Voluntary Clean Water Guidance for Agriculture Chapters

The purpose of this guidance is to describe best management practices (BMPs) that agricultural producers can use to protect water quality. It is intended to both support healthy farms while helping producers meet clean water standards. 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 overall introduction before this chapter.

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

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

Chapter 2--Draft

Crop Systems: Conservation Crop Rotation, Contour Farming, Intercropping, Strip Cropping, Alley Cropping and Cover Crops

Voluntary Clean Water Guidance for Agriculture

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Table of Contents

List of Figures and Tables

Tables

Recommendations for Crop Systems: Conservation Crop Rotation, Contour Farming, Intercropping, Strip Cropping, Alley Cropping and Cover Crops

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Introduction

This chapter focuses on different cropping strategies that can be used to prevent or minimize impacts to water quality. These practices also have additional benefits, such as improved soil health and crop diversity, water and nutrient retention, and benefits to insect and wildlife communities. While these different cropping strategies can provide water quality benefits on their own, most are not sufficient to fully protect surface waters from runoff that may be contaminated with sediment, nutrients, or pathogens. As a result, many of these practices have references to other in-field and edge-of-field practices that are described in other chapters (e.g. Chapter 5- Sediment Control: Soil Stabilization and Sediment Capture (Vegetative)), that when implemented in combination with specific crop systems, can more fully protect water quality.

Scope of Guidance

The purpose of this chapter is to outline BMPs that, when implemented, will help prevent negative impacts to water quality from agricultural pollutants. Because there are many types of crops and cropping systems utilized in Washington state, this chapter is meant to be an overview of these types of systems with some examples. For detailed information about specific crops, see local conservation districts.

Definitions Used in this Document

General Definitions

Concentrated Flow: Any surface runoff that is not shallow overland or sheet flow.

Ephemeral (surface water): Flow typically with a short-lived presence.

Groundwater: As opposed to surface water, groundwater is water that has infiltrated from the land surface and is retained in the soil or in pores and crevices in rock.

Gully Erosion: Similar to rill erosion with larger channels.

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

Intermittent (surface water): Flow that occurs at irregular intervals as opposed to perennial flow which has a continuous presence.

Perennial (surface water): Flow that occurs continuously, though of varying levels.

Prevailing Wind: a surface wind that blows predominantly from a particular direction.

Rill Erosion: Erosion by concentrated flow in small, sometimes parallel, channels.

Riparian Buffer: A vegetative strip, of varying width, adjacent to a surface water, that provides for water quality benefits through shading and runoff pollutant removal.

Sheet Erosion: A shallow uniform layer of water that picks up and transports sediment over a wide area.

Swale: A shallow depression in the ground that collects and transports water.

Definitions of Crop Rotation Practices

Conservation Crop Rotation: A planned sequence of various crops grown on a piece of land to prevent or minimize erosion and the transport of nutrients and other contaminants from entering the waterways and to improve soil health (NRCS 328).

Contour Farming: Aligning the ridges, furrows, and roughness formed by tillage. Also, planting and performing other operations at a grade near the contour to alter the velocity or the direction of water flow to prevent or minimize erosion and the transport of nutrients and other contaminants from entering the waterways (NRCS 330).

Intercropping and Strip Cropping: Growing crops in a systematic arrangement of strips in a field to prevent or minimize erosion and the transport of nutrients and other contaminants from entering the waterways (NRCS 585).

Alley Cropping: Trees or shrubs planted in sets of single or multiple rows with alleys of agronomic crops or forage between the sets of woody plants to prevent or minimize erosion and the transport of nutrients and other contaminants from entering the waterways and to improve soil health and microclimate (NRCS 311).

Cover Crops: Herbaceous vegetative cover planted as seasonal cover in rotation with annual production crops to prevent or minimize erosion and the transport of nutrients and other contaminants from entering the waterways (NRCS 340).

Best Management Practices for Crop Systems

The following are best management practices (BMPs) designed to prevent or minimize erosion and the transport of nutrients and other contaminants from entering the waterways. Additional benefits may include improvements to soil health, microclimate, and forage for native species.

- Conservation Crop Rotation
- Contour Farming

- Intercropping and Strip Cropping
- Alley Cropping
- Cover Crops

Conservation Crop Rotation

Conservation crop rotation (CCR) is defined as a planned sequence of crops grown on the same ground over multiple growing seasons (i.e., the rotation cycle) for a variety of conservation purposes. While crop rotation can serve many goals, CCR can be applied for the following water quality concerns (NRCS, 2014a):

- **Reduce sheet, rill, and wind erosion** by maintaining sufficient canopy and residue cover.
- **Reduce water quality degradation due to excess nutrients** by reducing erosion, removing excess nitrogen (N) and reducing the need for additional N fertilizers, and reducing the need for pesticide use by breaking pest lifecycles.
- **Reduce the concentration of salts and other chemicals from saline seeps** by reducing excessive seepage due to improved plant water uptake.

NRCS also notes these additional benefits:

- Maintain or increase soil health and organic matter content.
- Improve soil moisture efficiency.
- Reduce plant pest pressures.
- Provide feed and forage for domestic livestock.
- Provide food and cover habitat for wildlife, including pollinator forage and nesting.

