S. Geological Survey. Reston, VA.

This investigation indicates that when water flow contains a substantial amount of larger particles (e.g. sand), then suspended sediment concentration (SSC) analysis methods and total suspended solids (TSS) analysis methods do not yield comparable results. TSS was developed for wastewater analysis and is more appropriate for evaluating samples whose solids are dominated by organic matter particles and finer mineral particles (e.g., clay and silt). SSC methods are more appropriate when evaluating the amount of sediment in runoff water derived from soil erosion.

40. Gregory, S.V., Swanson, F.J., McKee, W.A., and Cummins, K.W. 1991. An ecosystem perspective of riparian zones; focus on links between land and water. *Bioscience* Vol. 41, No. 8.

This is a general conceptual discussion of riparian ecosystem functioning. Notable quotes:

"We define riparian zones functionally as three-dimensional zones of direct interaction between terrestrial and aquatic ecosystems (Meehan et al. 1977, Swanson et al. 1982).

"Boundaries of riparian zones extend outward to the limits of flooding and upward into the canopy of streamside vegetation. Dimensions of the zone of influence for a specific ecological process are determined by its unique spatial patterns and temporal dynamics."

"As channel width increases, the canopy opening over the stream increases and the influence of streamside vegetation on solar inputs to the stream channel decreases."

"Solar radiation striking the water's surface also contributes energy in the form of heat. Riparian vegetation plays a major role in modifying solar inputs and influencing stream temperatures (Barton et al.1985). Density of the riparian canopy is one of the most critical factors in determining the heat input in a given reach of stream. The upstream length of forested channel, riparian vegetation width and density, canopy opening, and groundwater influence the contribution of heat to a reach."

"Riparian zones are uniquely situated within watersheds to intercept soil solution as it passes through the riparian rooting zone before entering the stream channel."

"In both deciduous and coniferous riparian sites, rates of denitrification were greater in riparian soils near the stream than in toeslope or hillslope soils, presumably a reflection of the soil moisture content and the availability of organic substrates for denitrifiers."

"Because of their central location at the base of terrestrial ecosystems, riparian zones play a critical role in controlling the flux of nutrients from watersheds."

41. Hansen, B., Reich, P., Cavagnaro, T., and Lake, P.S. 2015. Challenges in applying scientific evidence to width recommendations for riparian management in agricultural Australia *Ecological Management and Restoration*. 16(1):50-57.

This article discusses evaluating riparian widths for waterways on agricultural lands in SE Australia in terms of meeting specific ecological objectives. The evidence reviewed supported the concept of variable width buffers. The evaluation concluded with high confidence that effective buffer widths for water quality protection (based on ≥75% reduction in nonpoint nutrients) should vary from 20m for low land use intensity, 29m for moderate intensity, and 38 meters for high intensity. Moderate confidence effective buffer widths for moderating stream temperatures was recommended to be 28m for low land use intensity, 46m for moderate intensity, and 64 meters for high intensity. Low intensity land uses were considered to be: grazing under low stocking rates; pasture cropping; timber plantations; forestry operations; and pesticide applications. Moderate intensity land uses were considered to be: low to moderate dairy stocking rates; grazing under moderate stocking rates; orchards; medium-low fertilizer applications (<15kg/ P/Ha/yr or ≤ 110kg N/Ha/yr); unsealed roads within 30m of streams; lower intensity dryland cropping (e.g. lucerne, clover); and lower intensity production crops (e.g. vines, hops, olives). High intensity land uses were considered to be: dairy under high stocking rates; irrigated dairy; dryland cropping (e.g. wheat, canola); grazing under high stocking rates; swine and poultry; vegetatble production; sealed roads within 30m of streams; high fertilizer application rates (>15kg/ P/Ha/yr or >110kg N/Ha/yr).

42. Hansen, B., Reich, P., Lake, S., and Cavagnaro, T. 2010. Minimum width requirements for riparian zones to protect flowing waters and to conserve biodiversity: a review and recommendations, with application to the State of Victoria. *Report to the Office of Water, Department of Sustainability and Environment.* School of Biological Sciences, Monash University.

This length report reviews buffer functions and effectiveness. Key points include (direct quote):

- Riparian zones act as filters, sinks, processors and exporters of nutrients
- Nitrogen removal is most effective where shallow groundwater flow passes through root zone
- Sediment and sediment-bound phosphorus retention is most effective with grassy, continuous buffers that convert channelised flow to uniform sheet flow
- Riparian zones can act as phosphorus sinks and therefore, need to be wider where excess phosphorus is a dominant management issue. Periodic removal of riparian vegetation may be necessary
- Dominant hydrological flow paths affect riparian buffering efficiency
- Nutrient removal and processing is most effectively achieved in headwater streams
- Wetlands are good nutrient sinks and sediment traps
- Riparian widths necessary for excess nutrient removal are typically >50m, depending on nutrient type, buffer type, soil type, slope and dominant land use
- Riparian vegetation along small streams (order 1-3) exerts a strong influence on stream water temperature and primary productivity
- The slope of the riparian zone will alter the amount of shading provided by vegetation
- Riparian shading influences terrestrial microclimate over greater distances than it influences stream temperature (typically >45m)
- Riparian zone widths required to provide stream shading are typically 10-30m (slope dependent)
- Intact riparian zones are required to maintain bed and bank stability via structural reinforcement of soils
- Loss of riparian vegetation can result in excessive mobilisation of sediments
- Stock access to riparian zones exacerbates sedimentation
- Existing Australian guidelines set a minimum riparian buffer width of 5m for erosion control, which is modified by adding the height of the bank plus the time taken for vegetation to mature (likely to be 100 years or more for species like river red gum) adjusted by the erosion rate
- International studies recommend wider buffer widths for controlling erosion, varying from 10m in New Zealand to 30m in North America
- Riparian zone widths of between 15 and 55 m are necessary to provide woody inputs for in-stream sediment retention
- The greater the land use intensity, the wider the riparian zone needs to be to buffer against catchment modifications and disturbances
- In order to maximise functional efficiency, riparian zones should be longitudinally continuous as well as sufficiently wide, targeting first degraded headwaters and then proceeding downstream

- Based on a meta-analysis of >200 studies, riparian buffer widths of between 30 and 200 m are recommended, dependant on land use intensity and management objective
- Recommended widths apply to both banks
- Riparian width recommendations should be used in landscape forecasting- where land use changes are proposed, riparian zones need to be adjusted to account for potential increases in disturbance impacts

  For water quality protection, 30m minimum is recommended adjacent to low intensity land use, 45m adjacent to moderate intensity land use, and 60m adjacent to high intensity land use. See report for what is considered low/moderate/high intensity and use.

43. Harris, G.L. and Forster, A. 1997. Pesticide contamination of surface waters-the potential role of buffer zones. Pp. 62-69, In: Buffer Zones: *Their Processes and Potential in Water Protection*, N. Haycock, T. Burt, K. Goulding and G. Pinay (Eds.). Harpenden, UK: Quest Environmental.

    This article reviews the mechanisms by which pesticides are transported to surface waters and the role that buffers can play in preventing delivery to surface waters. One point made in the article is that pesticides can significantly harm vegetation and animals within buffers zones and so the primary objective should be to minimize the amount of pesticides that will reach the buffer through aerial drift, surface runoff, and/or subsurface runoff. The authors suggest that linear, continuous buffers are most suitable for conservation purposes while targeted buffers that focus on places where pesticides are likely to concentrate and be transported are more suitable for preventing delivery to waterways. They suggest that buffers of 2 to 10m may be sufficient to prevent delivery to waterways, although buffers up to 15m may be needed in some locations.

44. Hawes, E. and Smith, M. 2005. Riparian buffer zones: functions and recommended widths. Yale School of Forestry and Environmental Studies. Prepared for: Eightmile River Wild and Scenic Study Committee.

    This document provides an overview of riparian functions, factors influencing buffer widths, discuss fixed vs. variable vs, 3-zone buffers, provides ranges of buffer widths from a handful of select literature sources, and provides buffer width recommendations. Buffer widths for temperature control range from 33 to 230ft; for nutrient control, 16.4 to 164ft; for sediment control, 30 to 328ft; for pesticide retention 49 to 328ft; for bank stabilization, 30 to 98ft. The overall buffer width recommended width for water quality protection is 5 to 30m.

45. Haycock, N., Burt, T., Goulding, K., and Pinay, G. (Eds.) 1997. Buffer Zones: Their Processes and Potential in Water Protection. Harpenden, U.K: Quest Environmental. 334pp.

    This publication is the Proceeding of the International Conference in Buffer Zones held in Sept. 1996. Part I addresses the processing of pollutants in buffer zones. Part II addresses how different aquatic and terrestrial habitats can act as buffer zones. Part III addresses the creation, restoration and maintenance of buffers. Much of the findings/conclusions are

captured in the annotated bibliography for the primary literature. One interesting method discussed is the creation of ponds and wetlands for nitrogen removal, but it is noted that siting should be planned at the watershed scale rather than the plot scale so that these features are installed where they would be most effective on the landscape. One interesting article discusses economic and policy case study on buffers in Illinois and shows that a 25m buffer would provide a greater $ per acre benefit than a 75m buffer; the drop in benefit for wider buffers is attributed to greater soil productivity and thus profitability farther from the stream channels. Another interesting article discusses how trenches filled with a soil/sawdust mixture can be used to remove nitrogen from polluted subsurface flow. Yet another discusses a riparian rental program in the U.K. where the payment rates vary according to the type of land taken out of production. In two years just under 100km of stream were enrolled.

46. Heathwaite, A.L., Sharpley, and A., Gburek, W. 2000. A conceptual approach for integrating phosphorus and nitrogen management at watershed scales. *Journal of Environmental Quality*. 29: 158-166.

    This paper identifies small near-stream areas as being critical source areas for addressing nonpoint phosphorus pollution and well-draining soils with high manure/fertilizer loading in upper portions of watersheds as being critical source areas for addressing nonpoint nitrogen pollution in Pennsylvania. Presents findings that conversion to no-till farming decreased total P loss in runoff, but increased N leaching to groundwater. Modified indices are presented for assessing potential P and N losses for different sites/areas in a watershed. The P index includes ratings for soil erosion, surface runoff potential, amount P existing in the soil, fertilizer application rate and method, and organic P application rate and method. The N index includes ratings for soil texture, soil permeability, fertilizer N rate and application method, manure N rate and application method. These ratings are applied within a geographic information system in order to spatially identify relative risks of N and P pollution on a field-by-field basis. The article also discusses N and P source and transport control strategies and considerations. N controls are most important in recharge areas. "Phosphorus controls are effective in surface runoff generating areas but ineffective in recharge areas". P accumulation in soils can lead to subsurface transport of P

47. Helmers, M.J., Isenhart, T., Dosskey, M., Dabney, S. and Strock, J. 2006. Buffers and Vegetative filter strips. Unpublished symposia session summary.

    This paper summarized research on the effectiveness of buffers and filter strips and has the following conclusions (direct quote):

    1. Buffers and grassed waterways are broadly accepted practices for reducing nutrient runoff from agricultural fields.

    2. Properly located, designed, and maintained buffers may be expected to trap on the order of 50% of incoming sediment, somewhat less for sediment bound nutrients, and much less for dissolved nutrients. This performance will vary depending on conditions of the buffer and flow through the buffer, and the trapping may be greater than this when flow is nearly uniformly distributed as has been the case in many plot studies to this point.

3. Impact will be much lower if not properly located designed or maintained. In-field management that reduces runoff load and distributes it evenly along a buffer is important to maximize the effectiveness of the systems.

4. Buffers are cost effective. Analysis of the 2-million-mile goal indicates a benefit: cost ratio of 4.1; a 4-million-mile goal is 4.3.

5. The accuracy of impact assessments remains limited by lack of research data on watershed-scale effects of buffers and grassed waterways.

48. Hickey, M.B.C. and Doran, B. 2004. A review of the efficiency of buffer strips for the maintenance and enhancement of riparian ecosystems. *Water Qual. Res. J. Canada*. Vol. 39, No. 3, 311-317.

The article reviews available research on buffer effectiveness for differing water quality and habitat functions. The authors assert that more research is needed on the effectiveness of buffers having widths of 1 to 10m, which are common in agricultural areas.

49. Hicks, M. 2018. Riparian characteristics and shade response experimental research study. Draft scoping document. *Washington State Cooperative Monitoring, Evaluation, and Research Committee (CMER) Report.* Prepared for the State of Washington Forest Practices Board Adaptive Management Program.

This report contains an informative review of the best available science on how shade from riparian areas influences stream temperatures in forested landscapes. Many of the associated references are included in Ecology's riparian buffer annotated bibliography. A discussion of Ecology's Shade.xls model is also included.

50. Hruby, T. 2013. Update on Wetland Buffers: The State of the Science, Final Report, October 2013. Washington State Department of Ecology Publication #13-06-11.

This document revisits the conclusions and key points from Ecology's 2005 review of the science on wetland buffers. There isn't really any new information here that isn't captured elsewhere.

51. Johnson, C.W. and Buffler, S. 2008. Riparian buffer design guidelines for water quality and wildlife habitat functions on agricultural landscapes in the intermountain west. *Gen. Tech. Report RMRS-GTR-203*. Fort Collins, CO. U.S. Dept. of Agriculture, Forest Service, Rocky Mountain Research Station. 53p.

This reference presents a protocol for determining variable width buffers to protect water quality and habitat, specifically for farm and ranch lands in SE Oregon, southern Idaho, SW Montana, SW Wyoming, and northern Utah. The authors promote a "balanced buffer" approach that entails: a narrow semi-fixed width section; a variable width section; zones of use and use regulation; conservation recommendations for lands adjacent to the buffer. Slope, soil hydrologic group, and surface roughness are considered primary site attributes for determining buffer width. The riparian management zone is recommended to have three sub-zones. The first is a no disturbance zone closest to the stream, extending out 70ft from the mean high watermark, or top of bank/edge of floodplain/wetland plus 35ft.

Zone 1 is a no-disturbance or no-harvest zone where land uses that involve disturbance to soils or vegetation should be avoided. Many of the intended Zone 1 functions, such as bank stabilization and shading, will not operate optimally if tree or shrub removal or other land uses occur in this area.

Permitted exceptions to these recommendations include site disturbances associated with streambank, wetland, or shrub-steppe reclamation/restoration; wildlife habitat enhancement; and chemical use (spot spraying) to control invasive exotic vegetation. In addition, drift boat launch sites may be permitted, but design and specifications should be reviewed before approval to proceed.

Zone 2 has a variable width and is intended to filter sediment and other pollutants but allows for limited land use that would not degrade buffer functions. Zone 3 is outside of the buffer and includes adjacent land uses to which BMPs are recommended. The appendices address the width determination for buffers based on hydrologic soil group, slope, and surface roughness (ranging from 70 to 220ft, plus adjustments based on hydrologic features and very steep slopes), and also addresses compatible land uses for zone 2, as noted below (direct quotes).

Uses that would compromise the desired functions of Zone 2 include, but are not necessarily limited to, residential and commercial development, septic disposal systems, roads, row crop agriculture on slopes >5 percent, and unregulated grazing.

- Water quality Best Management Practices (BMPs) should be observed at all times.
- New roads and borrow pits should not be developed in buffer areas.
- No more than 40 percent of the volume of timber over 6 inches in DBH should be removed in any 10-year period from Zone 2 buffer areas
- A 35-ft no-harvest strip should be maintained adjacent to all perennial surface water features (in other words, perennial streams, ponds) in Zone 2 that are directly connected by surface flow to the in-stream resource being protected.
- Harvesting operations in Zone 2 buffers should be curtailed when harvesting equipment creates significant soil disturbance (for example, mineral soils are exposed, or sheet and rill erosion is evidenced). Operations should be limited to periods when the soils are frozen solid.
- Agriculture should be limited to the production of sod forming grasses or alfalfa on slopes <5 percent.
- All grazing in Zone 2 should be seasonal, of short duration, and observe best range management practices. Cattle watering facilities should be located outside Zone 2. If impractical, river access should be fenced and armored at the stream bank edge.
- If significant soil disturbance should occur, remediation should be undertaken immediately with logging slash and other appropriate materials. Remediation should

accomplish restoring conditions to the point where they are functionally similar to the predisturbance condition.

Zone 3 optional Recommendations (direct quote)

"Irrigated and non-irrigated crops, grazing, and increasing exurban residential development are predominant uses. Research has shown that implementation of BMP (field borders, buffer strips, filter strips, grassed waterways, storm water management, and other NRCS practices) can significantly reduce sediments and pollutants originating with these land uses (Schnepf and Cox 2006). Thus, BMPs are recommended for Zone 3 to protect long-term buffer functional efficiency."

52. Knutson, K.L, and Naef, V.L. 1997. Management recommendations for Washington's priority habitats: riparian. WA Dept. of Fish and Wildlife. Olympia, WA. 181pp.

This is the older version of the priority habitat and species guidance for riparian areas and has been superseded by the more recent PHS reference: Riparian Ecosystems, Volume 2: Management Recommendations. 2020. Amy Windrope, Timothy Quinn, Keith Folkerts, and Terra Rentz. A Priority Habitat and Species Document of the Washington Department of Fish and Wildlife, Olympia.

53. Krutz, L.J., Senseman, S.A., Zablotowicz, R.M., and Matocha, M.A. 2005. Reducing herbicide runoff from agricultural fields with vegetative filter strips: a review. *Weed Science*, 53: 353-367.