Crops used in CCR include high-residue producing crops such as wheat or corn grown for grain, in rotation with low-residue producing crops such as vegetables or soybeans. Crop rotations have the potential to improve water quality by taking up nitrate that would otherwise be lost to leaching or runoff and by reducing the overall amount of N fertilizer that must be applied over the whole rotation period, if a legume crop is included in the rotation (Simão et al., 2024). The rotation may also involve growing forage crops in rotation with other field crops. One important feature of CCR is to minimize the fallow years in the rotation and, where the climate and soils are favorable, establish cover crops during the fallow periods, thereby reducing soil erosion. Crop rotations vary with climate, soil type, crops produced, farming operations, and how the crop residue is managed. The most effective crops for soil improvement are fibrous-rooted high-residue producing crops, such as grass and small grain. Perennial plants used for forage are very effective in crop rotations due to increases in organic matter and reduced soil erosion. In addition to water and soil quality benefits, crop rotations help break insect, disease, and weed cycles. Rotations add diversity to farm operations and often reduce economic and environmental risks.

CCR is especially appropriate when it replaces a cropping system that alternates fallow with a monoculture crop. Basic crop rotation, especially those that include legumes (e.g., corn-triticale), can replace monocultures (e.g., continuous corn) in many agricultural regions. A two-year annual corn-soybean rotation is the most commonly implemented rotation system in the U.S. Corn Belt. A three-to-four-year corn silage-grass-hay rotation is a common practice in dairy and other livestock agricultural systems. More diverse rotations, such as those including high-residue producing crops with low-residue producing crops or those that include a forage crop, may be especially beneficial from both an agronomic and environmental standpoint.

CCRs can work well with conservation tillage practices (see Chapter 1 for recommendations on tillage practices), though in some cases climate may place limitations on crop rotation; some crops may be challenging to establish or grow in regions with dry, short growing seasons. CCR is an appropriate BMP to apply in areas where erosion, soil loss, and nutrient delivery to surface and groundwater from cropland are important issues and where improvement of soil health is an important objective. Conservation Districts can help with regional and site-specific crops and planting timings, however general recommendations about the overall rotation are listed below.

Recommendations and Considerations

- Multi-crop rotations are recommended with a minimum of a two-crop rotation (e.g. wheat-barley, corn-triticale, corn-sudan grass).
- A cover crop is also recommended for the fallow years, especially with low residue crops (see cover crop section below and Chapter 5 for more information on cover crops).
    - Replacing the fallow year with forage triticale is also an effective alternative in years of adequate rainfall.
    - Native species are the preferred cover crop option, however legumes and grasses may provide more function in areas with low-nitrogen or a high potential for erosion.
- Additional crops in rotation (e.g. corn-triticale-wheat) and crop rotations to achieve other objects are encouraged but will depend on regional and site-specific factors (see below for some examples).

Some NRCS variants of CCR that may be applied to serve other objectives:

- E328E **Soil health crop rotation** (NRCS, 2023a):
    - Increases diversity of the cropping system.
    - Maintains residue cover throughout the year.
    - Keeps a living root.
    - Minimizes soil chemical, physical, and biological disturbance.
- E328J **Improved crop rotation to provide benefits to pollinators** (NRCS, 2023b):
    - Minimum of three different crops in a minimum five-year crop rotation.
    - Pollinator-friendly crop planted on $\geq$5% of cropland acreage per year.

- Use of insecticides is limited for pollinator friendly crop.

- E328L **Leaving tall crop residue for wildlife** (NRCS, 2023c):
  - Fields may be harvested but must leave crop residue standing ≥14 inches.
  - Residue will be left through winter and into spring to provide winter cover and forage for wildlife.

Contour Farming

Contour farming is the practice of aligning tillage (especially the ridges, furrows, and roughness formed by tillage), planting, and other operations with land slope contours (NRCS, 2017b). Contour farming is an established Natural Resources Conservation Service (NRCS) conservation practice. NRCS has separate practice standards for contour farming of annual crops (NRCS practice code 330) and contour farming of orchards, vineyards, and other perennial crops (NRCS practice code 331) (NRCS, 2015, 2017b). The effectiveness of the two NRCS contour farming practices are addressed in this evaluation together under the general term of "contour farming" because the two practices and the processes by which they protect water quality are essentially the same.

Contour farming reduces pollutant (e.g. sediment, nutrient, pesticide, and pathogen) transport in surface runoff by (NRCS, 2017b):

- Altering the velocity or direction of water flow.
- Increasing infiltration of water into the soil.
- Reducing sheet and rill erosion.

Contour farming on annually cropped lands is of high value throughout Washington for reducing erosion, soil loss, and pollutant transport from sloped agricultural lands, particularly for the Palouse region where much of the farmland is sloping and the soil is highly erodible. Similarly, contour farming of orchards, vineyards, and other types of perennial croplands has high value throughout the state, because the process of establishing perennial crops on sloping lands can result in increased surface runoff and substantial soil erosion when contour farming is not practiced (Cerdà et al., 2009). Contour farming of perennial crops may have its greatest relevance and value along the eastern flank of the Cascade Mountain range where orchards and vineyards are prevalent. Contour farming for both annual and perennial crops have low relevance on flat lands (<2% slope) within the state.

Annual Crops

Key management factors influencing contour farming effectiveness include row grade, ridge height, soil cover, soil roughness, and complementary practices (NRCS, 2017b).

The closer the row grade is to the true contour, the greater the erosion reduction and the greater the improvement in soil moisture use efficiency (NRCS, 2017b). Deasy et al. (2010) noted that if cultivation deviates from the contour, it may increase sediment and nutrient losses and may promote gully formation as runoff becomes concentrated in hillslope depressions.

The height of ridges on the contours is influenced by the operation of tillage and planting equipment (NRCS, 2017b). Taller ridges will be more effective in slowing overland flow. As both residue cover and roughness increase, overland flow velocities decrease, which, in effect, increases the slope length at which this practice is effective; however, increasing roughness alone is not sufficient to produce this effect (NRCS, 2017b).

Field borders may be needed to allow farm implements room to turn and control erosion along the field edge. Vegetative practices (e.g., grassed waterways, critical area planting) and/or structural practices like water and sediment control basins and underground outlets should be used to protect areas of existing or potential concentrated flow erosion (NRCS, 2017b).

Perennial Crops

Management factors that influence water quality protection effectiveness of contour farming of perennial crops (e.g., orchards) include the establishment of benches or berms and the implementation of complementary BMPs (NRCS, 2015). Inward-sloping benches or berms should be established at or near the tree or vine row to improve infiltration and reduce transport of sediment and other associated contaminants. Outward sloping benches may increase erosion caused by runoff from slopes above the bench. Where slow soil drainage may increase disease problems or where furrows could fill with water and overtop, it may be appropriate to slightly deviate from the level contour in order to promote drainage (NRCS, 2015).

The effectiveness of the contour farming practice can be increased by implementing complementary BMPs (NRCS, 2015). Vegetative ground cover (within alleys between the rows of trees/shrubs/vines, in row furrows, and on terraces and diversions) can increase infiltration, reduce surface runoff, reduce soil erosion, and facilitate nutrient cycling.

Recommendations and Considerations

- Contour farming is recommended for annual and perennial crops on farmland with slopes between 2 – 10%.
- Additional BMPs are needed in areas with a higher likelihood of erosion, such as:
  - Farmland with highly erodible soils (e.g. the Palouse region).
  - Areas with a history of erosion.
  - Slopes at the steeper end of the range (i.e. 5-10%).
- BMPs to supplement contour farming practices:
  - Conservation Tillage (Chapter 1)
  - Contour Filter Strips (Chapter 5)
  - Cover Crops (Chapter 5, and below)

- Additional edge of field practices like field borders, grassed waterways, and riparian buffers may be needed to help control areas of concentrated flow (e.g. edge of a row where machinery turns to shift to another row or contour).
- Contour farming is not recommended in areas where the slope is not uniform (e.g. rolling hills, hummocky lands).

Intercropping and Strip Cropping

NRCS (2017c) defines strip cropping (Practice Code 585) as growing planned rotations of erosion-resistant and erosion-susceptible crops or fallow in a systematic arrangement of strips across a field on the contour. For example, a strip of forage grasses or small grains downslope from a row-crop strip of corn or sugar beets can slow runoff, prevent formation of channelized runoff, filter eroded sediment and particulate pollutants, and promote water infiltration.

Intercropping (a practice component of Conservation Crop Rotation (328)) is very similar to strip cropping and is defined as the practice of growing two or more crop species simultaneously in the same field during part or all of their life cycles (NRCS, 2021). As defined by the NRCS (2021), intercropping also includes the seeding of a cover crop into an existing main crop or planting of a main crop into a living cover crop. Incorporating intercropping into an agricultural operation increases diversity and interaction between plants, arthropods, mammals, birds, and microorganisms, resulting in a more stable crop-ecosystem and a more efficient use of space, water, sunlight, and nutrients. Soil health benefits by increasing ground coverage with living vegetation, which reduces erosion, and by increasing the quantity and diversity of root exudates, which enhances soil fauna.

Per NRCS practice standards (NRCS, 2017c, 2021), two main differences between strip cropping and intercropping are the applicability of crop types and the planting layout. Strip cropping is applicable to grain, seed, vegetable, hay, and silage production whereas intercropping is only applicable to grain, seed, and vegetable crops. In strip cropping there are multiple rows of each plant type per strip and the strips are planted perpendicular (or nearly so) to the contour or prevailing direction of erosive winds. In intercropping, individual rows of different plant types are adjacent and the rows are not necessarily planted along the contour.

Strip cropping and intercropping protect water quality by reducing (Nie et al., 2012; NRCS, 2017c; Stoltz & Nadeau, 2014):

- Sheet and rill erosion.
- Wind erosion.
- Sediment transport to surface waters.
- Nutrients lost to surface runoff or through leaching.
- Pesticide transport to surface waters.

These practices have substantial value for source control of pollutants on cropland where conventional mono-cropping does not provide adequate protection against runoff transport, soil erosion, and/or nutrient runoff. Intercropping also has value for reducing the leaching of nitrogen (N) and phosphorus (P) through improved nutrient utilization or by reducing fertilizer requirements. The crop types, cultivation sequence, planting patterns, and crop rotations can be tailored to address site-specific conditions such as climate, soils, and the processes by which runoff generation and pollutant transport occur.

Both strip cropping and intercropping are applicable where winter/spring soil erosion is a concern, particularly in the hilly aeolian soils of the Palouse. Both practices are highly appropriate in western Washington where runoff during the rainy season can contaminate shellfish beds, which is an ongoing water quality problem. Strip cropping and intercropping may also help address ongoing problems of eutrophication and hypoxia in Puget Sound inlets from excessive N loading.