This article reviews studies of herbicide retention in buffers. Notable quotes: "There is a direct correlation between nominal inflow concentration and the retention of herbicides transported in the dissolved phase of surface runoff. Consequently, at higher inflow concentrations, the probability of herbicide–sorbent contact increases resulting in greater retention by a sorption mechanism. This is significant in that it may be invalid to compare the retention of different herbicides by VFS when their nominal inflow concentration cannot be controlled (i.e., experiments whereby herbicide is applied to a source area)." "Herbicides entering the VFS are retained by sedimentation, infiltration, and sorption to leaves, stems, and thatch." "…elevated levels of organic carbon in VFS soil will not significantly reduce the mobility of herbicides or herbicide metabolites (or both) that are ionic or considerably polar (or both) because factors other than OM control their sorption (i.e., clay mineral surfaces, iron oxides, etc.)" "In most studies, microbial numbers, microbial activity, and soil enzymatic activity are generally higher in VFS soil compared with adjacent CS." "In most instances, researchers have reported enhanced degradation of herbicides in VFS compared with adjacent CS [crop soil]." "The relationship between the retention of strongly sorbed herbicides and VFS width is nonlinear with substantial retention occurring in the first few meters but curtailing sharply as width increases beyond approximately 5 m."

Uptake of herbicides by buffer vegetation is a topic needing more study.

54. Lacas, J-G., Voltz, M., Gouy, V., Carluer, N., and Gril, J-J. 2005. Using grassed strips to limit pesticide transfer to surface water: a review. *Agron. Sustain. Dev*. 25. 253 -266.

This is a review of pesticide retention in grassed buffers. Results of studies using simulated flow conditions may not be representative of what happens under actual field conditions. The article covers infiltration, sedimentation, dilution, and adsorption as processes affecting pesticide transport through buffers. The authors assert that more study is needed about what happens to pesticides captured in buffers. They state that research should include pesticide degradation products and should examine transport in subsurface flow. In France, the following buffer guidelines for pesticides have been recommended: for diffuse runoff, 10m wide buffers for hillslope lengths less than 100m, and 20m for slope lengths greater than 100m; for concentrated runoff, flows should be directed through grassed waterways, and should be stepped if the contributing area is greater than approx. 100 hectares. NRCS guidelines for addressing pesticides are cited in the article as being a 50ft buffer having a 50% effectiveness.

55. Lammers-Helps, H., and Robinson, D.M. 1991. Literature review pertaining to buffer strips. Soil and Water Conservation Information Bureau. University of Guelph. Guelph, Ontario.

This is a somewhat outdated literature review that discusses results of studies already included in Ecology's primary literature annotated bibliography. The importance of buffer soil characteristics is glossed over, which is a major flaw of the review.

56. Larson, L.L., Larson, S.L. 1996. Riparian shade and stream temperature: a perspective. *Rangelands.* 18: 149-152.

This article discusses processes and conditions affecting shading and heating of streams. The authors assert that shade does not control stream temperature (subsequent research has shown that although shade doesn't "control" water temperature, it is one of the most important factors influencing maximum water temperatures in small to mid-size streams) The authors assert that shade objectives should establish the amount of total shade needed (i.e. by vegetation and topography) instead of the quantity and size of woody vegetation because shading potential varies by stream size, channel orientation, and vegetation type.

57. Leinenbach, P., McFadden, G., and Torgerson, C. 2013. Effects of riparian management strategies on stream temperature. Unpublished. Science review team temperature subgroup of the Interagency Coordinating Subgroup.

This report reviews factors influencing temperature in streams as well as studies that examine the effects on shade and temperature from various riparian forest management strategies.

58. Liu, Y, Engel, B.A., Flanagan, D.C., Gitau, M.W., McMillan, S.K., and Chaubey, I. 2017. A review on effectiveness of best management practices in improving hydrology and water quality; needs and opportunities. *Science of the Total Environment*. 601-602. 580-593.

This article examines the current knowledge of BMP effectiveness and identifies important knowledge gaps. Stated knowledge gaps include: "Few studies have documented longterm BMP efficiencies on water quantity and quality; Most simulation efforts have assumed constant long-term BMP performance; Efficiencies of BMPs likely change over time irrespective of maintenance; Limited empirical data have been collected to describe the

performance of BMPs". "Results frommultiple studies in the review paper indicated that buffer strips reduced runoff volume by 0 to 100% (average 45%), sediment by 2 to 100% (average 76%), weakly sorbed pesticides by 0 to 100% (average 61%), moderately sorbed pesticides by 0 to 100% (average 63%), and strongly sorbed pesticides by 53 to 100% (average 76%)." "Negative efficiency values were found for buffer strips in

reducing DRP, riparian wetlands and floodplains recharged with surface water in reducing TP and DRP, and riparian wetlands and floodplains treating agricultural tile drainage water in reducing TP and DRP." Their review found median load reductions for vegetative filter strips of 63% for TP, 65% for TN, and 83% for TSS (median buffer widths were not reported).

59. May, C.W. 2003. Stream-Riparian Ecosystems in the Puget Sound lowland Eco-region. A review of best available science. *Watershed Ecology, LLC*.

    This publication presents an extensive review of the scientific literature on riparian buffers and management zones (RMZ). Buffers are defined as vegetated strips that are in addition to the RMZ and help protect the ecological functions within the RMZ. The author generally recommends minimum RMZs of: 30m for sediment removal and erosion control; 30m for nonpoint pollutant removal; 1 SPTH (~50m) for LWD recruitment; 30m for water temperature regulation; 100m for wildlife habitat; and 100m for microclimate. It is noted that "A larger RMZ and buffer may be required in specific cases, including, but not limited to, areas with steep slopes, active floodplain systems, and streams contiguous with wetlands." For streams in ravines, the author suggests that the RMZ should extend to the upper break in slope, and from that point a buffer should be implemented in order to help prevent mass wasting of ravine slopes.

60. Mayer, P.M., Reynolds, Jr. S.K., Canfield, T.J., and McCutchen, M.D. 2005. Riparian buffer width, vegetative cover, and nitrogen removal effectiveness: a review of current science and regulations. *EPA/600/R-05/118*. U.S. Environmental Protection Agency. Cincinnati, OH.

    From the summary and conclusions: *"Buffers extending along the length of both stream banks and in which there is prolonged contact time with the root zone will offer greater likelihood of nitrogen uptake by plants. Buffers will be most effective at controlling nitrogen through denitrification when 1) water flow (overland and subsurface) is evenly distributed and soil infiltration rates are high, 2) anaerobic (saturated) conditions persist in the subsurface, and 3) sufficient organic carbon is present. Therefore, to maintain maximum effectiveness, buffer integrity should be protected against soil compaction, loss of vegetation, and stream incision. Maintaining buffers around stream headwaters will likely be most effective at maintaining overall watershed water quality while restoring degraded riparian zones, and stream channels may improve nitrogen removal capacity."* For more info, see the associated publication, Mayer et al., 2007, in the primary literature annotated bibliography.

61. Merrill, A. and Clancy, M. 2014. Kittitas SMP: Rationale and explanation for proposed wetland buffers. Memorandum. Environmental Science Associates. Seattle, WA.

    This a review of scientific literature on wetland buffer widths, and evaluation/recommendations addressing adjustments to buffers in Kittitas County's SMP.

62. Moore, D.R., D.L. Spittlehouse, and A. Story. 2005. Riparian Microclimate and Stream Temperature Response to Forest harvesting: A Review. *Journal of the American Water Resource Association*. 41(4):813-834.

This is a somewhat lengthy review of processes affecting stream temperatures, and how forest harvesting affects riparian microclimate and stream temperatures. *"Forest harvesting can increase solar radiation in the riparian zone as well as wind speed and exposure to air advected from clearings, typically causing increases in summertime air, soil, and stream temperatures and decreases in relative humidity… Edge effects penetrating into a buffer generally decline rapidly within about one tree height into the forest under most circumstances. Solar radiation, soil temperature, and wind speed appear to adjust to forest conditions more rapidly than air temperature and relative humidity."* In comparison to areas without tree canopy, surface and shallow subsurface temperatures of soils below forest canopy have been observed to be as much as 10 to 15°C lower during the day and 1 to 2°C higher at night. Microclimate differences between outside of a forested stand to inside of the forest stand are generally no longer observable at a distance of 15 to 60m into the forest stand. The authors suggest that in forestlands, buffer widths equal to one-tree height "should be reasonably effective" at minimizing the effects of logging on riparian microclimate and stream temperature.

63. Mosley, J.C., Cook, P.S., Griffis, A.J. and O' Laughlin, J. 1997. Guidelines for managing cattle grazing in riparian areas to protect water quality: review of research and best management practices policy. *Report No. 15.* Idaho Forest, Wildlife, and Range Policy Analysis Group. University of Idaho, Moscow, ID.

Contains very little useful info on buffer effectiveness but does provide a fair amount of info on grazing impacts to riparian areas and how to go about developing a grazing plan to reduce impacts, it does not minimize them, to riparian areas.

64. Naiman, R.J. and Descamps, H. 1997. The ecology of interfaces: riparian zones. Annual Review of Ecology and Systematics. Vol. 28: 621-658.

This is an extensive overview of the ecological functions of riparian zones.

65. National Council of the Paper Industry for Air and Stream Improvement, Inc. 1994. Forests as nonpoint sources of pollution, and effectiveness of best management practices. *Technical Bulletin No. 672*. NCPIASI. New York, N.Y.

This bulletin provides an overview of ways in which logging may potentially influence water quality and aquatic habitat. The literature review implies that buffers are necessary to protect streams, but there is surprisingly little useful information about buffer effectiveness.

66. Osborne, L.L. and Kovacic, D.A. 1993. Riparian vegetated buffer strips in water-quality restoration and stream management. *Freshwater Biology*. 29: 243-258

This study found reductions in the concentrations of N and P as shallow groundwater traversed a 39m grassed and a 16m forested buffer (up to 90%). Their evidence suggested that denitrification was greater in forested buffers and that both grass and forest buffers

temporarily uptake and store phosphorous, although the forests appeared to retain less than the grassed buffers.

67. Parkyn, S. 2004. Review of Riparian Buffer Effectiveness. MAF Technical Paper No. 2004/05. Prepared for the Ministry of Agriculture and Forestry. Wellington, NZ.

    Parkyn presents a lengthy review of buffer effectiveness. It is suggested that buffers of 10 to 20m can fulfill most intended functions, including moderate to high pollutant removal, self-sustaining vegetation communities with minimal weed control, and aquatic functions such as facilitating habitat development.

68. Polyakov, V., Fares, A., and Ryder, M.H. 2005. Precision riparian buffers for the control of nonpoint source pollutant loading into surface water: a review. *Environmental Review*. 13: 129-144.

    This paper is about optimizing buffer effectiveness by adjusting their size and placement relative to site specific spatial and temporal variability. The article points out that using buffer area ratio to predict buffer effectiveness has worked under field conditions where the ratio was developed, but it has been found to provide inaccurate effectiveness estimates in areas where conditions are different. One of the basic premises of precision buffers is that surface and subsurface runoff within a watershed does not uniformly enter the entire length of riparian areas. A second is that runoff infiltration rates for soils are often critical for buffer effectiveness and these rates can have high spatial variability. A third premise is that subsurface conditions in riparian areas affects what happens to pollutants being transported in subsurface flow (e.g., denitrification rates for nitrate), and these conditions are often non-uniform (e.g., variability in soil permeability, storage capacity, preferential flow paths, etc.). A fourth premise is that we can use watershed data to estimate where runoff is more likely to develop, where erosion is more likely to occur, and where buffer effectiveness is likely to be greater (e.g., identification of portions of riparian areas that are more likely to become saturated and thus have a higher denitrification rate).

    An argument is made that just as BMPs are adjusted to address variability in upland conditions, so too should buffers be adjusted to address spatial and temporal variability in conditions that affect pollutant capture. The author argues that in this regard, variable width buffers are likely to be more efficient than fixed width buffers. Area and slope indices can be used to determine where runoff is likely to converge or diverge, and thus can be used to determine where buffers should be wider or narrower. The author notes that there should be a balance between buffer optimization and buffer feasibility in order to make the system practical since focusing on identifying “hot spots” at a fine scale can produce buffer widths that are too highly variable to be practically implemented. Since different sections of buffers have different pollutant abatement efficiencies, it may be desirable to prioritize buffers where they would have a relatively low cost, but high environmental benefit.

69. Poole, G.C. and C.H. Berman. 2001. An ecological perspective on in-stream temperature: Natural heat dynamics and mechanisms of human-caused thermal degradation. *Environmental Management* 27(6):787-802.

This is a discussion of the external drivers of stream heating and the factors that buffer stream temperature.

70. Poole, G.C., Risley, J. and Hicks, M. 2001. Issue Paper. Spatial and Temporal Patterns of Stream Temperature (Revised). Prepared as Part of Region 10 Temperature Water Quality Criteria Guidance Development Project. United States Environmental Protection Agency, EPA-910-D-01-003, Oct 2001.

Abstract: "Stream temperature is an aspect of water quality that affects every aquatic organism. Yet taking that temperature is not as easy as it may seem. Placing a thermometer in a stream and recording the reading are simple enough. The problem is that the result does not represent the entire stream, whose temperatures vary markedly over both time and location. Instead of a single measurement, what is needed is a set of measures that describes a stream's "temperature regime." Even then, the process is complicated. Many factors affect the temperature regime, including climate, riparian or stream bank vegetation, and channel form and structure. The factors with the strongest influence vary from time to time and place to place. What's more, patterns of variation in stream temperature differ depending on the timescale of observation and the size of the area within which temperature is measured. For instance, Variation in stream temperature over a single day is apt to differ from variation over an entire year. Similarly, the patterns of temperature observed within a single pool or riffle in a stream are apt to differ completely from the patterns observed along the entire stream course. Stream temperature regimes are difficult to quantify, but available evidence suggests that stream temperature regimes in the Pacific Northwest are now typically different from those that existed before Euro-Americans settled the region. Evidence further shows that a variety of human activities often are responsible for changes in temperature regimes over time and that the effects of human activities often ae cumulative: individual land use activities that alone would not substantially alter stream temperature can do so when combine with other activities or with natural disturbances. Alteration of these regimes in turn may contribute to a decline in the family of fish known as salmonids, which until recently has successfully adapted to historical variations in stream temperature. In many streams where large salmon runs once were typical, the temperature regimes no appear inhospitable. Thus, from a scientific perspective, restoration of temperature regimes compatible with desired populations is an important factor in their recovery."

71. Pullin, A.S., and Stewart, G.B. 2006. Guidelines for systematic review in conservation and environmental management. *Conservation Biology*, Vol. 20, No. 6. 1647-1656.

This paper describes protocols for applying an evidence-based framework to systematic reviews of conservation and environmental issues.

72. Quinn, T., Wilhere, G., and Krueger, K. (Managing Editors). 2018. Riparian Ecosystems, Volume 1: Science synthesis and management implications. 2018. A Priority Habitat and Species Document of the Washington Department of Fish and Wildlife, Olympia.

This document describes the value and functions of riparian zones. The authors conclude that in areas with riparian forest potential, a buffer width equal to one site-potential tree

height will fully protect riparian functions (including WQ protection) and associated contribution to aquatic habitat. In areas without riparian forest potential, the authors conclude that a buffer width of 100ft should protect riparian functions and aquatic habitat.

73. Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., and Yoder,.C. 1997. Predicting soil erosion by water: a guide to conservation planning with the revised universal soil loss equation (RUSLE). 1997. U.S. Dept. of Agriculture, Agricultural Handbook No. 703, 404pp.

    This is a guide for evaluating soil erosion. Surface flow typically becomes concentrated after a slope length of <400ft. "Where erosion and deposition rates are low and erosion has not recently occurred, deposition begins at the point where slope has decreased to about 5%."

74. Schultz, R.C., Isenhart, T.M., Simpkins, W.W., and Colletti, J.P. 2004. Riparian forest buffers in Agroecosystems – lessons learned from the Bear Creek Watershed, central Iowa, USA. *Agroforestry Systems*. 61: 35-50.

    This document discusses considerations for buffer design and implementation in agricultural areas with an emphasis on a 3-zone buffer. A list of common landowner concerns related to buffers as well as list of field assessment questions are presented. The authors identified landowner reluctance to install 3 zone buffers because they didn't want trees falling into streams and slowing down water that they thought should be drained rapidly from the landscape. The authors go on to describe a modification to the three-zone buffer in which three zones are retained, but depending on the circumstances, differing combinations of grass, shrub, and tree zones are used. Differing situations in which alternative buffer designs may be used are discussed. Buffer planting and maintenance considerations are also discussed.

    The article notes the numerous buffer related studies in the Bear Creek watershed and notes the following major conclusions (direct quote):

    a. A 7-m wide native-grass filter can reduce sediment loss by more than 95% and total nitrogen and phosphorus and nitrate and phosphate in the surface runoffby more than 60%. Adding a 9-m wide woody-buffer results in removal of 97% of the sediment and 80% of the nutrients. There also is a 20% increase in the removal of soluble nutrients with the added width.
    b. Water can infiltrate up to five times faster in restored six-year-old buffers than in row cropped fields or heavily grazed pastures.
    c. Soils in riparian buffers contain up to 66% more total organic carbon in the top 50 cm than crop field soils. Poplar hybrids (Populus spp.) and switchgrass living, and dead biomass sequester 3000 and 800 kg C ha^{-1} yr^{-1} and immobilize 37 and 16 kg N ha^{-1} yr^{-1}, respectively. Riparian buffers have more than eight times more below ground biomass than adjacent crop fields.
    d. Buffers show a 2.5-fold increase in soil microbial biomass and a four-fold increase in denitrification in the surface 50 cm of soil when compared to crop field soils of the same mapping unit.

e. Tracer tests and isotope evidence shows that denitrification is the major groundwater nitrate removal mechanism in the buffers.

f. Stratigraphy below buffers can determine the effectiveness of nutrient removal from shallow groundwater. With a shallow confining layer of till below a loamy root zone buffers can remove up to 90% of the nitrate in groundwater. When the confining layer is found well below the rooting zone and porous sand and gravel are found between the till and the loam, residence time and contact with roots is dramatically reduced and buffers are unable to remove much nitrate from the groundwater. The difficulty in describing the stratigraphy below buffers makes it difficult to quantify the role that specific buffers might play in remediating agricultural chemicals in groundwater.

g. Buffered stream banks lose up to 80% less soil than row cropped or heavily grazed stream banks.

h. Riparian buffers can reach maximum efficiency for sediment removal in as little as 5 years and nutrient removal in as little as 10–15 years.

i. Streamside buffers cannot remove materials from field drainage tiles. But an acre of tile–intercepting wetland can remove 20–40 tons of N over a period of 60 years.

j. Stream segments with extended buffers exhibit greater stream substrate and fish species diversity. Vole and mouse species common to the region strongly prefer riparian forest buffers with prairie grass and forb zones instead of introduced cool-season grass zones. Riparian forest buffers support five times as many bird species as row-cropped or heavily grazed riparian areas.

k. To have a significant effect on stream water quality continuous riparian buffers should be placed high up in the watershed.

l. Eighty percent of farmers and town's people agree that buffers are an effective tool for improving stream water quality. These same persons believe that water quality in streams should be improved by 40%.

m. Ninety percent of financial agents who appraise agricultural land and lend money to farmers believe buffers are a net asset when considering market (financial) and nonmarket (conservation, aesthetic, environmental, etc.) benefits and government assistance. When market benefits exclusively are considered, only 46% think that buffers are 'a net asset.'

n. Buffers enhance recreational opportunities. Fishing, hunting and watching wildlife are popular uses.

75. Sharpley, A.N. 2000. Practical and innovative measures for the control of agricultural phosphorus losses to water: an overview. *J. Environ. Qual.* 29:1-9.

This article discusses the issue of excess phosphorous on ag lands and discusses some of the ways to address it in order to protect water quality. Along with other traditional conservation practices, buffers are more effective at addressing particulate P. Runoff containing P that is infiltrated into the subsurface may continue to be transported if soils have high hydraulic conductivity or if macropore or drain tile flow is significant. The authors assert that BMPs should focus on hydrologically active source areas, but that effectively controlling P exports likely requires seeking to balance the P inputs onto a farm with the P removed from the farm in agricultural products.

76. Sheldon, D., T. Hruby, P. Johnson, K. Harper, A. McMillan, T. Granger, S. Stanley, and E. Stockdale. March 2005. Wetlands in Washington State - Volume 1: A Synthesis of the Science. Washington State Department of Ecology. Publication #05-06-006. Olympia, WA.

This is a very lengthy document that includes a review of wetland types and functions, effects of land use on wetlands, and effectiveness of buffers at protecting wetland functions.

"McMillan (2000) recommends an approach to determining buffers that attempts to balance predictability with flexibility by setting standard buffer widths that can be altered on a case-by-case basis to adapt to site-specific factors. This approach for determining buffer width incorporates a rating system for wetlands, plus an assessment of the intensity of proposed or existing adjacent land use, to establish buffer widths ranging from 25 to 350 feet (8 to 107 m). It is perhaps the method that is closest to fitting the four bulleted criteria outlined at the beginning of this section. It incorporates an understanding of the condition of the wetland, the buffer, and the proposed adjacent land use."

The document mentions the USDA 3-zone buffer and notes that it is recommended for agricultural parcels.

From the summary of key points on buffers (direct quote):

- Many researchers have recommended using four basic criteria to determine the width of a buffer:
  – the functions and values of the aquatic resource to be protected by the buffer
  – the characteristics of the buffer itself and of the watershed contributing to the aquatic resource
  – the intensity of the adjacent land use (or proposed land use) and the expected impacts that result from that land use
  – the specific functions that the buffer is supposed to provide including the targeted species to be managed and an understanding of their habitat needs
- Protecting wildlife habitat functions of wetlands generally requires larger buffers than protecting water quality functions of wetlands
- Effective buffer widths should be based on the above factors. They generally should range from:
  25 to 75 feet (8 to 23 m) for wetlands with minimal habitat functions and low-intensity land uses adjacent to the wetland
  75 to 150 feet (15 to 46 m) for wetlands with moderate habitat functions and moderate or high-intensity land uses adjacent to the wetland
  150 to 300+ feet (46 to 92+ m) for wetlands with high habitat functions,

regardless of the intensity of the land uses adjacent to the wetland.

- Fixed-width buffers may not adequately address the issues of habitat fragmentation and population dynamics. Several researchers have recommended a more flexible approach that allows buffer widths to be varied depending on site-specific conditions.

77. Swanson, F.J., S.V. Gregory, J.R. Sedell, and A.G. Campbell. 1982. Land-water interactions: The riparian zone. In: *Analysis of Coniferous Forest Ecosystems in the Western United States*. US/IBP Synthesis Series 14 Stroudsburg, Pa. Hutchinson Ross Publishing Co.

    This is an overview of the ecological structure and functions of riparian ecotones in the Pacific northwest. Most of the focus is on riparian plant communities and their influence upon aquatic ecosystems.

78. Sweeney, Bernard W. and J. Denis Newbold, 2014. Streamside Forest Buffer Width Needed to Protect Stream Water Quality, Habitat, and Organisms: A Literature Review. J*ournal of the American Water Resource Association*. 50(3): 560-584.

    This is an often-cited literature review of buffer widths estimates for protecting water quality, habitat, and organisms for small streams (e.g., watershed area ≤ 100km^2). The authors analyzed data from 30 studies for nitrate removal. They found that nitrate removal was not significantly correlated with either buffer width or vegetation type. They applied a negative decay function to compare nitrate removal rates (i.e., removal per unit of buffer distance) for buffers of differing widths. This of course does not seem to appropriately account for spatial (hot spots) or temporal variability (hot moments) in denitrification/plant uptake along a buffer transect. Their resulting equation explained 37% of the variance in nitrate removal efficiency. Their buffer efficiency predictions, based on an estimated water flux of 125l/m/day, were 35% removal for 20m buffers, 48% for a 30m buffer, and 90% for a 100m buffer. According to their equations, buffer efficiency increases as water flux decreases. The median water flux for the studies they reviewed was 58l/m/day. Much caution should be applied in interpreting these results as they do not address some of the variables known to influence denitrification such as organic carbon supply and dissolved oxygen levels. Based on highly variable estimates for nitrogen removal from surface flow, the authors surmised that buffer widths from 20 to 30m "should be reasonably effective". For sediment, they found that removal; was correlated with buffer width, but not vegetation type. Their equation based on data extracted from 17 studies explained 28% of the variance in sediment removal. It appears as though they mixed suspended sediment and suspended solids data. The form of the equation they used is forced through zero (i.e. 0% removal for 0m buffers). They predicted a 64% removal for a 10m buffer, 78% at 20m, and 84% removal for a 30m buffer. As with nitrate, their sediment removal efficiencies should be viewed with caution; for example, their analysis dis not account for differences in runoff infiltration rates among studies. The authors concluded that 10m wide forested riparian areas provide "some" streambank protection, but that more study is needed using buffers of different widths. For temperature, the authors review found that 10 to 30m buffers are frequently fully protective of water temperatures. They concluded that buffers at least 20m wide can keep temperature increases within 2^{0}C of what would occur in a fully

forested watershed but estimated that buffers at least 30m wide are needed to fully protect water temperatures. Again, these estimates should be viewed with caution since they combined results from studies with potentially incomparable methodologies. For large wood, the authors concluded that a natural rate can be supplied to streams from a buffer that is generally 30m wide or equal to the height of dominant riparian trees. Similarly, their review concluded that buffers of at least 30m are needed to protect both fish and aquatic macroinvertebrate diversity and abundance. In regard to variable width buffers, the authors state that “on the basis of this review of the literature, we conclude that, although we currently have a relatively advanced scientific understanding of buffer function in some areas, the available field data are only sufficient to describe broad relationships between buffer width and function and remain inadequate for developing quantitative recommendations for defensible, variable-width buffers.”

79. Tyrrel, S.F., and Quinton, J.N. 2003. Overland flow transport of pathogens from agricultural land receiving faecal wastes. *Journal of Applied Microbiology,* 94, 87S-93S.

    This paper summarizes pathogen transport processes in overland flow but is not particularly informative.

80. USDA NRCS, 2020. Conservation Practice Standard. Riparian Forest Buffer. Code 391. National Habitat Conservation Program.

    Contains specifications, considerations, and recommendations for implementation of forested riparian buffers. For addressing sediment in runoff, and for improving terrestrial and aquatic habitat, the minimum width is 35ft (but later states that 50ft is the minimum recommended width for providing aquatic species habitat. For addressing pathogens, chemicals, pesticides, or nutrients a minimum width is 50ft is required, or the addition of an associated practice that targets the pollution concern.

81. USDA NRCS, 2014. Conservation Practice Standard. Riparian Herbaceous Cover. Code 390. National Habitat Conservation Program.

    Contains specifications, considerations, and recommendations for implementation of herbaceous riparian buffers. A 35ft minimum width is required for water quality protection. Concentrated flows and mass soil movement in the contributing area must be controlled prior to implementation.

82. USDA NRCS, 2000. Conservation buffers to reduce pesticide loss. USDA-NRCS. Including slideshow accessed 2/25/2019 at: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1044701.ppt

    This is a review of the role of buffers in preventing pesticide delivery to surface waters, along with considerations and recommendations. The results of buffer studies are discussed.

    Pesticide losses from fields without buffers can range from 1% to 10%. Pesticide capture is a function of soil adsorption potential (i.e., K_{oc}). Pesticides with K_{oc} values roughly below 500 tend to be dissolved in water more so than adsorbed to soil particles. Pesticides with a K_{oc} above 1,000 highly adsorb to soil. Buffers need to facilitate infiltration and maximize

contact of runoff with soil and vegetation for low K_{oc} pesticides. Runoff needs to move as sheetflow, not concentrated flow. Buffers are most effective on headwater streams; not much overland runoff enters 3rd order and higher streams relative to the amount of water contributed to the stream by 1st and 2nd order tributaries. Grading, level spreaders, waterbars, vegetated barriers perpendicular to runoff flow help disperse concentrated flow; natural berms along field edges promote concentrated flow. Grassed buffers should have at least 50 stems per square foot to inhibit wind and water flow, with stiff-stemmed species performing better. Factors influencing effective buffer widths for pesticides include soil type, antecedent moisture, soil structure, soil compaction, climate/weather, slope, and vegetation. “A buffer strip that achieves 100 percent removal of contaminants or completely reduces the water discharge to zero would be difficult and impractical to design and maintain. Most practical designs are based on contaminant removals of at least 50 to 60 percent (up to 80 percent for sediment) and at the same time allow some discharge at the end of the buffer.”

Under most conditions a buffer of at least 50ft is needed, with the NRCS draft standard (at the time) being a 30ft minimum to trap soil adsorbed pesticides.

> “A draft NRCS Conservation Practice Standard for Filter Strips requires a minimum flow length of 30 feet for the purpose of reducing sediment and sediment-adsorbed contaminant loadings. It also sets ratios of filter strip area to field area based on Universal Soil Loss Equation R factor values (rainfall amount and intensity) of regions: “The ratio of the field or disturbed area to the filter strip area shall be less than 70:1 in regions with USLE R factor values 0 to 35, less than 60:1 in regions with USLE R factor values 35 to 175, and less than 50:1 in regions with USLE R factor values of more than 175.” Consult the local NRCS Field Office Technical Guide for filter strip standards because these criteria vary depending on local conditions.”

Buffers require management to maintain pesticide removal effectiveness. Sediment must be periodically removed where it may influence runoff flow patterns. “The draft NRCS Conservation Practice Standard for Filter Strips requires that average sheet and rill erosion above the filter strip be less than 10 tons per acre per year.” Mowing can help control weeds, and promote vegetative growth, but mowing too short can harm buffer performance. Periodic grass/tree harvest can help manage nutrient buildup. Pesticides may injure buffer vegetation if loading is too high, with the most crucial period being during buffer vegetation establishment. Overspray of pesticides onto buffer vegetation can also be detrimental. Operators should avoid driving vehicles on buffer areas, especially during wet soil conditions. Grazing can harm buffer performance by compacting soil and removing vegetation. Any grazing should be short-term under soil moisture conditions that are favorable for growth, but not when soils are wet. Besides mowing, weed control may be achieved by spot applications of herbicides. Buffers should be managed to harbor beneficial insects. Using pesticides to control insect crop pests in the buffer should be done carefully, with intention to minimize risks to aquatic ecosystems. “Considering the relatively small load of pesticide intercepted by buffers compared to that applied to crop fields, and the

adsorption and degradation of pesticides by soil and vegetation in buffers, increased leaching of pesticides does not appear to be a significant risk from conservation buffers."

The publication also briefly discusses how to integrate buffers with other BMPs that help manage pesticide transport risks, such as integrated pest mgmt, application timing, conservation tillage, contour planting, crop rotation, terracing/sediment basins, irrigation mgmt., and managing subsurface drainage.

83. USDA NRCS. 2007. Part 630 Hydrology. National engineering handbook. Chapter 7. Hydrologic Soil Groups. 210-VI-NEH.

    Reference for information about soil hydrologic groups.

84. USDA NRCS. 2010. Part 630 Hydrology. National engineering handbook. Chapter 15. Hydrologic Soil Groups. 210-VI-NEH.

    Reference for information about shallow concentrated flow depth.

85. USFWS et al. 1999. Forest and Fish Report.

    This report was presented to the Forest Practices Board and the Governor's Salmon Recovery Office on February 22, 1999 and represents the recommendations of the authors for the development and implementation of rules, statutes and programs designed to achieve, the biologically and economically practical goals for improving and protecting riparian habitat on non-federal forestlands in Washington State.

86. Vidon, Philippe, Allan, C., Burns, D., Duval, T.P., Gurwick, N., Inamdar, S., Lowrance, R., Okay, J., Scott, D., and Sebestyen, S. 2010. Hot Spots and Hot Moments in Riparian Zones: Potential for Improved Water Quality Management. Journal of the American Water Resources Association. JAWRA 46(2):278-298.

    "The objectives of this paper are to: (1) summarize current knowledge related to the occurrence of hot phenomena (spots and moments) for a variety of chemical constituents across the stream, riparian zone, and upland continuum; (2) identify variables that control the occurrence and magnitude of hot phenomena in riparian zones for a wide array of contaminants ⁄ solutes; and (3) discuss the implications of hot phenomena for multi-pollutant riparian zone management and recognize that the effects of hot phenomena are important at the watershed scale." Hot spots for denitrification have been found in sand-peat interfaces where nitrate laden groundwater interacts with organic carbon enriched groundwater; the interface between a gravel/sand aquifer and loamy soil; glacial outwash; alluvial deposits; stream channels; hyporheic zones; streambank seeps along low gradient agricultural streams; inundated riparian forest soils. However, the occurrence of a hot spot is influenced by the rate of water flow. For P, soils with oxic conditions tend to retain P, while soils with reduced conditions are generally more likely to be hotspots of P release. For pesticides, the root zone and organic matter accumulations in riparian zones and streams are thought to be hotspots for pesticide removal. Riparian soils and wetlands are hotspots for mercury mobilization. Hot moments for pollutant transport can occur when pulses of surface or subsurface flow occur, especially where preferential flows paths exist,

infiltration is minimal, and/or concentrated flows occur. Hot moments for P can occur due to stream bank erosion. “Forms of riparian management include: (1) ‘‘denitrifying walls’’ which are strategically placed trenches that are filled with OM such as sawdust to intersect and treat NO3)-rich groundwater (Schipper et al., 2005); (2) permeable reactive barriers to remove contaminants such as NO3) and trace metals from tile drains and subsurface flows (Blowes et al., 1994, 2000); and (3) vegetation buffers that take up NO3) and lower riparian water tables to minimize overland bypass flow (Lowrance, 1998; Yamada et al., 2007). “Biogeochemical processes in riparian zones may be managed by altering the availability of reactive OM through brush management, biomass harvesting, and wood chip application (Homyak et al., 2008). Soil grading either adds or removes OM to riparian soils and has the potential to affect the removal of a variety of contaminants in riparian hot spots.” There’s a lot of detail in this paper, including a handy table, that cannot be readily summarized here.

87. Vitousek, P.M. Gosz, J.R., Grier, C.C., Melillo, J.M., Reiners, W.A., and Todd, R.L. 1979. Nitrate losses from disturbed ecosystems. *Science.* Vol 204. Pp. 469-474.

    This paper addresses the processes influencing nitrogen loss from disturbed forests. It concludes that without nitrogen uptake from vegetation, the net effect of all other nitrogen immobilization/transformation processes is insufficient to prevent high nitrate losses in response to forest cover removal.

88. Walker, S.E., Mostaghimi, S., Dillaha, T.A., and Woeste, F.E. 1990. Modeling animal wastes management practices: impacts on bacteria levels in runoff from agricultural lands. Paper No. 89-2008. *Transactions of the ASAE*. Vol. 33(3).

    The authors modeled minimum and maximum bacteria levels in runoff following a storm event after manure application to fields. They concluded that long-term manure storage is the most practical means for preventing high bacteria levels in runoff. Manure incorporation was effective, but more expensive than storage. Implementation of buffer strips alone was determined to be non-protective of water quality.