Recommendations and Considerations

- Strip cropping, intercropping, or relay intercropping is recommended for low-residue crops (e.g. potatoes) that are susceptible to erosion during storm events before a cover-crop can be established.
- Strip cropping can be applied to all cropland, especially sloping cropland, and is most appropriate for:
    - Grain, seed, vegetable, hay, and silage production throughout Washington.
    - Replacing conventional mono-cropping systems in areas where surface runoff occurs during the growing season.
    - Establishing strips of a cover crop or perennial vegetation that will provide soil cover, reduce runoff, and reduce nutrient transport beyond the cultivation period of an erosion-susceptible crop. For example, strips of perennial species used for forage can be grown with strips of potatoes, corn, soybeans, or other cash crops.
- Intercropping can be applied to both annual and mixed cropland and is most appropriate for:
    - Grain, seed, and vegetable production throughout Washington; the practice is not applicable for annual hay or silage crops (NRCS, 2021).
    - Replacing conventional mono-cropping systems where surface runoff and/or nutrient leaching occur during the growing season.
    - Replacing conventional mono-cropping systems to reduce fertilizer applications (e.g., through use of N-fixing legumes) or pesticide applications.
- Relay intercropping is a variation on intercropping, and involves:
    - Planting a cover crop prior to harvest of a main crop to provide soil cover, reduce runoff, and provide nutrient scavenging outside of the main crop growing season, and/or to reduce fertilizer needs for the subsequent main crop by

planting a legume. For example, this can occur where climate conditions inhibit establishment of a cover crop following the harvest of a main crop.

    - Establishing a cover crop before the planting of a main crop to provide soil protection, reduce runoff, reduce nutrient leaching, and/or reduce fertilizer needs for the main crop (i.e., by planting a legume); the main crop is subsequently planted into the existing live crop.

Additional considerations (NRCS, 2017c) include the following:

- To improve cropping system diversity and associated benefits, consider a crop rotation at least 3 years in length, including at least three crop species from different plant families.
- To capture and manage soil moisture, select crops, crop sequence, and crop varieties with sufficient density and cover to intercept runoff and blowing snow. When appropriate, manage the height of standing residues to maximize snow trapping potential.
- When this practice is used in combination with diversions or terraces, coordinate the strip layout with the diversion or terrace grade and spacing so that strip boundaries will parallel terraces wherever possible within the criteria for row grade. Where grass-back or narrow-base terraces are used, account for the uncropped width along the terrace so that the same strip width is maintained for all strips in the field.
- Stable outlets may be necessary where runoff tends to result in concentrated flow erosion. Acceptable stable outlets include grassed waterways, field borders, filter strips, or water and sediment control basins.

Intercropping

Potential variations of intercropping NRCS (2021) include the following:

- Simultaneous intercropping: planting two or more crops at the same time in the same field. For example, plant chickpeas and flax together either in alternate rows or mixed within rows.
- Relay intercropping: two or more crops can be grown on the same field with the planting of the second crop before the first crop is harvested. This cropping strategy enables production of a second crop in areas where time for seeding the second crop is considered inadequate for double cropping (e.g., seeding soybeans into wheat that is still growing).
- Strip intercropping: crops can be grown in alternate strips wide enough to permit separate crop production machinery, but close enough for crops to interact (e.g., planting alternating strips of corn and soybeans six rows each or alternating strips of corn and Sudan grass). Generally, the maximum width of individual strips for effective interaction of crop pests and their natural enemies is about 30 ft.

Alley Cropping

Alley cropping (AC) is an agroforestry practice in which agronomic, horticultural crops or forages are produced in alleys between (single or multiple) rows of trees or shrubs that supply additional products (NRCS, 2017a). The primary functions of the practice that influence water quality include (Kim & Isaac, 2022; NRCS, 2017a; O'Connor et al., 2023; Pavlidis & Tsihrintzis, 2018; Salceda-Gonzalez, 2023):

- Reduced surface water runoff and erosion.
- Decreased offsite movement of nutrients and/or chemicals.
- Altered subsurface water quantity or water table depths.

Additional functions of AC may include (NRCS, 2017a):

- Increased carbon storage in plant biomass and soils.
- Enhanced microclimatic conditions to improve crop or forage quality and quantity.
- Improved soil health by increasing utilization and cycling of nutrients.
- Enhanced wildlife and beneficial insect habitat.
- Increased crop diversity.
- Improved air quality.
- Supported development of renewable energy systems (i.e., through biomass production).

The mixing of trees/tree crops with row crops or forage that is supported by AC may be applicable to the large extent of orchard production in Washington. In areas where row crops and orchards co-occur, AC could be used to intermingle crop production in place of monocultures on separate fields. This practice would combine multiple BMPs into a single cropping strategy. When planting on the contours the trees/shrubs act as contour buffer strips and can provide wind protection as well (see Chapter 5). Additionally, the row crops can be used as conservation cover between the rows of trees/shrubs (as long as cover crops are established during fallow periods).

AC could significantly contribute to inhibiting the formation of concentrated surface runoff flows on sloping land. Shallow overland flow typically becomes concentrated flow after a maximum slope length of roughly 100 ft to 300 ft (IADNR, 2023; USACE, 2024). The presence of in-field tree/shrub rows with a spacing of <100 ft may disperse and infiltrate surface runoff, thereby reducing the risk of concentrated overland flow generation and the resulting erosion and delivery of pollutants to surface waters.

AC will be most appropriate for addressing leaching of nutrients (and potentially pesticides) when the period in which most leaching tends to occur coincides with the period in which trees/shrubs are actively taking up water and nutrients from soils.

AC is applicable to all cropland and hay land where trees, shrubs, crops, and forages can be grown in combination. AC is most appropriate where a producer seeks to achieve one or more of the functions listed above.

Recommendations and Considerations

- Alley Cropping is recommended for areas where contour farming, contour filter strips, conservation cover, and windbreaks are needed to prevent or minimize runoff and promote infiltration.
    - The practice of AC combines these BMPs into a single strategy (see above and Chapter 5 for recommendations on each practice).
- Additional considerations to prevent or minimize runoff and erosion are:
    - Tree or shrub rows should be oriented on or near the contour to reduce water erosion.
    - Selected species of trees and shrubs should be relatively deep rooted to encourage infiltration.
    - To reduce surface water runoff and erosion, herbaceous ground cover should be established in conjunction with the tree or shrub rows.
    - To reduce wind erosion, tree or shrub rows should be oriented as close as possible to perpendicular to erosive winds.
- Strip cropping in the alleys could be used to simultaneously produce two (or more) crops wherein the shadier portion of the alley is used for a shade-tolerant crop, while the central portion of the alley can be used for a less shade-tolerant crop.

Cover Crops

Cover crops are defined as grasses, legumes, and forbs that are planted for seasonal vegetative cover, particularly in row crop or commercial crop production. Cover crop planting can serve multiple purposes (NRCS, 2014b):

- Reduce soil erosion from wind and water.
- Reduce water quality degradation by using excess soil nutrients.
- Maintain or improve soil health and organic matter content.
- Suppress excessive weed pressures and break pest cycles.
- Improve soil moisture use efficiency.
- Alleviate soil compaction.

Cover crops reduce soil erosion by improving soil structure, stability, and permeability, in addition to providing groundcover to serve as a physical barrier between raindrops and the soil surface. By improving soil permeability, taking up soil moisture, and increasing surface roughness, cover crops can often reduce surface runoff or water percolation below the root zone. Through the combination of reduced runoff or subsurface flow, decreased soil loss, and enhanced nutrient uptake, cover crops can significantly reduce runoff and/or leaching losses of nutrients and other pollutants from cropland.

Traditional cover crops like rye or oats are generally applied in the fall, are not fertilized, and then are plowed down or killed in the spring. In some cases, commodity cover crops such as winter wheat can be planted without additional fertilizer application and harvested before spring planting. Cover crops can be seeded in the fall by drilling or broadcasting after crop harvest or by aerial broadcast into a standing crop before harvest. Effectiveness of cover crops is generally enhanced by early establishment; however, in cold regions, successful establishment of a cover crop may be limited by fall weather. The presence of a cover crop is generally most important in the spring (eastside) or fall (westside), when most runoff events occur, and lack of soil cover makes the soil more vulnerable to erosion. Depending on the subsequent crop to be grown and the tillage methods used, cover crops may need to be tilled under or killed with herbicides before spring planting. Research has generally shown a very small or negligible effect of cover crops on crop yield (Tonitto et al., 2006).

Cover crops represent a valuable management practice for protecting water quality, especially groundwater quality, which is often difficult to protect from nonpoint sources of soluble nutrients like nitrate (NO_3^-).

Cover cropping generally applies to seasonally grown row crops, either commodity or vegetable crops, where a significant amount of bare soil would otherwise be present after harvest and before new plantings. According to the WSU Extension (Roberts, 2018), cover crops were commonly grown in eastern Washington prior to the widespread use of synthetic fertilizers. As a best management practice (BMP), cover crops can be applied to commodity and vegetable crops across the state of Washington, subject to the design and management considerations discussed below. Roberts (2018) evaluated the feasibility of cover cropping and companion cropping for the inland Northwest and noted that spring-seeded cover crops grown in place of fallow could pose a risk to germination of a fall-seeded crop because the cover crop would likely reduce soil moisture needed for germination. The author recommended that a companion crop—a cover crop grown together with a cash crop—could be a viable alternative to post-harvest cover cropping.

Washington agriculture includes over 2.25 million acres of small grains such as wheat and barley, 164,000 acres of potatoes, some 160,000 acres of corn production, and numerous acres of vegetable crops. All these cropland acres may be appropriate for some type of cover crop, although establishment might be challenging in areas that are dry or have a relatively short growing season in the eastern portion of the state. Cover cropping has value where pollutant transport in surface runoff is a concern, particularly during winter/spring in the hilly aeolian soils of the Palouse, and to a lesser degree in western Washington during the rainy season from October through April.