89. Wallace, C.W., G. McCarty, L. Sangchul, R.P. Brooks, T.L. Veith, P.J.A. Kleinman, and Sadeghi, A.M. 2018. Evaluating Concentrated Flowpaths in Riparian Forest Buffer Contributing Areas Using LiDAR Imagery and Topographic Metrics. Remote Sensing 10(4):614.*

    Abstract: “Riparian forest (CP22) buffers are implemented in the Chesapeake Bay Watershed to trap pollutants in surface runoff thus minimizing the amount of pollutants entering the stream network. For these buffers to function effectively, overland flow must enter the riparian zones as dispersed sheet flow to facilitate slowing, filtering, and infiltrating of surface runoff. The occurrence of concentrated flowpaths, however, is prevalent across the watershed. Concentrated flowpaths limit buffer filtration capacity by channeling overland flow through or around buffers. In this study, two topographic metrics (topographic openness and flow accumulation) were used to evaluate the occurrence of concentrated flowpaths and to derive effective CP22 contributing areas in four Long-Term Agroecosystem Research (LTAR) watersheds within the Chesapeake Bay Watershed. The study watersheds include the Tuckahoe Creek watershed (TCW) located in Maryland, and

the Spring Creek (SCW), Conewago Creek (CCW) and Mahantango Creek (MCW) watersheds located in Pennsylvania. Topographic openness identified detailed topographic variation and critical source areas in the lower relief areas while flow accumulation was better at identifying concentrated flowpaths in higher relief areas. Results also indicated that concentrated flowpaths are prevalent across all four watersheds, reducing CP22 effective contributing areas by 78% in the TCW, 54% in the SCW, 38% in the CCW and 22% in the MCW. Thus, to improve surface water quality within the Chesapeake Bay Watershed, the implementation of riparian forest buffers should be done in such a way as to mitigate the effects of concentrated flowpaths that continue to short-circuit these buffers."

90. Walter, M.T., Archibald, J.A., Buchanan, B., Dahlke, H., Easton, Z.M., Marjerison, R.d., Sharma, A.N., and Shaw, S.B. 2009. New paradigm for sizing riparian buffers to reduce risks of polluted storm water: a practical synthesis. *Journal of Irrigation and Drainage Engineering. Vol 135, No. 2.*

    This paper proposes delineating buffer based on identification of the probable location of variable source areas. The premise is that fixed-width buffer often cover areas that are unlikely to generate runoff. The method is designed mainly for dealing with dissolved pollutants, e.g., not sediment, which may require modified methodology. The authors present a method for using a rainfall-runoff model to determine the location and spatial extent of areas likely to generate runoff, and then delineate fixed and variable width buffers based on topographic considerations. Basically, the method is to calculate how much runoff typically occurs in a watershed for a given storm size (e.g., 10yr frequency storm)- which requires, then figure out where this runoff is likely to occur based on a topographic index- these become the buffered areas. This generally requires stream gauging data; without it, one would need to do some guesstimation. Buffer width sized for a given runoff amount is determined by first using an equation to determine the average and maximum runoff contributing area (using equations provided) and then dividing the contributing area by 2 times the stream length. The location of the buffers is determined using a GIS-based topographic index. The authors state that the topographic index may be improved through the use of LiDAR.

91. Thomas, J.W. et al. 1993. Forest Ecosystem Management: an ecological, economic, and social assessment. Report of the forest ecosystem management assessment team. USFS, U.S. Fish and Wildlife Service, U.S. National Marine Fisheries Service, U.S. National Park Service. U.S. Bureau of Land Management, U.S. EPA.

    This is the source of the original FEMAT curves depicting riparian function as it relates to site potential tree height. These curves (pg V-28) are conceptual (based on findings of a limited number of forestry studies) and are not directly derived from quantitative data.

92. Washington Sea Grant. 2009. Protection of marine riparian functions in Puget Sound, Washington. Prepared for Washington Department of Fish and Wildlife. WDFW agreement 08-1185.

    This lengthy publication reviews the science and management of marine riparian areas for the purpose of protecting ecological functions. The target was 80-100% effectiveness at protecting functions. The authors adapted the USFS FEMAT curves to apply to marine riparian areas. The minimum approximate buffer widths based on these curves were: 82ft for sediment; 197ft for TSS; 197ft for nitrogen; 279 ft for phosphorus; 121ft for shade; 131ft for large wood; 79ft for litterfall.

93. Wenger, S. 1999. A review of the scientific literature on riparian buffer width, extent, and vegetation. Institute of Ecology. University of Georgia. Athens, GA.

This is an often-cited review of the scientific literature on buffer effectiveness. It examined many of the same literature sources contained in Ecology's bibliography. Three buffer guideline options are presented. The first and most protective option is a 100ft buffer plus 2ft per 1% of slope (slopes >25% and impervious surface don't count toward the width), extended to the edge of the floodplain, expanded to include adjacent wetlands, applied to all perennial and intermittent streams; the second option of moderate protection is the same as the first except that the base width is 50ft, the entire floodplain is not included, either excludes ephemeral streams or applies only to 2nd order and larger perennial and intermittent streams; option 3 is a 100ft fixed width buffer applied to all streams at 1:24000 scale, or perennial and intermittent streams 2nd order and greater. All options call for native forest vegetation and exclusion of major sources of pollution- impervious surface, dirt roads, mining, septic drain fields, crop fields, waste disposal sites, livestock, clearcutting.

94. Windrope, A., Quinn, T., Folkerts, K., and Rentz, T. 2020. Riparian Ecosystems, Volume 2: Management recommendations. A Priority Habitat and Species Document of the Washington Department of Fish and Wildlife. WDFW, Olympia.

This is the second volume of WDFW's priority habitat and species guidance for riparian areas. The focus is upon management actions within the riparian management zone. This document is detailed and cannot be readily summarized here.

95. Windrope, A., Quinn, T., Folkerts, K., and Rentz, T. 2020. Riparian Ecosystems, Volume 2: Management recommendations. A Priority Habitat and Species Document of the Washington Department of Fish and Wildlife. WDFW, Olympia.

This is the second volume of WDFW's priority habitat and species guidance for riparian areas. The focus is upon management actions within the riparian management zone. This document is detailed and cannot be readily summarized here.

96. Winger, P.V. 1986. Forested wetlands of the southeast: review of major characteristics and role in maintaining water quality. *Resource Publication 163*. U.S. Dept. of Interior, Fish and Wildlife Service. Washington, D.C.

This report reviews the functions of forested wetlands, with a focus on the southeastern U.S. There is an interesting table estimating pesticide degradation rates under aerobic and anaerobic conditions.

97. Wyman, S., D. Bailey, M. Borman, S. Cote, J. Eisner, W. Elmore, B. Leinard, S. Leonard, F. Reed, S. Swanson, L. Van Riper, T. Westfall, R. Wiley, and A. Winward. 2006. Riparian area management: Grazing management processes and strategies for riparian-wetland areas.

Technical Reference 1737-20. BLM/ST/ST-06/002+1737. U.S. Department of the Interior, Bureau of Land Management, National Science and Technology Center, Denver, CO. 105 pp.

This is a general guide for developing livestock grazing plans and strategies that are compatible with riparian area ecological functions.

98. Xiang, W-N. 1993. Application of a GIS-based stream buffer generation model to environmental policy evaluation. *Environmental Management*. Vol. 17, No. 6, pp. 817-827.

This article presents a GIS method for variable width buffer delineation along with a case study demonstrating its implementation. The main parameters in the model were soil moisture capacity, saturated hydraulic conductivity, buffer width, Manning's roughness coefficient, and slope. Buffers of ~50ft were deemed appropriate for less than 10% of parcels (and inadequate for 87.1% of parcels; buffers of 120ft were deemed appropriate for less than 18% of parcels (and excessive for 35.3 – 41.9% of parcels). This suggests that there is a distribution of appropriate buffer widths for a watershed, with a median width that is too wide for ½ of the parcels and not wide enough for ½ of the parcels. It was noted that the GIS method cannot delineate optimum buffer width, that is, maximize environmental protection and minimize consequences to land development.

99. Yuan, Y., Bingner, R.L., and Locke, M.A. 2009. A review of effectiveness of vegetative buffers on sediment trapping in agricultural areas. *Ecohydrology*. 2, 321-336.

This paper reviews the literature on sediment removal effectiveness for buffers and presents a quantitative evaluation of effectiveness. Most of the research evaluated is included in the Ecology annotated bibliography. Sediment trapping efficiency was >80% for all buffer widths greater than roughly 5m. Based on their equation, a 95% sediment removal rate would require a buffer of approximately 45m in width, which does not seem supported by the body of effectiveness studies. The authors found a weak relationship between slope and sediment removal, and no relationship between vegetation type and sediment removal.

Section 4: Tertiary Sources (grey literature) Relevant to Riparian Management Zones

1. Barnowe-Meyer, S., Bilby, R., Groom, J., Lunde, C., Richardson, J., and Stednick, J. 2021. Review of current and proposed riparian management zone prescriptions in meeting westside Washington State antidegradation temperature standards. Draft report. Technical Type Np Prescription Workgroup. Prepared for the Timber, Fish, and Wildlife Policy Committee. Forest Practices Adaptive Management Program. State of Washington. Dept. of Natural Resources.

This report explores buffer alternatives intended to minimize water temperature increase on non-fish bearing streams in forestlands. The authors estimate that to minimize temperature increases shade loss to streams associated with tree harvest needs to be kept below 7%. A 0% shade loss is estimated to require an average buffer width of approximately 105ft (90% credible interval of 75 to >120ft) It is also estimated that keeping temperature increases below 0.3°C would require buffers of 75ft average width, with a 90% credible

interval of 60 to 95ft. A 0°C increase is estimated to require a minimum average buffer width of 80ft.

2. Bavins, M., Couchman, D., and Beumer, J. (2000) *Fisheries Guidelines for Fish Habitat Buffer Zones*. Fish Habitat Guideline FHG 003. Department of Primary Industries, Queensland, Australia, 37 pp.

   This document provides guidelines for establishing riparian buffers in Australia, from the standpoint of helping to protect fisheries. General guidelines for buffer widths to protect specific functions are provided, but the guidelines are not based on a limited review of the research.

3. Bentrup, G. 2008. Conservation buffers: design guidelines for buffers, corridors, and greenways. *Gen. Tech. Rep. SRS-109*. Asheville, NC: Department of Agriculture, Forest Service, Southern Research Station. 110 p.

   This publication provides general guidance on the establishment of buffers (and corridors and greenways). Buffers should be narrower where surface runoff diverges and wider where it converges. Lower buffer area ratios (e.g. 20:1) tend to be more effective than higher ratios (e.g. 50:1). Areas with steeper slopes and finer textured soils typically need wider buffers. Phosphorus should not be trapped in portions of a buffer where floods may mobilize it. Dissolved P is not effectively removed from shallow groundwater. Buffers along incised streams may not intercept groundwater, but there may be other areas where the GW is shallow enough that a buffer may help. A buffer width design tool and instructions for use is provided (based on the published literature of Dosskey et al. 2008). A 100ft buffer width is the minimum recommended to inhibit tree windthrow, provide large wood, promote aquatic species diversity, and help protect stream temperature regimes. The minimum riparian buffer width for ground-based pesticide applications is 20ft (up to 100ft), for aerial application, 80ft (up to 500ft). To attenuate floods, the buffer should cover the entire floodplain.

   Direct quotes of select information:

General management considerations

- Manage land to reduce runoff and increase infiltration.
- Maintain vegetative cover as much as possible.
- Avoid potentially polluting activities on areas most prone to generating significant runoff.
- Minimize potentially polluting activities during times of year most prone to generating runoff.
- Use a system of upland buffers to reduce runoff and pollutant load to riparian buffers.

General targeting considerations

- Riparian buffers will often be more effective along small or low-order streams than larger or high-order streams since most water delivered to channels from uplands enters along low-order streams.
- Groundwater recharge areas, ephemeral channels, and other areas where runoff collects are important areas to buffer.
- In some regions, surface runoff is generated primarily from areas that become saturated during storms. Where these runoff source areas correspond to a pollution loading area, such as a cultivated field, these areas should be buffered.
- Surface runoff from cultivated areas is higher where slopes are steeper, and soils are finer textured. These areas are important to buffer.
- GIS are useful for conducting landscape-scale assessments to target buffers.

Key design considerations

- Most nitrate reduction in shallow groundwater occurs within 30 to 100 feet of entering a buffer.
- The greatest nitrate removal occurs on sites where groundwater flow is confined within the root zone (shallower than about 3 feet) by a dense soil layer (aquitard) or bedrock.
- Select plants with adequate rooting depth to intercept the groundwater flow.
- Select plants tolerant of seasonal water table fluctuations and with higher root biomass.
- Because natural groundwater flow patterns can be very complex, consult with appropriate professionals.
- In areas where groundwater drainage has been augmented with drain tile pipes or ditches, groundwater flow will often bypass buffers untreated. Placing constructed wetlands at the end of tile drains or ditches can help reduce this problem.
- Incorporate topography and bank shade in the design.
- Trees and shrubs provide the most shade, but un-mowed or un-grazed grass buffers can provide shade on streams < 8 feet in width.
- Buffer shading effectiveness decreases as stream width increases.
- Windthrow may be common in buffers retained after timber harvest and wider buffers may be necessary.
- Buffers may need to be wider (150 to 1,000 feet) to maintain other microclimatic factors (e.g., soil temperature, humidity).

4. Hoffman, T. 2019. *Suncalc* online application. Accessed online at: https://www.suncalc.org/

   Useful website for calculating the shadow length of an object (e.g. tree) of a specified height at specified date and time.

5. NOAA, 1973. Precipitation-Frequency Atlas of the United States, Washington. Atlas 2, Vol. IX.

Reference for precipitation intensity/frequency numbers.

6. Palone, R.S., Todd, A.H. 1997. Chesapeake Bay riparian handbook: a guide for establishing and maintaining riparian forest buffers. NA-TP-02-97. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern State and Private Forestry.

   This is a guide for things to consider when planning and implementing buffers. Only Section VI was included in the acquired version of the document. Section I is supposed to contain a discussion of the value of 3 zone buffers.

7. Washington State Department of Ecology. Draft 2019 Stormwater Management Manual for Western Washington.

   This publication addresses standardized BMPs for addressing stormwater runoff in western WA. It is not particularly relevant for evaluating buffer effectiveness.

8. Washington State Department of Ecology. 2012 Stormwater Management Manual for Western Washington (2014 update)

   This publication addresses standardized BMPs for addressing stormwater runoff in western WA. It is not particularly relevant for evaluating buffer effectiveness. However, it does contain a useful table of soil hydrologic groups for WA soils.

9. Washington State Department of Transportation. 2006. Regional precipitation-frequency analysis and spatial mapping of precipitation for 24-hour and 2-hur durations in eastern Washington. Research Report. WA-RD 640.1

10. Welsch, D.J., 1991. Riparian forest buffers: function and design for protection and enhancement of water resources (Vol. 7). US Department of Agriculture, Forest Service, Northeastern Area, State & Private Forestry, Forest Resources Management.

    This appears to be the original reference for the USDA three-zone buffer configuration.

Chapter 12 Appendix Part B: Implementation Considerations (Riparian Areas and Surface Water Protection)

Introduction

This section includes an overview of riparian buffer implementation considerations for Washington state (WA). It focuses on implementation considerations for riparian buffers and identifying ways to encourage the voluntary adoption of riparian buffers that provide effective control of nonpoint source pollution in support of achieving and maintaining water quality standards. This guidance is applicable to riparian areas along all perennial, intermittent, and ephemeral streams located adjacent to agricultural lands within WA. This includes streams that have been modified (e.g., channelized, ditched, or straightened) for agricultural purposes. Agricultural lands include parcels upon which either commercial or hobby operations keep livestock and/or grow crops. Riparian buffers are defined as linear patches of vegetation adjacent to streams, lakes, reservoirs, or wetlands that are intended to protect aquatic ecosystems and riparian habitat from undesired effects of upland land use. Implementing and maintaining riparian buffers of protective native vegetation is critical for reducing nonpoint source pollution and protecting water quality that fully supports aquatic life, fish and shellfish harvesting, water-based recreation, and domestic water supply. Riparian buffers provide additional benefits beyond water quality such as protection from flooding and erosion, windbreaks and shade for livestock, wildlife and pollinator habitat, and insect pest control.[10] See the Effectiveness Evaluation for this chapter and Washington Department of Fish and Wildlife's (WDFW) Priority Habitats and Species (PHS) resources for more information.[11]

Some water quality practices potentially have greater value to farmers (e.g., heavy use areas, waste management, and conservation tillage) while others have less operational value despite having high environmental value. By implementing a suite of practices with riparian management zones (RMZ), especially in the context of funding programs, there is opportunity to balance relative costs to farmers. For example, a farmer may have to lose some land for RMZs but gains off-steam water and improvements to confinement areas and waste storage.

[10] Craig W. J., and Buffler, S. 2008. Riparian Buffer Design Guidelines for Water Quality and Wildlife Habitat Functions on Agricultural Landscapes in the Intermountain West.

[11] https://wdfw.wa.gov/species-habitats/at-risk/phs

This section includes information on the design, construction, and maintenance of riparian buffers. Additional information on the acceptance and resistance to riparian buffers, barriers to implementation, costs and benefits, conservation and incentive programs, related land permits, and other educational resources are provided in this section.

Information was gathered through a literature review and refined with input from the Implementation Workgroup and case study interviews.

Acceptance and Resistance

This section covers factors influencing acceptance and resistance to voluntary implementation of riparian buffers. This information is meant to inform future work by Ecology, local conservation districts (CD), local government agencies, and other partners to increase the implementation of riparian buffers.

WA has approximately 70,439 miles of rivers. GIS data could be used to estimate the length of waterways flowing across private agricultural lands or estimate acres of riparian buffers implemented on private lands. Local conservation programs may track the number of buffers implemented through their programs, which could give an indication of riparian buffers that have been implemented in WA.

Research in New York state found that landowners with forest and wetlands as primary land cover had more riparian buffer coverage than agricultural landowners.[12] In the same study, landowners with weaker perceived land use efficacy also had greater buffer coverage. Another study along the east coast found that landowners were likely to implement riparian buffers with other water quality practices if they owned larger parcels, held positive environmental attitudes, and had high environmental awareness, including knowledge of environmental quality, riparian areas, or streams.[13] Overall, existing farm infrastructure and land management practices could provide a better understanding of factors that affect voluntary adoption of riparian buffers.

Tables 43 and 44 summarize some of the barriers and motivators to adopting riparian buffers.

[12] https://link.springer.com/article/10.1007%2Fs00267-020-01271-y

[13] https://www.sciencedirect.com/science/article/abs/pii/S0169204611003628

Table 41: Barriers to adopting Riparian Buffers

Barrier	Description
Economic loss	By reallocating land to riparian buffers, landowners lose that land to production and may consequently experience economic losses.
Non-economic barriers	Small farms may be more open to diversifying revenues on their lands and enrolling in a conservation program since they "may lack the resources needed to remain viable in the long run without significant off-farm income". 50 percent of all farms are those on which the principal operator is retired or has a primary occupation other than farming. However, the voluntary adoption of riparian buffers outside existing conservation programs may be difficult for small farms in the absence of any financial incentives due to competing land use priorities. Small farmers also tend to be attached to their land since they see their farm as a residential setting.[14]
Land aesthetics and visual appearance	Riparian land is important to landowners for maintaining the visual appearance of the countryside and well-managed farm. Small residential farms may use their streamside for recreation. Some research shows that farmers prefer riparian buffers that give the appearance of neatness while forest buffers may make a farm appear overgrown.
Existing infrastructure	Existing infrastructure can be an obstacle to implementing riparian buffers. In these scenarios, landowners could implement buffers to the extent possible given barriers with existing infrastructure.

[14] R.L. Ryan, D.L. Erickson, R. De Young, Farmers' motivations for implementing conservation practices along riparian zones in a mid-western agricultural watershed, J. Environ. Plan. Manag. 46 (2003) 19–37, http://dx.doi.org/10.1080/713676702.

Table 42: Motivators to Adopting Riparian Buffers

Motivator	Description
Economic motivations	Larger commercial farms may be more focused on maximizing agricultural production and revenue. This may reduce the likelihood of allocating land for riparian buffers. However, commercial farms that are interested in demonstrating good stewardship may find it easier to implement riparian buffers if they have the necessary income or have more eligible land to enroll in conservation programs.
Environmental sensitivity	Farmers may be motivated to adopt riparian buffers to address specific issues on their land (e.g., a highly erodible land).
Proximity to salmon bearing streams	Many streams in WA are historical salmon spawning streams. Salmon serve as a "cultural icon to the native tribes, source of their subsistence, and a large commercial industry in the Northwest".[15] While the focus of this guidance is not species restoration, implementing riparian buffers can enhance water quality, improve habitat quality, and contribute to salmon recovery efforts. Farmers near sensitive streamside areas may be familiar with the importance of having cool, clean water to protect fish and be inclined to using riparian buffers. Federal, state, and local agencies, including the Department of Ecology, offer water quality grants and loans to address these specific issues.[16] Certification programs focused on fish-friendly habitat may provide incentives for voluntary adoption of riparian buffers.[17]
Interest in long-term sustainability	Farmers with greater concern for long-term sustainability may be inclined to implement conservation practices.
Exposure to information networking	Information-seeking landowners are likely to adopt conservation practices. More community outreach is necessary to promote riparian buffers and share information on other landowners' experiences. Identifying "local messengers" within the community of farmers to disseminate information could also support outreach efforts.[18]
Attachment to land	Landowners and farmers prioritize maintenance to ensure that their land can be transferred to future generations.

[15] https://whatcomwatch.org/index.php/article/nooksack-river-salmon-and-agriculture/
[16] https://ecology.wa.gov/About-us/How-we-operate/Grants-loans/Find-a-grant-or-loan/Water-Quality-grants-and-loans
[17] https://salmonsafe.org/certification/farms/
[18] G.B. Habron, Adoption of conservation practices by agricultural landowners in three Oregon watersheds, J. Soil Water Conserv. 59 (2004) 109–115

Motivator	Description
Social pressure	Social pressure could also be a key motivator, particularly when responding to local needs (e.g., protecting historically cultural places and reducing their environmental impact on the area).

Responding to specific needs on the farm also impact landowners' use of riparian buffers. These needs include:

- Soil erosion;
- Need for improved water availability/distribution;
- Herd health;
- Eliminating calving risk areas;
- And herd movement/grazing distribution.

Other factors that may influence the acceptance or resistance of riparian buffers include:[19]

- Perceived threat to landowner and developers;
- Economic loss;
- Capability of existing programs;
- Longstanding history of agencies requesting landowners to either remove or plant vegetation;
- And scientific and technical information needs.

Incentives and Barriers

Some incentives for voluntary implementation of riparian buffers include:

- Improved stock water availability, herd health, and herd movement and grazing distribution;
- Decreased risk of livestock injury;
- Cost-sharing program assistance;
- Avoiding future regulations;

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[19] https://nepis.epa.gov/Exe/ZyNET.exe/9100LE7K.TXT?ZyActionD=ZyDocument&Client=EPA&Index=1995+Thru+1999&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5Czyfiles%5CIndex%20Data%5C95thru99%5CTxt%5C00000027%5C9100LE7K.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=1&SeekPage=x&ZyPURL

- And conservation ethics.[20]

Common barriers to voluntary implementation of riparian buffers include:

- **Lack of knowledge** of the critical importance of riparian areas for water quality protection. More education may be needed as to how riparian buffers protect aquatic ecosystems and water quality.
- **Costs and resources** needed to implement and maintain the buffer. Early research indicates that the cost of implementing riparian buffers may be one of the key concerns for landowners.
- **Loss of farmable land and associated revenue** since land transitioned for riparian buffers affects revenue generation and economic stability.
- **Administrative challenges** due to specific regulatory and/or program application requirements.
- **Implementation and maintenance** since farmers may not be aware of the option to implement riparian buffers or they may lack the information about specific implementation requirements and available assistance programs.[21]
- **Agricultural land conditions** including landscape, stream gradients, harvest practices, and impacts of fixed-width riparian buffers present barriers to implementation.[22] Additionally, there are some risks with implementing riparian buffers on certain sites that experiences heavy rain or snow which can cause snow drift if there are forested hedge rows.

Benefits and Costs

Direct and Indirect Benefits

Common benefits from implementing riparian buffers, especially along headwater streams, include:

- Protection of water quality;
- Interception of non-point pollutants carried by surface water runoff and removal of excess nitrogen, phosphorus, and other pollutants that negatively impact water bodies;
- Stabilization of stream banks and reduced erosion;
- Decreased flooding and low stream flows;

[20] Whitescarver, B. 2015. Bobby's 7 Principles: Selling Riparian Forest Buffers.

[21] United States Department of Agriculture (USDA), National Resource Conservation Service (NRCS). 2002. Adoption of Conservation Buffers: Barriers and Strategies.

[22] https://salishsearestoration.org/images/f/fe/GEI_2002_agricultural_riparian_buffers.pdf

- Prevention of sedimentation in waterways;
- Prevention of harmful high temperatures through shading;
- Reduce instream nutrients and heavy metal concentrations associated with construction;[23]
- Additional food and habitat for wildlife;
- Replenished groundwater and protection of associated wetlands. [24]

In some circumstances, riparian buffers offer indirect benefits by controlling insect pest populations, protecting agricultural land from extensive flood damage, generating leaf litter with high nutrient content and soil-enriching qualities, and reducing impacts on downstream users.[25]

Direct and Indirect Costs

An industry-funded study on WA counties found that "on a per mile basis, the costs of [fixed-width] buffer zones could range between $11,000 to $81,000 for affected crops". Additionally, the total annual direct and indirect county income per 100 acres of fixed-width riparian setbacks was estimated between $190,000 and $240,000.[26] Studies in other similar regions of the U.S. estimated the annual cost of establishing and maintaining fixed-width riparian buffers at approximately $100 per acre.[27] Costs for implementation of fixed-width and variable width riparian buffers vary based on the magnitude of restoration efforts.

Opportunity Costs

Opportunity costs represent the "loss of earnings from crops/pastureland that would have otherwise been grown in place of the buffer. Landowners can calculate opportunity costs by considering other possible uses for the land where the buffer is being implemented."[28] For example, opportunities gained could include access to colder and cleaner water, improved fish habitat, access to recreation area, improved sale value of the land, and improved aesthetics.

Adopting riparian buffers can produce economic benefits for agricultural producers by improving soil stability, flood control, and water quality which can increase crop yields and reduce maintenance costs over time.[47] When comparing total cost, hydrologically adapted buffer zones were found to be more cost effective per hectare than fixed width buffers.

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[23] https://www.sciencedirect.com/science/article/abs/pii/S0169204611003628
[24] https://conservationtools.org/guides/131-the-science-behind-the-need-for-riparian-buffer-protection
[25]https://www.waterboards.ca.gov/northcoast/water_issues/programs/agricultural_lands/pdf/120402/Kallestad_and_Swandson_Riaprian_Buffers_for_Washington.pdf
[26] https://salishsearestoration.org/images/f/fe/GEI_2002_agricultural_riparian_buffers.pdf
[27] Roberts D.C. et al. Estimating Annualized Riparian Buffer Costs for the Harpeth River Watershed. Applied Economic Perspectives and Policy (2009) https://doi.org/10.1111/j.1467-9353.2009.01472.x
[28] Maryland Cooperative Extension. 2000. When a Landowner Adopts a Riparian Buffer – Benefits and Costs

Additionally, riparian buffers with wetlands and low productive forest areas allow for effective protection of RMZs that are sensitive to disturbances at no additional costs to landowners.

Case Examples

Case Study: South Fork Palouse River, Colfax, WA

Setting: The landowner's site was located southeast of Colfax, along the South Fork Palouse River. The riparian buffers were initially funded and planted in 1995 by the Palouse Conservation District (CD). Funding was also provided through the Conservation Reserve Program (CRP). The landowner was interested in using riparian buffers to help revive their land and improve aesthetics, since a lot of sediment had accumulated overtime. The landowner had not considered using riparian buffers to promote water quality and was more concerned with using buffers for protection from silt accumulation in the river. The economic loss of land was insignificant since roughly four acres were reallocated for riparian buffers.

Construction and Implementation: The CD worked with the landowner to determine which plants should be used for the riparian buffers. The CD ultimately decided which plant species would be used and the riparian buffer sizes. 200 willow posts were installed, and a mixture of pine, hawthorn, and serviceberry plants were planted. A 60-foot buffer was planted along one part of the river and a 10-foot buffer was planted on the other side of the river. Based on this experience, the landowner suggested that CDs conduct nature walks with landowners to better understand the sites and identify native plant species that are already in the area.

Maintenance: The CD continued to provide support with maintenance activities over the years and replant buffers that were damaged by flooding and/or livestock. While the CD was very reliant on funding to perform maintenance activities, their support was essential since they understood how to best maintain the riparian buffers. Since the CD covered implementation and maintenance costs, the landowner's out-of-pocket costs were allocated for routine weed control.

Challenges: Flooding between 1995 and 1996 significantly damaged the riparian buffers and replanting has been a challenge over the years. Livestock from neighboring farms would cross through fencing and trample over the buffers too. Deer and beaver predation was a consistent challenge since the dear would pull out plants and kill trees in the buffers. The landowner also noted that it would have been helpful if the riparian buffers were planted with some space for their tractor to more easily cross through.

Conclusion: Overall, the landowner shared that CDs should invest more in educating landowners on the benefits of riparian buffers since there are misconceptions about this practice. By providing resources and educations, CDs can rebuild trust among landowners and further collaborate on implementation to ensure that the buffers are tailored to landowners' priorities. By building relationships between CDs and landowners, the perception of riparian buffers and planting more trees and plants across farms could improve.

Case Study: Colfax, WA

Setting: The site is located between Colfax and Dusty, WA. The landowner worked with Whitman CD to implement riparian buffers over the past four years. Approximately 1,000 feet were allocated throughout the site for the riparian buffers and there was not any existing infrastructure that created barriers to implementation. The landowner intended to apply for funding from the Farm Service Agency (FSA) since the land was located along a potentially salmon-bearing stream, however they did not meet criteria for that funding and instead used funds from the Department of Ecology.

Construction and Implementation: The CD chose which plants to use for the buffers and worked with the landowner to determine the buffers' size. Buffers were incrementally constructed over four phases to assess performance and initially there were some challenges with acquiring enough trees for the buffers. As a result, some trees that were not well-suited for the site's conditions were planted and they have not been as effective. With this, the landowner recognized the value of choosing plants based on site conditions to ensure that they will survive. Ecology provided funding to implement a 50-foot buffer, however Ecology allowed the landowner to construct a 35-foot buffer since the land was flat for ¼ of a mile before any hillside occurred and a 50-foot buffer was not as practical. Throughout the first year, the buffers had sufficient moisture but in the past year they became too dry due to the drought.

Maintenance: Primary maintenance activities include chopping and spraying noxious weeds, identifying trees that have died, and replanting new trees. One of the buffers was recently replenished with 500 trees. Volunteers in the area have been critical to supporting the landowner with maintenance since the local CD did not provide funding and resources for maintenance activities.

Challenges: Originally, plastic ground covers were used when planting trees for the buffers, but the landowner is concerned about the degradation of plastic into their land. With this, the landowner recommended that weed suppression covers made from mulch or other biodegradable materials be used. Another challenge was encountered with constructing the off-stream watering system around the buffers. The landowner expressed challenges with having minimal follow-up from their CD for maintaining the riparian buffers over the years. With this, CDs and other agencies should equally invest in both implementation and maintenance of buffers since landowners do not have the resources and capacity.

Conclusion: The landowner has seen riparian buffers implemented differently across neighboring sites and raised the value of constructing buffers that meet landowners' needs. CDs and other agencies should support the entire implementation process by providing their expertise and construction crews to ensure that the buffers are correctly planted. Another major element for landowners to consider is constructing the buffers so that they are protected from cattle. In conclusion, the landowner recognized the effectiveness of the riparian buffers on their land, particularly with sediment control, but they are anticipating that floods will cause some damage and more buffers will be needed overtime.

Case Study: Snoqualmie Valley Agricultural Production District, WA

Setting: The landowners who shared insights for this case study participated in a pilot program in 2015 to secure funding to clean ditches on their land. The landowners were required to implement riparian buffers on their property to receive funding. They were under a farmland preservation easement which provided them with funds to farm across 100 acres. Their county conservation district and watershed improvement district provided the necessary funding and permitting for riparian buffer implementation. The agencies also provided planting incentives, including a Washington Conservation Corps crew, for riparian buffer implementation and maintenance over three years.

Construction and Implementation: When designing the riparian buffers, the landowners chose to use hedge rows. Maintaining the landowners' sight line over the hedge rows was necessary for monitoring calves during predator season. A combination of flowers were planted with the hedge rows. The landowners used guidance from their county and conservation district to determine which plants were acceptable and available.

Maintenance: The landowners were provided with funding for maintenance activities over three years. Fortunately, most of the plants were established enough to not require maintenance. The landowners continually install new plants when other plants died out.

Challenges: Throughout the implementation process, the landowners learned how communication was necessary between crew members and crew leaders to prevent implementation errors. Additionally, agency staff who led the pilot project failed to visit the landowners' site which contributed to misunderstandings with riparian buffer implementation. Another challenge was finding a contractor who understood the bureaucracy of the landowners' involvement with the pilot project, permitting processes, and funding sources. Meeting with county representatives to address questions around the permitting process became costly and contributed to delays in implementation activities. Despite best efforts, the crew provided by the pilot project could not regularly visit the site for maintenance and this hindered plant survival. The landowners were eventually assigned a new project manager who helped schedule the crew to visit more often although, plants were stunted in growth at that point.

Conclusion: The landowners recommended that other landowners and crews should regularly communicate to ensure mutual understanding of their plan for riparian buffer implementation. The landowners found it helpful to work with their conservation district when navigating the planting and permitting processes. Lastly, the landowners recommended using funds from multiple sources since this also allowed multiple agencies to be involved with the success of the farm's riparian buffers.

Riparian Area & Field Buffers Management Practices

Practice Category: Riparian Management Zone

This section covers RMZ implementation that applies to both riparian herbaceous and forest covers. RMZs are not a substitute for implementing other agricultural best management practices (BMP). A lack of BMPs can increase runoff and pollutant loads that can render RMZs ineffectual. Controlling pollutants that were generated from high intensity land uses or transported from farther away may require structural and vegetative BMPs, such as sediment control basins, terraces, and grassed waterways.

Riparian herbaceous covers are defined as dedicated buffers dominated by non-woody plants that remove pollutants from upland runoff and ensure source control in the riparian zone. They are applicable where the ecological site potential is predominantly herbaceous plants.

Riparian forest covers are defined as buffers dominated by trees and shrubs to remove pollutants from upland runoff, provide temperature control, and ensure source control in the riparian zone.

The following phases are involved in implementing either riparian herbaceous or forest covers:

1. **Establish the RMZ layout. See Ecology's buffer width and configuration recommendations.** Landowners may also consider other resource concerns, site characteristics and land conditions. Design the RMZ consistent with Ecology recommendations to address water quality issues and any other identified resource concerns. Develop the implementation plan.
2. **Site Preparation and Planting.** This step involves preparing the riparian buffer, selecting native vegetation to be planted in the riparian buffer based on site conditions, and planting the selected vegetation species mixture. Based on the initial site conditions, achieving an effective riparian buffer may range from complete revegetation on highly denuded sites to natural recruitment of plants on sites with a pre-existing native plant community having a high potential for natural recovery.
3. **Operation and Maintenance Activities.** Periodically evaluate the effectiveness and functional condition of the buffer and take necessary management actions to ensure water quality objectives are achieved. The most common causes of change in buffer function and structure include agricultural practices, urbanization, unmanaged livestock grazing, road construction, dams and diversions, wildlife, recreation, invasive species competition, and flooding.[8]

Table 3: Implementation Considerations for Riparian Herbaceous Buffers and Riparian Forest Buffers

Considerations	Details
Riparian Herbaceous Cover Applicability	Herbaceous cover buffers should be implemented where there is ecological site potential to support herbaceous (rather than tree and shrub) species as the dominant vegetation. Herbaceous cover buffers should be implemented only on sites that do not support trees and shrubs as the dominant vegetation.
Riparian Forest Cover Applicability	Forest riparian buffers can be broadly implemented across most WA regions.