Recommendations and Considerations

General recommendations concerning cover crops can be found in Chapter 5. Specific considerations on when, where, and what cover crops to use are found below:

- **Soil type and texture:** Cover crops may perform differently on different soils. Greater efficacy of cover crops at reducing nitrate leaching was evident with increasing soil sand content.
- **Climate:** Adequate moisture supply, provided by either natural precipitation or irrigation, is required to support establishment and growth of cover crops. Adequate growing season for establishment after harvest of the cash crop is required to allow development of a cover crop stand sufficient to protect the soil during winter and spring conditions.
- **Tillage:** Cover crops can generally be used under conventional tillage, reduced tillage, and no-till management, but performance will differ across the range of soil disturbance. Seeding cover crops will require different approaches on conventional vs. no-till cropland. The incremental benefit of cover crops may be greater on conventional tillage than on reduced tillage because reduced tillage soils already have some protective cover. No-till management also has lower labor demands with no fall plowing, which may allow more time for establishing a cover crop.
- **Cover crop species:** Traditional cover crop species include wheat, rye, barley, forage radish, annual legumes, oats, brassica *sp*., and mixed grasses. Traditional cover crops do not receive fertilizer and are not harvested. Commodity cover crops are planted for harvest in the spring and may include barley, rye, wheat, spring oats, and canola. Different plant species used for cover crops may offer different pollutant reduction performance (Kaspar et al., 2012; Nouri et al., 2022).
- **Planting method:** Cover crop seed may be planted in several different ways: broadcast, drilled, or aerial seeding. Seeding method will influence the quality of the cover crop stand, which in turn will influence the effectiveness of the cover crop. Choice of method depends mainly on the production crop, season, and available equipment. In general, broadcast or drilled seeding is most effective because of good contact with the soil, with aerial seeding (which may be required to seed into a standing crop) being the least effective.
- **Planting date:** In general, net cover crop effectiveness is enhanced by an early planting date, while much of the benefit of a cover crop may be lost in late planting, especially if the remaining growing season is inhospitable for developing a good ground cover.
- **Cover crop termination:** Management of the biomass produced by the cover crop will vary depending on the tillage practice and the crop(s) grown. For row crops planted in conventional spring tillage, for example, the cover crop biomass can be plowed down before planting, adding organic matter and nutrients to the soil in the process. For crops planted into reduced- or no-tillage, however, cover crops may need to be killed with herbicide prior to cash crop planting, adding another dimension to farm management.
- **Interactions with other practices:** Cover cropping can be readily combined with other cropland BMPs to increase sediment/nutrient efficiency. Management demands for

cropping should be considered when integrating cover cropping with other management activities. Addition of cover cropping to other BMPs such as nutrient management, wetland/bioreactor treatment, and conservation drainage can enhance nutrient removal efficiency. The added N fixed by legume cover crops can be factored into nutrient management and potentially reduce the quantity of purchased N fertilizers required for subsequent crops.

Related NRCS Practices

- Alley Cropping (311)
- Conservation Crop Rotation (328)
- Contour Buffer Strips (332)
- Contour Farming (330)
- Contour Orchard and Other Perennial Crops (331)
- Cover Crop (340)
- Critical Area Planting (342)
- Field Border (386)
- Grassed Waterway (412)
- Intercropping and Strip Cropping (E328N and 585)
- Nutrient Management (590)
- Residue and Tillage Management, No Till (329)
- Residue and Tillage Management, Reduced Till (345)
- Riparian Forest Buffer (391)
- Riparian Herbaceous Cover (390)
- Row Arrangement (557)
- Strip cropping (585)
- Terrace (600)
- Underground Outlet (620)
- Vegetative Barrier (601)
- Water and Sediment Control Basin (638)

Commonly Associated Practices

- Tillage and Residue Management (Chapter 1)
- Nutrient Management (Chapter 3)
- Sediment Stabilization and Capture - Vegetative (Chapter 5)
- Sediment Control Basins (Chapter 6)
- Runoff Control (Chapter 9)
- Riparian Areas and Surface Water Protection (Chapter 12)

Chapter 9 Appendix Part A: Effectiveness Synthesis Crop Systems

Conservation Crop Rotation

In general, research has shown that CCR and other measures to diversify crop sequences have had a positive impact on water quality from agricultural crop land (e.g., Her et al. (2016); Koropeckyj-Cox et al. (2021a); Yuan et al. (2022)). The following sections review scientific findings pertaining to water quality effectiveness at the plot to watershed scale, as well as complementary environmental benefits of CCR.

Water Quality Benefits: Plot to Field Scale

Reports of water quality benefits from CCR are difficult to summarize as the simple pollutant loss efficiencies that are often reported for other BMPs because of the large variety of rotation patterns and the general dearth of reporting from full rotation cycles vs. single crop years. For example, although the NRCS practice standard attributes reduced soil erosion to CCR, no studies were found that examine the effectiveness of a complete rotation cycle on erosion or sediment loads. Note that findings for cover crop effectiveness are applicable to CCR during the cover crop phase of a rotation.

In the United States, extended rotations are generally less widely practiced than shorter rotations. A two-year annual corn-soybean rotation is the most commonly implemented rotation system in the U.S. Corn Belt and this rotation has been the most extensively studied. However, much of the data reported for corn-soybean rotations are not highly relevant to this analysis because it is not a common cropping pattern for Washington and because contemporary ideas of CCR tend to go beyond the basic corn-soybean model.