Planning, Implementation, and Maintenance Cost	Please note that costs included below are indicative only. Indirect and direct costs vary between sites and are contingent on factors including land conditions, hydrology, soils, crops, practice design, management characteristics and opportunity costs.
	
	Capital costs/Net costs
	• Fixed-width riparian buffers have five primary economic costs[29]
	    ○ Cost to remove land from production
	    ○ Loss of economic benefits from agricultural production on those lands
	    ○ Costs to monitor, administer, and maintain buffers
	    ○ Loss of tax base
	    ○ Loss of economic infrastructure
	
	Planning costs
	• Costs vary with given land values, land differences, and location across western, central, and eastern Washington.
	• Costs associated with buffer practices include the land removed from production and establishing/maintaining buffers.
	• Costs associated with restoration of stream channels, bank stabilization, and/or floodplain connectivity to prepare sites for buffer implementation.
	
	Implementation costs
	• Ecology recommends a suite of BMPs be implemented to effectively control pollution. Therefore, landowners may need to consider costs to implement BMPs related to their livestock and crop field operations along with plans for buffer implementation. For example, costs related to other BMPs could include stream crossings for farm vehicles or livestock.

[29] https://salishsearestoration.org/images/f/fe/GEI_2002_agricultural_riparian_buffers.pdf

Considerations	Details

	• Costs vary if landowners engage in the buffer preparation and planting themselves and/or hire a contractor to provide machinery, provide consultation, and/or complete planting.
	• Costs are also associated with hiring licensed professionals to apply herbicides during site preparation for larger projects.[30]
	• Labor costs for planting trees and other plants should also be considered.
	  ○ Planting – Machine planting can be less expensive, and the property owner avoids having to hire laborers, who may or may not be available.[5]
	  ○ Reforestation is another affordable option although this comes with drawbacks with choosing plant and tree species.
	  ○ Plant costs:
	    ▪ Grass buffers tend to cost less than tree buffers to plant and maintain.[31]
	    ▪ Costs of trees and shrubs may vary depending on species.
	    ▪ Grasses, sedges, and rushes may have a different cost than perennials, ferns, and forbs.
	    ▪ Total number of acres planted.
	    ▪ Indicative prices of seeds[32] – Excess seedlings/container plants should be planted due to plant mortality. Planting density should approximately be 10 to 20 percent greater than the planned density for the mature buffer. Harsher site conditions will require additional planting. Whereas areas with rapid natural recruitment of plants requires less additional planting.
	• Purchase of equipment including small hand tools, chest waders and boots, brush cutters, backpack sprayers, herbicide and spraying equipment, shovels, plant maintenance/monitoring tools, and safety gear.
	• Associated livestock management costs such as fencing, water points, hardened crossings, etc. are addressed in the pasture and range management BMP guidance. Costs may be higher for establishing buffers in an area where livestock have been pastured.
	• Costs associated with local, state, and federal permitting processes.
	
	Maintenance costs
	• Treatment of weed infestations in watersheds.

[30] https://www.brandywine.org/sites/default/files/media/BrandywineConservancy-RiparianBufferGuide.pdf
[31] https://www.extension.umd.edu/sites/extension.umd.edu/files/_docs/programs/riparianbuffers/FS774.pdf
[32] http://soundnativeplants.com/nursery/retail-pricelist/?doing_wp_cron=1563214760.1066789627075195312500

Considerations	Details
	• Maintenance of pesticide records and treatment data. • Watering plants to help ensure survival. • Mulching, weed control, irrigation, animal browse protection, and replacing plants. • Cost for herbicides can range between $27-$200. Herbicide costs are based on prices of a range of chemicals used for grass control. • Re-planting if necessary. **Resources for cost estimates** • Local CDs can offer information about buffer implementation and help landowners to navigate the different stages of planning, implementation, and funding sources. In some situations, and at the landowners' request, local CDs can also conduct site visits to help with the initial site assessment. • Contractors can be hired to help with establishing the layout of the buffer zone, site preparation, planting, and maintenance of the buffer. WSU has a Consulting Forester and Silvicultural Contractor Directory[33] where landowners can find various contractor services offered across the WA State. • Other organizations including salmon recovery groups, tribes, nonprofit organizations, and other local government agencies can also support riparian restoration work.

Planning, Site Preparation, and Installation	**Planning:**
	• RMZ designs should be based on climate region (eastern WA vs. western WA); forested vs. non-forested riparian potential, channel size; and soil hydrologic group.
	• See Recommendations section for riparian buffer zone width and composition. Width recommendations vary given site-specific conditions on agricultural lands. Widths should address multiple agricultural impacts including[34]:
	  ○ Vegetation traps sediment;
	  ○ Filters pollutants;
	  ○ Retains storm water;
	  ○ Thermal protection from shade;
	  ○ And stabilizes streambanks on agricultural lands
	• The NRCS Riparian Buffer Conservation Strategy for Working Lands indicates that conservation planners will encourage adoption of buffers wider than the

[33] http://forestry.wsu.edu/consultingdirectory/
[34] https://salishsearestoration.org/images/f/fe/GEI_2002_agricultural_riparian_buffers.pdf

Considerations	Details

	minimum. Financial assistance may be provided up to 180 feet on each side of the channel for most reaches. When financial assistance program rules allow, funding for buffers exceeding 180 feet may be approved by Area and/or State specialists where the objective is to restore floodplain habitat and function.[35]
	• Evaluate site conditions to then determine which plants are most appropriate.
	  ○ Selected plant species for buffers must be tolerant of periodic flooding or saturated soils.
	  ○ Plant selection is informed by plants' abilities to improve water quality. Producers may also consider plant's ability to provide wildlife habitat.
	  ○ Riparian planting zones can be used to determine where riparian species should be planted in relation to the waterline. Riparian zones that may exist include toe zone, bank zone, overbank zone, transitional zone, upland zone. Not all waterlines look the same, so on the field, some of these zones may be absent.[36]
	• Complete necessary local, state, and federal processes and forms for restoration projects.
	• Submit necessary landowner agreements, permitting, cultural resource determinations, and/or BMP plans for restoration projects.
	
	Site Preparation:
	• Invasive vegetation should first be removed from the site to reduce competition for new native plant species. Mowing, cutting, and herbicide application can be utilized to remove invasive vegetation. Aquatic-safe herbicides are recommended.[6]
	  ○ Mowing, cutting, and herbicide application vary according to site conditions.[6]
	• Impacts on wildlife species, habitat and aesthetics should be considered when selecting site preparation methods.[37]
	• Additional activities to consider during site preparation and planting
	  ○ Soil de-compaction.
	  ○ Installation of weed suppression mats.

[35] https://efotg.sc.egov.usda.gov/references/public/WA/Strategy_for_Working_Land_Buffers_120115.pdf
[36] https://efotg.sc.egov.usda.gov/references/public/WA/TN24_RiparianPlantingGuidance.pdf
[37] https://efotg.sc.egov.usda.gov/references/public/WA/490_stnd_011607.pdf

Considerations	Details
	◦ Installation of erosion control and slope stabilization measures to protect riverbanks until native plants are established. Relevant activities include willow wattles, fascines, willow fences, or willow brush layers where bank erosion exists. ◦ Controlling access by vehicles or equipment during or after site preparation to minimize erosion, compaction, and other site impacts. **Installation:** • Ecology recommends cultivating and maintaining plant communities in the RMZ that resemble or mimic plant communities that would occur naturally in that riparian area. • The NRCS Riparian Buffer Conservation Strategy for Working Lands provides the following plant community and species recommendations based on desired buffer functions: ◦ To address overhanging vegetation, provide litter input to stream, or root stability for supporting undercut banks – use a combination of deciduous trees and shrubs with conifers ◦ To provide a source of large woody debris or crop pollinator habitat – use a combination of conifers and deciduous tree species • After selecting which plants to install, determine protective measures that need to be taken for planted species such as fencing, stream crossings and/or alternative watering sources. • Landowners may need to develop a plan to set up their draining system where they can easily access the system for future maintenance. There have been examples where the draining system was on a straight stream with drain tiles which hindered landowners from accessing the system after the buffers were planted. ◦ Furthermore, landowners should be careful with which plants are used in existing tile drained fields. For example, cottonwood was found to completely clog the drainage with roots. Note: tile drains can be a source of pollution that bypasses the buffer. • **Alternative to planting:** To minimize costs, landowners could consider using fencing or setting back land use to allow for natural reforestation. This may be appropriate where there are already some native trees and vegetation at the site. One limitation of this approach though is that landowners cannot select trees and plants for the riparian area.

Considerations	Details
Operations, Monitoring, and Maintenance	**Ongoing Maintenance Checklist** **Riparian buffers:** • Periodically inspect the condition of the riparian buffer. Evaluation of the site in the first implementation year may need to be done more frequently to monitor plant survival and ensure the buffer is evolving in line with project purposes. Vegetation monitoring should be conducted to maintain survival and reduce noxious weed species. • Implement BMPs to manage grazing in the inner and outer zones of the RMZ to protect the riparian area.[38] • Degree of establishment of planted vegetation: The goal is to have established diverse non-invasive vegetation. • Amount of tree or shrub cover. • Changes in water quality: The goal is to have cooler water temperatures with more oxygen present and to observe less algae and aquatic plants, while seeing an increase in woody debris and/or leaf packs. • Changes in bank stability: The goal is to observe less visible erosion. • Wildlife population estimates and habitat use measurements: The goal is to observe more diversity and abundance of both visiting and resident wildlife.[13] **Plant Maintenance:** • Promoting healthy plant community in the buffer will require some sort of plan which will account for site specific recommendations. Ecology recommends avoiding the use of pesticides and fertilizers in the buffer. If necessary, Ecology recommends herbicides with low toxicity to organisms or tend to be less mobile/readily stick to soil to prevent runoff. • In the first year of the planting, proper maintenance is needed to ensure survival rate. Before replanting, address the initial cause of seedling failure. ○ Common causes include vole damage (visible as girding at the base of seedlings), excessive vegetative competition (usually vines that crowd seedlings within shelters), and improper shelter maintenance (fallen shelters or shelters not sunk into soil).[39] • Backfill any patches of significant mortality with new plantings, as consistent shade discourages invasive growth.[10] • Clean out debris and control invasive plant species as needed. While the use of herbicides is generally accepted as the most effective way to maintain a

[38] https://extension.usu.edu/rangelands/ou-files/Riparian_grazing.pdf

[39] Brandywine Foundation. 2016. Forested Riparian Buffer Planting Guide for Landowners and Developers. https://www.brandywine.org/sites/default/files/media/BrandywineConservancy-RiparianBufferGuide.pdf

Considerations	Details

	newly planted buffer, those wishing to limit the use of herbicides can mulch and mow to control and remove competitive vegetation instead.[13]
	• Watering plants, replacing dead plants, controlling noxious weeds, and animal browse protection.
	
	Contractor Support:
	• Landowners can hire contractors to determine operation and maintenance plans for implemented buffers.
	• Plans should address necessary activities to allow the plant community in the buffer to mature and become vigorous.
	• Plans vary given differences across sites, but they should address these considerations:
	  ○ Impact of annual wear and tear plus and post major storm events.
	  ○ Weed control, which may include mowing, mulching, and other integrative vegetation management (IVM) techniques.
	  ○ Replanting and reseeding.
	  ○ Pruning and thinning of plants/trees as years progress.[40]
	  ○ Establish goals and objectives to achieve intended buffer outcomes. For example, quantitative objectives to measure buffer success and effectiveness over time.
	  ○ Monitoring activities to measure buffer progress and indicate whether additional actions are needed from landowners.
	
	Other Maintenance Activities:
	• Fencing: Implement, repair, and maintain exclusion fencing and continue instream habitat improvements to protect riparian forest buffers.
	• Flow erosion: Control of concentrated flow erosion or mass soil movement can be continued in the up-gradient area to maintain riparian function.
	• Other impacts:
	  ○ Control or eliminate harmful pests present on the site.
	  ○ Protect streams from direct and indirect impacts of domestic animals.[41]
	
	Monitoring Activities:
	• Project effectiveness monitoring can be used to ensure plant survival and density.

[40] Land Studies' 'Riparian Buffer Maintenance' Recommendations - https://landstudies.com/dont-just-plant-leave-alone-riparian-buffer-maintenance/

[41] https://salishsearestoration.org/images/f/fe/GEI_2002_agricultural_riparian_buffers.pdf

Considerations	Details
	• Monitoring involves addressing specific questions that provide useful information about buffer effectiveness and collecting data to inform further management action. ○ For example, if a management objective is to have 90 percent vegetative soil cover within three years, monitoring can be used to determine if additional planting is needed to achieve the management objective.
Other Activities	**Education, Outreach, and Technical Assistance** • Install educational signage at project sites. • Engage in public notification, distribution of factsheets, and meetings for residents to engage in water quality opportunities and share project updates. • Engage in informative workshops with other landowners or producers to discuss enrollment in cost-share/rental programs, buffer implementation and maintenance, and share findings from riparian buffer monitoring data. • Provide other landowners with pollution reduction recommendations and implementation guidance.
Resources	**Landowners can work with consultants, the NRCS, local CDs, and others to develop plans that involve:** • Implementation and maintenance of riparian buffers; • Native plant species mixtures for herbaceous cover in given regions; • Implementation assistance programs (technical expertise, grants, etc.); • And regulations and permit requirements for installing riparian buffers. **Existing resources** • Review the FEMA flood zones[42] to determine levels of flood risk. • Review the Washington State Noxious Weed Control Board[43] to identify invasive plants. • Consult the Washington Natural Heritage Program[44] to find out if any endangered or threatened plant or animal species will be affected. • Landowners can review the Washington Geospatial Open Data, the Soil Classification in WA State, WA State Technical Soil Services Assistance[45], and

[42] https://www.fema.gov/flood-zones
[43] http://www.nwcb.wa.gov/
[44] https://www.dnr.wa.gov/NHPlists
[45] https://www.nrcs.usda.gov/wps/portal/nrcs/detail/wa/soils/?cid=nrcs144p2_036339

Considerations	Details
	the USGS topographic maps[46] to understand the geographic characteristics of their farmland **Existing resources for buffer site preparation, planting, and maintenance** • Landowners can contact the county WSU Extension Office or use their online resources to learn about aquatic-safe fertilizers and pesticides.[47] • Review a list example of Native plant nurseries in Washington State. • Review the Washington Native Plant Society to find out what native vegetation is best suited for given counties. • Review the DNR guidelines for maintaining tree seedling vigor.[48] • For a comprehensive overview of the functions and values of riparian ecosystems in Washington State, refer to the Washington Dept. of Fish & Wildlife's *Riparian Ecosystems, Volume I: Science Synthesis and Management Implications* (Quinn et al, 2020).

[46] https://www.usgs.gov/core-science-systems/national-geospatial-program/topographic-maps
[47] https://ecology.wa.gov/About-us/Get-involved/What-you-can-do/Washington-Waters-ours-to-protect
[48] https://ecology.wa.gov/DOE/files/b9/b9935925-df3d-479f-b3fa-031764eb5e0a.pdf

Practice Category: Agroforestry and Silvopasture

Riparian forest buffers are comprised of trees with stable root systems close to the stream and smaller woody species and native grasses farther away from the stream. As an option in Ecology's recommendations, parts of riparian management zone (inner/outer zones) can be managed to produce harvestable crops along with conservation benefits.[49] With this, riparian forest buffers could be implemented in conjunction with silvopastures. Silvopasture is an agroforestry system that combines trees and forages with livestock management. Silvopasture offers the potential of significant combined economic and environmental benefits on the farm and is one of the most promising forms of agriculture for fighting climate change.[50] USDA's silvopasture guidance offers various resources for implementing silvopasture practices.[51] Silvopastures provide both short and long-term sources of income and provide opportunities to introduce native pasture grasses and rotational grazing systems. Figure 20 provides an overview of the necessary activities to manage silvopastures and potential results.

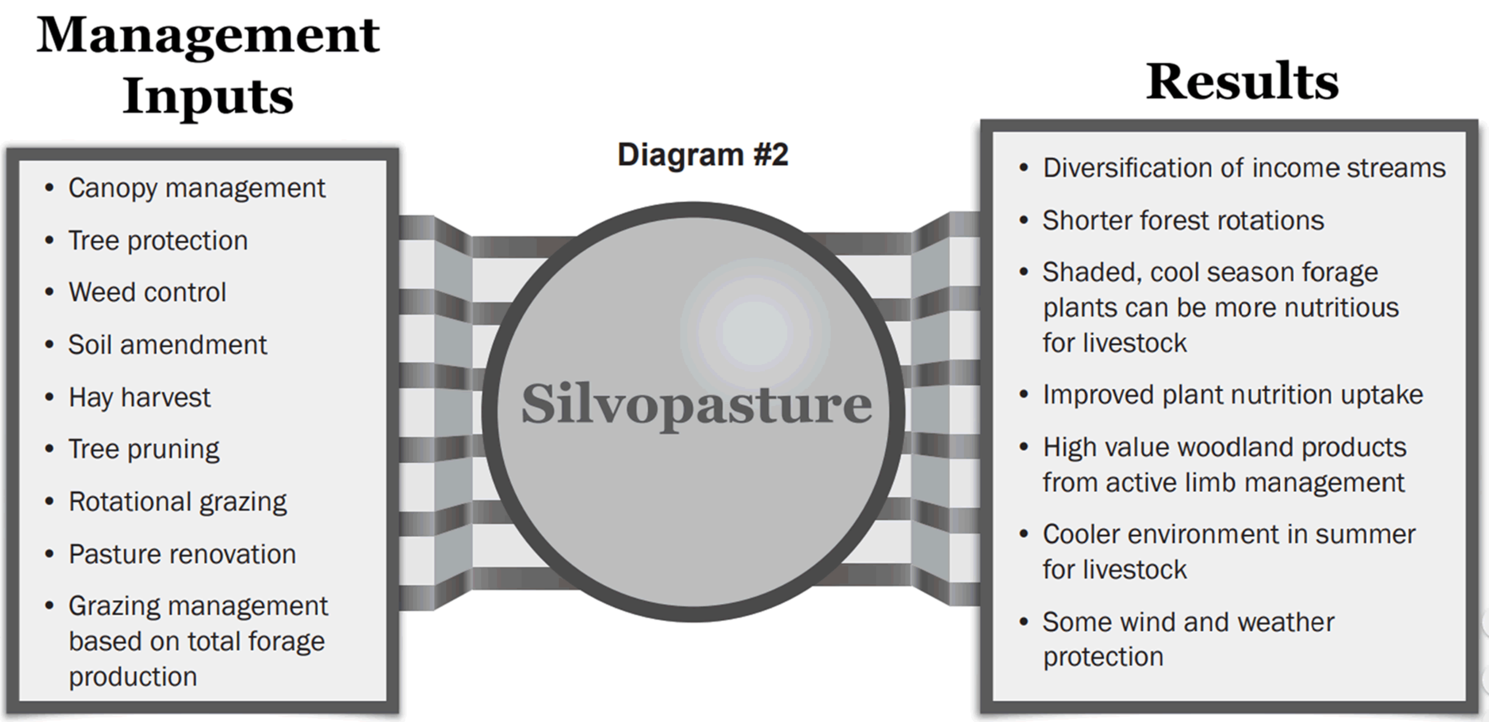

Figure 19. Forest Grazing, Silvopasture, and Turning Livestock into the Woods, Agroforestry Note #46, Silvopasture #9.[52]

Tree species for silvopastures should be selected based on economic potential and forage light requirements.[52] Tall Trees need to be planted in sufficient numbers in the inner zone to ensure

[49] https://www.fs.usda.gov/nac/practices/riparian-forest-buffers.php
[50] https://www.stonebarnscenter.org/event/agroforestry-and-silvopasture/
[51] https://www.fs.usda.gov/nac/practices/silvopasture.php
[52] https://www.fs.usda.gov/nac/assets/documents/agroforestrynotes/an46si09.pdf

shad and temperature goals are met. Table 4 provides an overview of the considerations for implementing silvopastures in WA.

Table 43: : Implementation Considerations for Silvopastures

Considerations	Details
Silvopasture Applicability and Benefits	• Placement and management of silvopasture systems is specific to the site conditions and landowner needs.[53] • Silvopastures are not intended to replace the use of riparian forest buffers, but rather help landowners increase buffer size and function while preserving economic benefits that are typically lost with riparian buffer implementation. See the Snohomish Conservation District guidance[54] on implementing silvopastures for more information. • Silvopasture management within riparian zones allow landowners to maintain livestock operations while planting trees along riparian areas. There are many environmental benefits when riparian buffers, exclusion fencing, silvopastures, and grazing management are properly implemented.[53]

Planning, Implementation, and Maintenance Cost	• Cost-share funds or public subsidies are available to aid landowners with implementing silvopasture systems.
	  ○ Programs include the Environmental Quality Improvement Program (EQIP), Conservation Stewardship Program (CSP), and others offered by local conservation districts, NGOs, and environmental protection partnerships.
	  ○ Landowners can contact their regional NRCS field technician[55] for funding application details:

Planning, Site Preparation, and Installation	• Site environmental conditions should be used to inform the design and implementation of silvopastures. • Weed pressures, proximity to streambank, flood potential, and tree types should be considered when choosing livestock type for the silvopasture. • Long-term silvopasture grazing systems should be implemented outside the recommended core zone. • Silvopasture systems should be designed on well-drained upland areas that are not prone to seasonal flooding. • Trees should be planted using techniques that prevent movement of manure and nutrients into the surface flow.

[53] https://static1.squarespace.com/static/54933166e4b00173e5357840/t/5919da5546c3c45c5c8e9aaa/1494866519588/Management+Template_Silvopasture_Final.pdf

[54] https://static1.squarespace.com/static/54933166e4b00173e5357840/t/5919da5546c3c45c5c8e9aaa/1494866519588/Management+Template_Silvopasture_Final.pdf

[55] http://www.nrcs.usda.gov/wps/portal/nrcs/main/wa/contact/local/

Considerations	Details
	• Consider using electric, temporary, or permanent fencing to protect trees in early development from livestock. Placement of trees will depend on the landscape and the intended cropping system. • See the Snohomish Conservation District guidance[56] for specific guidance on tree types. • Alder trees are ideal for silvopasture systems.
Other Activities	• Prescribed grazing must be implemented to ensure successful implementation and environmental benefits.
Resources	• Snohomish Conservation District guidance[57] • CSP Silvopasture for wildlife habitat guidance[58] • Palouse Conservation District Video Library[59] • Palouse Commodity Buffer Cost-Sharing Program[60] • Palouse Regional Conservation Partnership Program[61]

Conservation & Incentive Programs

Existing federal, state, or local conservation programs that agricultural landowners could use to implement riparian buffers are summarized below. Future approaches could include financial incentives and technical assistance (e.g., cost sharing, low-interest loans, tax incentives) and public/nonprofit purchase of private riparian lands or interests in lands (e.g., conservation easements).[62] Riparian buffers have been promoted by various agencies that targeted specific agricultural areas and landowners. Other considerations to support landowners with riparian buffer implementation funding include:

- Educating landowners on technical and financial resources;
- Building relationships between producers and local conservation districts;
- Overtime, follow-up with landowners to discuss different project opportunities;
- Provide compensation to landowners for lost production value;

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56 https://static1.squarespace.com/static/54933166e4b00173e5357840/t/5919da5546c3c45c5c8e9aaa/1494866519588https://static1.squarespace.com/static/54933166e4b00173e5357840/t/5919da5546c3c45c5c8e9aaa/1494866519588/Management+Template_Silvopasture_Final.pdf/Management+Template_Silvopasture_Final.pdf

57 https://static1.squarespace.com/static/54933166e4b00173e5357840/t/5919da5546c3c45c5c8e9aaa/1494866519588/Management+Template_Silvopasture_Final.pdf

58 https://www.nrcs.usda.gov/wps/PA_NRCSConsumption/download?cid=nrcseprd1393756&ext=pdf

59 https://www.palousecd.org/pcd-video-library

60 https://www.palousecd.org/commodity-buffers

61 https://www.palousecd.org/rcpp

62 National Research Council. 2002. Riparian Areas – Functions and Strategies for Management.

- Ensure that contracts for cost-sharing are clear to landowners;
- And work with landowners to build mutual understanding of regularly requirements for their land.

Note that some work within the riparian zone may require a permit. Activities requiring permits include:

- Grading, clearing or excavating;
- Building any type of structure;
- And modifying the stream or river.[63]

Landowners can contact county government and/or local Conservation District offices for more information on required permits.

Financial incentives

Farmers adopting riparian buffers can benefit from financial assistance through various conservation programs, including easements, tax incentives, cost-share programs, and rental payments. A characterization of some of these programs can be found below.

This information is provided for informational purposes only, other details or restrictions may apply. To find out more about the different conservation practices and eligibility requirements, contact your local conservation district, NRCS, or the Washington State Farm Service Agency office. Other local organizations may also have grant funding. Most of the conservation programs are guiding farmers through the application process and offering technical assistance for buffer planning, installation, and maintenance through the local conservation districts and other partner organizations.[64]

Some of the major conservation programs are listed below for reference. Some programs are available to individual farmers, and some are only available to public bodies and not-for-profit groups. This second category offers an opportunity to potentially implement riparian buffers on multiple neighboring lands and have a significant impact on water quality at local level. Types of programs include financial incentives and technical assistance (e.g., cost sharing, low-interest loans, tax reductions) and public/nonprofit purchase of private riparian lands or interests in lands (e.g., conservation easements).[29]

Some of the major conservation programs are listed below for reference:

- The Conservation Reserve Enhancement Program (CREP) is one of the largest riparian programs in Washington with projects covering 11,426 acres along 634.4 miles of streams which equates to an average buffer width of approximately 75ft on either side

[63] http://www.fridayharbor.org/DocumentCenter/View/610/Shoreline-Joint-Aquatic-Resource-Permit-Help-and-Guidance-PDF

[64] https://www.fsa.usda.gov/state-offices/Washington/index

of a stream.[65] CREP is a joint federal and state funded program under which cropland is set aside for buffers for a period of 10-15 years in return for rental payments.

  - CREP provides start-up and yearly rental payments for on-farm riparian buffers. Non-agricultural landowners are not necessarily ineligible for CREP, and program participation requires meeting cropping history and other Conservation Reserve Program eligibility requirements.[66]

- Examples of cost-sharing programs include the Ecology's 319 and Centennial grant program, Environmental Quality Incentive Program, National Estuary Program, and others.
- County conservation district cost-share programs. For example, the King Conservation District (KCD) has a cost-share program that covers 90percent of the costs to plan, implement, and maintain buffer plantings.[67]
- Conservation easements are also available through which a third party holds the easement and is responsible for buffer implementation in return for various tax incentives to the landowner.

Tax Incentive Programs

Some programs offer landowners to apply for property tax incentives if their land has riparian buffers. For example, the South Dakota Buffer Tax Credit Program uses guidelines from the Department of Environment and Natural Resources to determine eligible properties. These guidelines include the land consisting of existing or planted perennial vegetation and a buffer strip of 50 to 120 feet wide.[68]

Local Cost-sharing Programs

The Conservation Program Explorer is a valuable resource for identifying funding opportunities across different local areas. The Explorer was developed by WDFW to raise awareness of different funding programs and connect landowners to agencies and organizations. The Explorer includes information on programs like the Forest Stewardship Program, Environmental Quality Incentives Program, and Family Forest Fish Passage Program.

The Farm Smart Certification Program provides certification that producers are growing crops in accordance with best management practices. The program was developed by local conservation districts in collaboration with the Department of Ecology. Landowners in the program can advertise their farm and agricultural products at a higher standard since they are

[65] WA State Conservation Commission. Conservation Reserve Enhancement Program
[66] https://www.sciencedirect.com/science/article/abs/pii/S0169204611003628
[67] King County. Borsting, M. 2018. Riparian Buffers in an Agricultural Setting.

[68] https://dor.sd.gov/individuals/taxes/property-tax/

following certain conservation practices outlined by the program which gives them a marketing advantage.

The Snake River Salmon Recovery Board offers regular, yearly grant cycles that provide funding for riparian buffers and instream networks. The Conservation Commission also provides funding through local conservation districts for livestock, technical assistance, riparian buffers, and natural resource investment. Funding from the Conservation Commission can be customized at the local-level which is beneficial for landowners pursuing different best management practices.

Land Retirement Programs

Land is rented to private owners for conservation purposes. These programs focus on conservation buffers and other water quality practices. Landowners are offered rental payments based on average agricultural land rental rate. Programs offer cost-share payments that cover 50 percent to 100 percent of cost to install practices that protect or enhance buffer effectiveness. Programs also provide annual payments for maintenance. Landowners then pay the remaining cost of installing practices and are responsible for maintenance and protection of the project for the contract's timeframe. This program offers the most incentives to install conservation buffers for counties that drain into bays.

Continuous Conservation Research Program (CRP) (Federal program)

- USDA-Farm Services Agency (FSA) and the Natural Resources Conservation Service (NRCS) offer the continuous Conservation Reserve Program (CRP) that focuses on initiatives for improving water quality and reducing soil erosion, such as conservation buffers. The program is referred to as the "continuous CRP" because producers can enroll their land at any time during the year as opposed to the regular CRP that has announced sign-up periods.
- **Program description:** When cropland or pasture is enrolled in the Continuous CRP to install a conservation buffer, the federal government is, in effect, retiring the land from active use and renting it from the landowner for conservation use. The basic contract is for 10 years, but if trees are grown in the buffer area, the landowner has an option to increase the term to 15 years.[38] FSA provides eligible participants with annual rental payments and cost-share assistance of up to 50percent of the re-reimbursable cost of installing the riparian buffer.
- **Eligibility:** A producer must have owned or operated the land for at least 12 months. Land must be cropland that is planted or considered planted to an agricultural commodity in four of the six most recent crop years and is physically and legally capable of being planted (no planting restrictions due to an easement or other legally binding instrument) in a normal

manner to an agricultural commodity. Certain marginal pastureland that may be devoted to riparian buffers is also eligible. [69]

- **Where to sign up:** Landowners can contact their local conservation district or the Washington State Farm Service Agency office.[33]
- **Barriers:** Landowners are hesitant to enroll in CRP due to:
    - Loss of base acres for commodity programs
    - Expectation of earning more from renting land than from an annual program payment
    - Reduced flexibility to adjust land uses as market conditions change
    - Potentially adverse effects on financial status
- **Benefits:** 40 to 45 million acres of cropland are retired under CRP which yields an annual cost of roughly $1 billion. However, this program generates $3.5 to $4.5 billion in annual water quality benefits. Both riparian forest buffers and vegetative filter strips qualify for the continuous CRP program. The continuous program offers 90percent cost share on establishment, $10 per acre per year for practice incentives, 20percent rental payment plus an average rental payment based on soils. Lastly, forest buffers qualify for a one-time bonus of at least $100 per acre for tree planting.

Environmental Quality Incentives Program (EQIP)

- The Environmental Quality Incentives Program (EQIP) provides financial and technical assistance to agricultural and forestry producers for various conservation practices, including riparian buffers.
- **Program description:** EQIP is a cost-share program and may pay up to 75percent of buffer implementation. Funding is secured through 5- to 10-year contracts. Participation incentives include nearly 50percent cost sharing on structural or vegetative practices and incentive payments for management practices. There is no annual limitation and the sum of all EQIP payments cannot exceed $450,000.
- **Eligibility**: The applicant is an agricultural producer that is engaged in livestock or agricultural production, OR the applicant is a private, non-industrial forest landowner. Applications for EQIP are accepted on a continuous basis. Applications are funded in the order they are ranked according to environmental benefits criteria.
- **Where to sign up:** The best way to learn if EQIP is a good fit for you is by contacting your local NRCS office.

[69] https://www.fsa.usda.gov/Assets/USDA-FSA-Public/usdafiles/Conservation/PDF/FSA-ContinuousCRP-Factsheet-SU52.pdfhttps:/www.fsa.usda.gov/Assets/USDA-FSA-Public/usdafiles/Conservation/PDF/FSA-ContinuousCRP-Factsheet-SU52.pdf

Agricultural Conservation Easement Program (ACEP)

- The Agricultural Conservation Easement Program (ACEP) helps landowners, land trusts, and other entities protect, restore, and enhance wetlands, grasslands, and working farms and ranches through conservation easements.[70]
- **Program description:** Through the program, *Agricultural Land Easements* prevent conversion of productive working lands to non-agricultural uses. Under these easements, NRCS may contribute up to 50 percent of the fair market value of the easement. Although, NRCS may contribute up to 75 percent of the fair market value of the easement for protection of grasslands of special environmental significance. Through Wetland Reserve Easements, NRCS provides technical and financial assistance to private landowners and Native American tribes for restoration, protection, and enhancement of wetlands.
    - Wetland reserve enrollment options with NRCS include:
        - Permanent easements
        - 30-year easements
        - Term easements
        - 30-year contracts
    - Landowners can also join the Wetland Reserve Enhancement Partnership (WREP), a voluntary program in which NRCS signs agreements to leverage resources for high priority wetland protection, restoration, and enhancement to improve wildlife habitat.
- **Eligibility:** Land eligible for agricultural easements includes cropland, rangeland, grassland, pastureland and nonindustrial private forest land. NRCS will prioritize applications that protect agricultural uses and related conservation values of the land and those that maximize the protection of contiguous acres devoted to agricultural use.
- **Where to sign up**: Contact the NRCS WA State Office[71].

Conservation Reserve Enhancement Program (CREP)

- The Conservation Reserve Enhancement Program (CREP) is one of the largest riparian programs in WA with projects covering 11,426 acres along 634.4 miles of streams, which equates to an average buffer width of approximately 75ft on either side of a stream.[30]
- **Program description**: CREP is a voluntary land retirement program that helps agricultural producers protect environmentally sensitive land. It combines federal, state, tribal and other private sources to cover costs for protection measures. CREP is a joint federal and state funded program under which cropland is set aside for buffers for a period of 10-15 years in return for rental payments. The payment is based on the county's rental rate levels where the land is located, and the types of soil found in the riparian area. The entire cost of project installation is covered and the project

51 https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/programs/easements/acep/?cid=stelprdb1242695
71 https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/contact/states/?cid=nrcsdev11_000240

maintenance cost is reimbursed for the first five years. Technical assistance for buffer planning, installation, and maintenance is being offered by the local conservation districts and NRCS. Participants are requested to grow riparian crop in exchange for a fixed price. Participants are expected to contribute effort and cover expenses to maintain the project. Landowners are reimbursed for up to 100percent of costs within caps to install practices. The CREP program is an enhanced version of CRP which provides more funding for installation, maintenance, rental payments, and incentive options to landowners. These enhancements were intended to increase program participation.

- **Eligibility:** A producer must have owned or operated the land for at least 12 months. The Land must be either cropland or marginal pastureland, be able to support the required vegetation, and have required cropping history. Property must border eligible stream segments. Generally, stream segments must have at least one species of Pacific salmon or steelhead present.
- **Where to sign up:** Contact your local conservation district, the Washington State Conservation Commission, or the Washington State Farm Service Agency[72] office.
- **Costs and Incentives:** An average rural riparian forest establishment with the average contract period of 15 years costs $4,695 per acre. With incentives and annual rental fees at roughly $128 per acre plus inflation.
- **Barriers:** CREP can be complicated since four agencies are involved and reimbursements come at different time periods for different costs. The Farm Service agency typically pays 50percent cost share when practices are completed, and the Soil and Water District covers 50percent of those costs at a different time. The practice incentive payments, signing bonus, and rent also come from multiple agencies. Although, some states have developed their own programs that are simpler than CREP to improve participation.