In Ohio, Aggarwal et al. (2022) found that, during the soybean years in a corn-soybean rotation, total N and dissolved phosphorus (P) losses in subsurface drainage discharge were reduced by an average of 7% and 14%, respectively, compared to corn years, while total P lost was about the same across years. Also in Ohio, Shipitalo et al. (2013) measured a reduction of dissolved P and total P losses in runoff in soybean years by 55% and 43%, respectively, when compared to corn years in a corn-soybean rotation; average sediment losses were about the same or more for soybean compared to corn. Pease et al. (2018), in an extensive Ohio edge-of-field network study, found that total P and dissolved P losses in runoff and subsurface discharge were generally higher for continuous corn and lower for corn-soybean and corn-soybean-wheat rotations, except in the case of dissolved P in runoff, where the average loss was highest for corn-soybean. The Iowa Nutrient Reduction Strategy (IDALS, 2017) reported a 42% reduction in nitrate-N (NO_3-N) loss for a corn-soybean-alfalfa-alfalfa-alfalfa rotation compared to conventional cropping systems from their literature review.

In an extensive literature review including data from across the United States and Canada, Koropeckyj-Cox et al. (2021a) reported that including legume crops in rotation systems, particularly perennial varieties, can reduce nutrient losses from agricultural fields. Crop rotations have the potential to improve water quality by taking up and immobilizing nitrate that would otherwise be lost to leaching or runoff and by reducing the overall amount of N fertilizer that must be applied over the whole rotation period. The authors cite extensive data on N credits from legume crops in rotation following corn crops and discuss factors that influence the magnitude of the credit (Koropeckyj-Cox et al., 2021b). The authors further report that crop rotation systems that include legumes have been widely found to reduce N losses compared to cereal monocultures such as continuous corn. While data show no appreciable difference in N losses between continuous corn and corn-soybean rotation, annual N losses from corn-soybean-wheat, continuous alfalfa, and corn-oats-alfalfa were reduced by 61%, 29%, and 57%, respectively. The review also cites numerous studies of NO_3-N, total nitrogen (TN), and total phosphorus (TP) losses in surface runoff and tile drainage from various rotations vs. continuous corn under different tillage systems (Koropeckyj-Cox et al., 2021b). Finally, the authors note that the nutrient losses reported in many studies occurred mainly in the off-season for annual crops, highlighting the importance of cover crops to take up residual nutrients.

In a Brazilian study testing an extended corn-grass-soybean-grass rotation against traditional cropping systems, Silva et al. (2021) measured a 98% reduction in total water loss (runoff + subsurface drainage) compared to continuous soybeans, a 76% reduction compared to continuous corn, and a 74% reduction compared to a corn-soybean rotation. It should be noted that in this study, the grass crop functioned as a cover crop as well as a rotational crop. The role of cover crops in reducing nutrient losses from crop rotations has been discussed by Fioratti Junod et al. (2024). See the Cover Crop section for more information.

From an extensive literature review, Yuan et al. (2022) found that direct water quality (NO_3-N) comparisons were only available for corn-soybean rotation vs. continuous corn. Changing from continuous corn to corn-soybean rotation reduced NO_3-N load from subsurface drainage discharge by an average of 33% (63% maximum). According to the authors, crop rotation was shown to be the most cost effective of the practices reviewed (CCR, cover crop, filter strip, nutrient management, bioreactor, and constructed wetland) for reducing NO_3-N load, with a net economic benefit of about $5/kg NO_3-N reduction for corn-soybean rotation compared to continuous corn.

Using a life-cycle analysis at an ecosystem scale, Lago-Olveira et al. (2023) evaluated the environmental and economic benefits of crop rotation in a Mediterranean region of Italy. Measured with respect to EU ecosystem service indices that incorporate both measured and modeled parameters, the results indicated that wheat-chickpea rotation system offered lower environmental impacts, regardless of the functional unit considered. Global warming (18%) and freshwater ecotoxicity (20%) were the categories with the largest reductions; freshwater eutrophication was reduced by 12%, marine eutrophication by 13%, and marine ecotoxicity by 7% under chickpea-wheat rotations vs. continuous wheat. Furthermore, a 96% increase in gross income margin was observed with the rotation system, due to the low cost of chickpea cultivation and its higher market price.

In Michigan, McDaniel et al. (2023) tested whether diversifying/perennializing plants in agroecosystems through extended rotations or grassland restoration would decrease losses of new plant residue inputs and, thus, increase retention of carbon (C) and N in soil, yielding decreases in NO_3-N leaching losses. Through measuring losses of wheat residue N (N_{wheat}) in leached soil solution, the authors reported that the total percentage of N_{wheat} remaining after 2 years was 38.7% for corn-soybean rotation vs. 44.0% for a corn-soybean-wheat-cover crop rotation. The increase in retained N was interpreted as an indicator of reduced nitrate leaching.

In Ohio, Hanrahan et al. (2023) compared P losses between corn-soybean and corn-soybean-wheat rotations and reported that corn-soybean-wheat rotation did not improve water quality in combined runoff and drainage. Both dissolved and TP losses were greater from corn-soybean-wheat fields (median 0.5 kg dissolved reactive P (DRP)/ha and 2 kg TP/ha) compared to corn-soybean fields (median 0.1 kg DRP/ha and 1 kg TP/ha), due to elevated soil test P in the corn-soybean-wheat fields. The fraction of applied P exported from fields as both DRP and TP was also greater in corn-soybean-wheat (DRP = 2%; TP = 9%) compared to corn-soybean (DRP = 1%; TP = 3%), further confirming more available P susceptible to loss. These results contradict other research showing the effects of CCR on P loss. The authors attributed this to elevated soil test P in all fields, which drove P loss in runoff. CCR was unable to mitigate the effects of elevated soil test P.