Conservation Stewardship Program (CSP)

- The Conservation Stewardship Program (CSP) offers enhancements to conservation practices that were implemented by landowners.
- **Program Description:** The program offers consultations by local conservation planners to evaluate landowners' management systems and available natural resources. Planners offer enhancement alternatives for landowners to consider based on existing conservation practices. Landowners have the flexibility to choose enhancements that best suit their operations and are compensated by CSP with annual incentive payments for installing enhancement practices. CSP also offers enhancement "bundles", for which landowners can receive higher payment rates. CSP enhancements are conservation activities to treat natural resources and improve conservation performance. Activities specific to Washington state include:

[72] https://www.fsa.usda.gov/state-offices/Washington/index

- Herbaceous weed treatment
- Increase riparian herbaceous cover width for nutrient reduction
- Increase riparian forest buffer width for nutrient reduction, to reduce sediment loading, and/or enhance wildlife habitat.
- Increase buffer stream shading for temperature reduction
- Extend buffers reduce excess nutrients in surface water, reduce excess pathogens, and/or reduce chemicals in surface water.
- Planting food-producing trees and shrubs for wildlife/human consumption within riparian forest buffers.
- Buffer bundles cover the following activities:
  - Extending existing buffers to address water quality degradation, fish/wildlife inadequate habitat, degraded plant condition plus an option for air quality impacts.
  - Other activities from the Washington state list can be added to the bundles.

- **Benefits:** CSP is the largest conservation in the country with 70 million acres of productive agricultural and forest land enrolled in the program. Benefits that CSP participants reported include:
  - Improved crop yields
  - Decreased inputs
  - Wildlife population improvements
  - Greater resilience to weather extremes

Agricultural Management Assistance (AMA)

- The Agricultural Management Assistance program (AMA) offers compensation for up to 75 percent of landowner costs to install conservation practices.
- **Program Description:** Payments do not exceed $50,000 per participant per fiscal year. Historically, AMA has offered higher cost-sharing for underserved producers. Land eligibility requirements for AMA include land for agricultural or livestock production, private non-industrial forest land, and land for risk mitigation with improvements to conservation practices.
  - Landowners must meet these conditions to be eligible for the program:
    - Engage in livestock or agricultural production
    - Have control of the land for the term of the proposed contract
    - Follow provisions for protecting interests of tenants and sharecroppers
    - Have an interest in farming operation associated with the land being offered for AMA enrollment.
- **Eligibility:**
  - Land on which agricultural commodities or livestock are produced (i.e. cropland, pastureland, rangeland, and grassland).
  - Land used for subsistence purposes, private non-industrial forestland
  - Land on which risk may be mitigated through operation diversification or change in resource conservation practices.

State Conservation Programs

Cost-Share Programs

- Cost share programs pay a fixed percentage of actual costs for installed practices and the landowner pays remaining costs.
- The King Conservation District (KCD) cost-share program that covers 90 percent of the costs to plan, implement, and maintain buffer plantings.[73]
- Landowners and managers within the KCD service area are eligible and must outline practices in a KCD-prepared farm conservation plan or technical assistance plan that includes advanced planning.
- Eligible practices include aquatic area buffer planting with a maximum reimbursement of $27,000. The program also covers building relocation from aquatic area/buffer with a maximum reimbursement of $10,000.
- Buffer fencing, bulkhead removal, stream crossings, watering and waste storage facilities are other practices covered by the program.
- Applicants can only apply for one practice at a time and in-kind labor and use of personally owned machinery are eligible for reimbursement.

Puget Sound National Estuary Program (NEP)

- The Puget Sound National Estuary Program (NEP) is a non-regulatory initiative to engage various organizations around coordinating implementation and monitoring efforts to protect and restore Puget Sound. The NEP is funded by the EPA and state funding. NEP guidelines and funding for the planning, implementation, and/or maintenance of riparian buffers has varied over time. NEP funding is allocated to Strategic Initiative Leads and the Northwest Indian Fisheries Commission to implement the Puget Sound Action Agenda.[74]

Partners for Fish and Wildlife Program (PFW)

- The Partners for Fish and Wildlife Program (PFW) offers financial incentives and direct technical assistance to landowners to support restoration and conservation efforts of fish and wildlife for the benefit of federal trust resources. The program specifically supports projects to improve wetland, riparian, and other habitats on private lands. Projects that improve habitat fragmentation, restore ecological integrity, promote self-sustaining ecosystems, and benefit habitats for migratory fish species are financially supported by this program. Both technical and financial assistance is provided for projects to addressing riparian buffers.

Centennial Clean Water Program

- Centennial is a state funding program providing grants to eligible public bodies for water quality projects among others, including riparian buffers.

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[73] King County. Borsting, M. 2018. Riparian Buffers in an Agricultural Setting.

[74] https://www.psp.wa.gov/NEP-solicitation-and-grants.php

- **Program Description:** The program provides compensation for site preparation and maintenance tasks as well as a rental payment. Projects that implement best management practices are required to collect and report data that estimate load reductions of nitrogen, phosphorus, and sediments. Ecology must report the reductions to EPA annually.[45]
- **Eligibility**: Eligible applicants include public bodies and not-for-profit groups. Applicants eligible for Centennial funding include counties, cities, and towns; water districts and sewer districts; port districts; conservation districts; irrigation districts; quasi-municipal corporations; federally recognized tribes; Washington State institutions of higher education if the project is not included in the institution's statutory responsibilities. These grants have announced application periods.[45]
- **Where to sign up:** Applicants submit applications for funding through the [Ecology Administration of Grants and Loans (EAGL) system][75]. After funding is awarded to local entities, those local entities fund on the ground projects. Landowners and producers can contact their local Ecology office to see if there are grant funds available in their area.

Clean Water Act Section 319 Program

- Section 319 provides grants for water quality projects, including stream restoration and buffers.
- **Program Description:** Grants fund nonpoint source pollution control projects. Additionally, both the Centennial Clean Water and Section 319 programs fund wastewater and stormwater facilities, onsite sewage systems, nonpoint source activities, and special categories including financial hardships, preconstruction, and Green Project Reserves.[76]
- **Eligibility**: Eligible applicants include public bodies and not-for-profit organizations. These grants have announced application periods. Applicants eligible for the Clean Water Section 319 Program funding include: counties, cities, and towns; water districts and sewer districts; port districts; conservation districts; irrigation districts; quasi-municipal corporations; federally recognized tribes; Washington state institutions of higher education if the project is not included in the institution's statutory responsibilities; not-for-profit organizations that are recognized as tax exempt by the Internal Revenue Service.[77]
- **Where to sign up:** Applicants submit applications for funding through the [Ecology Administration of Grants and Loans (EAGL) system][78]. After funding is awarded to local entities, those local entities fund on the ground projects. Landowners and producers

[75] https://ecology.wa.gov/About-us/How-we-operate/Grants-loans
[76] C:\Users\benr461\AppData\Local\Microsoft\Windows\INetCache\Buffers\o https:\www.epa.gov\nps\319-grant-program-states-and-territories
[77] https://fortress.wa.gov/ecy/publications/documents/1710019.pdf
[78] https://ecology.wa.gov/About-us/How-we-operate/Grants-loans

can contact their local Ecology office to see if there are grant funds available in their area.

Clean Water State Revolving Fund (CWSRF)

- The Clean Water State Revolving Fund (CWSRF) is administered by Ecology and provides funding to local governments, tribes, and partners for water quality improvement projects.
- **Program Description:** The program also funds nonpoint source planning and implementation activities. Ecology also uses CWSRF to provide special funding for financially challenged (hardship) communities. CWSRF loans are used for financing land acquisition, purchasing conservation easements, and protecting streams, rivers, and other drinking water sources. Ecology reviews funding applications.[79] CWSRF is a loan program. Loan terms could be from 1 to 30 years.
- **Eligibility**: Applicants eligible include counties, cities, and towns; water districts and sewer districts; port districts; conservation districts; irrigation districts; quasi-municipal corporations; federally recognized tribes; Washington State institutions of higher education if the project is not included in the institution's statutory responsibilities. These grants have announced application periods.[46]
- **Where to sign up:** Applicants submit applications for funding through the Ecology Administration of Grants and Loans (EAGL) system[80]. After funding is awarded to local entities, those local entities fund on the ground projects. Landowners and producers can contact their local Ecology office to see if there are grant funds available in their area.

Implementation Evaluation References

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4. United States Department of Agriculture (USDA), National Resource Conservation Service (NRCS). 2002. Adoption of Conservation Buffers: Barriers and Strategies.
5. Maryland Cooperative Extension
6. Sound Native Plants Retail Price List
7. Forested riparian buffer planting guide for landowners and developers
8. Riparian Buffers for Western Washington Agriculture
9. Bringing Discovery Farms to King Conservation District to Evaluate the Effectiveness of Riparian Buffers on Agricultural Lands, 2018
10. NRCS Conservation Practice Standard: Tree/Shrub Site Preparation, 2007
11. Trees and Shrubs for Riparian Plantings
12. Management Recommendations for Washington's Priority Habitats: Riparian

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79 https://wecprotects.org/programs/evergreen-forests/clean-water-state-revolving-fund/
80 https://ecology.wa.gov/About-us/How-we-operate/Grants-loans

13. Brandywine Foundation. 2016. Forested Riparian Buffer Planting Guide for Landowners and Developers.
14. Managed Grazing in Riparian Areas
15. Efficacy and Economics of Riparian Buffers on Agricultural Lands
16. Brandywine Foundation. 2016. Forested Riparian Buffer Planting Guide for Landowners and Developers.
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18. Washington State Join Aquatic Resources Permit Application Help & Guidance
19. Washington Waters – Ours to Protect
20. Washington Waters Presentation – Ours to Protect
21. Maintaining Tree Seedling Vigor
22. R.L. Ryan, D.L. Erickson, R. De Young, Farmers' motivations for implementing conservation practices along riparian zones in a mid-western agricultural watershed, J. Environ. Plan. Manag. 46 (2003) 19–37, http://dx.doi.org/10.1080/713676702.
23. Whatcom Watch Online – Nooksack River: Salmon and Agriculture
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26. G.B. Habron, Adoption of conservation practices by agricultural landowners in three Oregon watersheds, J. Soil Water Conserv. 59 (2004) 109–115
27. National Research Council. 2002. Riparian Areas – Functions and Strategies for Management.
28. Washington State Farm Service Agency
29. WA State Conservation Commission. Conservation Reserve Enhancement Program (CREP)
30. King County. Borsting, M. 2018. Riparian Buffers in an Agricultural Setting.
31. South Dakota Buffer Strip Program
32. Three-Year Implementation Plan Narrative for Lake Washington/Cedar/Sammamish Watershed
33. Conservation Reserve Program – Continuous Enrollment Period
34. USDA Service Center Locator map https://offices.sc.egov.usda.gov/locator/app
35. USDA Natural Resources Conservation Service – Invasive Species and Pests
36. A map of eligible stream segments for CREP enrollment can be found at the following link: https://uploads-ssl.webflow.com/5ec2d4f7da309c68cdc0655a/5f29d568c249c7d48b1e4b10_CurrentStreamMap.jpg
37. https://uploads-ssl.webflow.com/5ec2d4f7da309c68cdc0655a/5f1b546a75c95e334083a21a_CREP_Landowners-General_041515.pdf
38. State Fiscal Year 2020 final Water Quality Funding Offer List and Intended Use Plan
39. Funding Guidelines State Fiscal Year 2019 – Water Quality Financial Assistance
40. Maryland Cooperative Extension. 2000. When a Landowner Adopts a Riparian Buffer – Benefits and Costs
41. Funding cycles of the Water Quality Combined Funding Program
42. King County. Borsting, M. 2018. Riparian Buffers in an Agricultural Setting.
43. USDA Natural Resources Conservation Service Washington - 2018 Farm Bill

Appendix: Literature Review

Please find below a list of resources reviewed for the Riparian Protection Implementation Guidance.

General - practice overview, opportunities and barriers to voluntary implementation

1. Awole, K., Monaghan, J., Covington, B. Bringing Discovery Farms to King Conservation District to Evaluate the Effectiveness of Riparian Buffers on Agricultural lands.
2. Conservation Technology Information Center
3. Craig W. J., and Buffler, S. 2008. Riparian Buffer Design Guidelines for Water Quality and Wildlife Habitat Functions on Agricultural Landscapes in the Intermountain West.
4. Everest, F.H., and Reeves, G. H. 2007. Riparian and Aquatic Habitats of the Pacific Northwest and Southeast Alaska: Ecology, Management History, and Potential Management Strategies
5. Kallestad, J., and Dr. Swanson, M.E. 2009. Riparian Buffers for Western Washington Agriculture. Tilth Producers Farm Walk Series.
6. National Association of Soil and Water Conservation Districts
7. Stroud Water Research Center
8. United States Department of Agriculture (USDA), National Resource Conservation Service (NRCS). Conservation Practice Effects. (source)
9. United States Department of Agriculture (USDA), National Resource Conservation Service (NRCS). 2002. Adoption of Conservation Buffers: Barriers and Strategies.
10. United States Department of Agriculture (USDA), National Resource Conservation Service (NRCS). 2000. Conservation buffers to reduce pesticide losses.
11. Washington State University Cooperative Extension, Riparian Buffers: Project Overview Function, Management & Economic Implications for Agriculture.
12. Whitescarver, B. 2015. Bobby's 7 Principles: Selling Riparian Forest Buffers.

Costs - capital cost, net cost-benefits, opportunity costs, operation and maintenance costs

1. American Rivers, Environmental Finance Center. 2016. The Economic Value of Riparian Buffers.
2. American Water Resource Association. Henri, C. J., PhD. Resource Consulting. 2004. Economics of Riparian Restoration on Western Washington Farms.
3. Dworak, T., M. Berglund, B. Grandmougin, V. Mattheiss, and S. Holen. 2009. International review on payment schemes for wet buffer strips and other types of wet zones along privately owned land. Study for RWS-Waterdienst. Ecologic Institute, Berlin/Wien.
4. Geotechnical Water Resources Environmental and Ecological Services Consultants. 2002 and 2005. Efficacy and economics of riparian buffers on agricultural lands.
5. Gordon, H. USDA NRCS. 2013. Basic Economic Analysis Using T-Charts.
6. Public Price List for Seedlings 2018-2019 Season, WA State DNR
7. Qiu, Z. and Prato T. 1998. Economic evaluation of riparian buffers in an agricultural watershed.

8. Tiwari, T., Lundstrom, J., Kuglerova, L., Laudon, H., Ohman, K., and Ågren, A. M. 2016. Cost of riparian buffer zones: A comparison of hydrologically adapted site-specific riparian buffers with traditional fixed widths.
9. Virginia Cooperative Extension. 2009. Understanding the Science Behind Riparian Forest Buffers: Resources for Virginia Landowners.
10. USDA NRCS. Conservation Practice Benefit-Cost Templates (source)
11. WA State DNR. Seedling Prices and Availability 2018-2019 Season
12. Washington State University. 2005. Analysis of forested riparian buffers 35', 75', and 180' wide - Summary of Results for Skagit Potato Enterprises.
13. Washington State University. 2005. Economic impact of riparian buffers on Skagit Valley Potato Farms. Presentation at 23rdAnnual Western WA Potato Workshop.
14. Zobrist, K. W. and Lippke, B. R. 2007. Economic Costs of Different Riparian Management Regulations in the Pacific Northwest.
15. USDA, The Forest Land Enhancement Program

Site Requirements - regional considerations, technical (operation and maintenance) requirements

1. Cindy Dittbrenner, Snohomish Conservation District, Paul Cereghino, NOAA Restoration Center, Erik Hagan, Pennsylvania State University. 2015. The Working Buffer Opportunity: A proposal for ecologically sound and economical viable riparian buffers on agricultural lands,
2. Conservation Reserve Enhancement Program (CREP) Factsheet, Washington State. 2010.
3. Emmingham, W.H., Bishaw B., and Rogers W. 2005.Tree Buffers along Streams on Western Oregon Farmland
4. King County. Borsting, M. 2018. Riparian Buffers in an Agricultural Setting.
5. Knutson, K. L., and Neaf, V. L. 1997. Management Recommendations for Washington's Priority Habitats – Riparian
6. Oregon State University. 2014. Got a Stream? Grow Plants.
7. Schultz, R., T. Isenhart, W. Simpkins, and J. Colletti. 2004. Riparian forest buffers in agroecosystems–lessons learned from the Bear Creek Watershed, central Iowa, USA. Agroforestry Systems **61**:35-50.
8. Washington State University. 2006. Analysis of forested riparian buffers. Summary of Results for Skagit Blueberry Enterprises
9. Washington State University. Kallestad, J. Clarks Creek Experimental Riparian Buffers: Monitoring, Function, and Implications for Agriculture.
10. USDA NRCS. Riparian forest buffer.

Conservation Incentive Programs

1. Adopt a Stream Foundation
2. Conservation Districts. Some examples:
    a. King Conservation District
    b. Pierce Conservation District
3. County Planning Departments
4. State and Federal Fish and Wildlife Agencies
5. USDA Farm Services Agency
6. USDA Natural Resources Conservation Service (NRCS)

7. WA State Department of Ecology
8. WA State Department of Natural Resources
9. WA State Conservation Commission. Conservation Reserve Enhancement Program (CREP)
10. WA State Department of Natural Resources. Forestry Riparian Easement Program (FREP). and FREP Overview.
11. Lessons learned from other states