Using edge-of-field data collected from multiple tile-drained cropland fields across northwest Ohio, Hanrahan et al. (2024) compared edge-of-field (subsurface and/or surface discharge) N balances and losses from corn-soybean and corn-soybean-wheat rotations. The study encompassed a wide range of tillage and fertilizer practices across the sites. For all rotations, highest N losses were measured during the corn phase; the lowest N losses were observed in the wheat phase of corn-soybean-wheat rotations. Annual mean NO_3-N and TN losses were 74% and 67% lower, respectively, from the wheat phase of corn-soybean-wheat rotations compared to the corn phase of corn-soybean rotations. Despite this, the median of average annual N balances for corn-soybean-wheat rotations was positive and further from equilibrium than corn-soybean, indicating that additional management changes (e.g., reducing N inputs) are needed to realize the full benefits of the CCR, particularly during corn phases.

Other Environmental Benefits

There has been considerable research published on other benefits of CCR, particularly with respect to soil health. Most studies have documented positive effects of CCRs on various metrics of soil health.

In Iowa and Wisconsin, Karlen et al. (2006) conducted soil quality analysis for bulk density, soil pH, aggregation, soil organic C, soil TN, extractable P, and other soil quality metrics at long term crop-rotation sites, including continuous corn, corn-soybean, oats with legume seeding, and meadow in various configurations. Extended rotations had a positive effect on soil quality indicators. Total organic C was the most sensitive indicator, showing significant increases at all locations, while bulk density showed significant differences at only one location. The lowest soil quality index (SQI) values and 20-year average profit were associated with continuous corn, while extended rotations that included at least 3 years of forage crops had the highest SQI values.

Shah et al. (2021) published a literature review documenting the benefits of diversified crop production (i.e., crop rotations) for sustainable agricultural production. The authors reported that diversified crop rotation improves the efficiency of farming systems all over the world, having the potential to improve soil condition and boost system productivity. Improved soil attributes such as increased soil water uptake and storage, and a greater number of beneficial soil organisms may improve yield tolerance to drought and other hard growing conditions in a variety of crop rotations. Crop rotations with a variety of crops benefit the farmers, reduce production risk and uncertainty, and enhance soil and ecological sustainability.

In Indiana and Ohio, Gonzalez et al. (2023) conducted field experiments to compare the effects of crop rotations (continuous soybean vs. soybean-corn), rye cover crop, and gypsum application on extractable nutrients and trace metals in soils. While all three treatments improved soil quality, the impact of crop rotation was greatest. The corn-soybean rotations, for example, removed 47%, 28%, and 42% more P, magnesium (Mg), and zinc (Zn), respectively, relative to continuous soybeans. Lower concentrations of extractable nutrients in soils tend to reduce the potential for nutrient losses in runoff and leaching.

In a meta-analysis of published literature, Iheshiulo et al. (2023) examined 148 rotational studies to document how crop diversity affected soil health properties. Overall, increased crop diversity (i.e., number of crop species in the rotation) significantly reduced bulk density (−1.6%), enhanced soil aggregation (15.9%), improved porosity (3.1%), and increased saturated hydraulic conductivity (112.8%), but did not significantly change infiltration rate compared to less diverse systems. Compared to using conventional tillage and cereals-only rotations, diverse rotations combined with conservation tillage or including grain legumes performed even better in enhancing both soil aggregation and porosity. Diverse crop rotations managed for 5–10 years showed greater benefits in regions experiencing mean annual precipitation exceeding 900 mm, and in medium- and fine-textured soils. Among soil physical health properties, saturated hydraulic conductivity was the most responsive to management practices.

Li et al. (2023) evaluated the effects of three crop phases of a rotation—wheat, alfalfa, and fallow—on soil nutrients from a plot study in irrigated agriculture in a semi-arid region of China. Soil organic C increased by 9% and 43% under wheat and alfalfa, respectively, compared to fallow. Soil TN increased by 17% and 47% under wheat and alfalfa, respectively. Soil available N increased by 26% and 30% under wheat and alfalfa, respectively. Changes in soil TP were negligible.

Iheshiulo et al. (2024) reported on the influence of crop rotations on soil hydraulic and physical quality under no-till on the Canadian prairies. Results revealed that improved crop rotations did not significantly impact bulk density or total porosity, but did improve macroporosity by 13%–127% and mesoporosity by 1%–36% compared to the conventional rotation, resulting in increased unsaturated hydraulic conductivity. At some sites, improved rotations led to significantly increased water content at field capacity and plant available water capacity.

Conclusions

It is difficult to make concise definitive statements concerning the effectiveness of CCR alone on water quality. In general, moving from a continuous monoculture such as corn to even a basic rotation that includes a legume crop (e.g., soybeans) decreases N losses, particularly NO_3-N in subsurface drainage water and provides an important carryover N credit for subsequent crops. There is scant data on the effectiveness of extended rotations in reducing N losses; losses have been reported for individual crops in rotation, but rarely for an entire sequence. Limited data suggest that reductions in annual N losses from extended rotations like corn-soybean-wheat, continuous alfalfa, and corn-oats-alfalfa can be significant. CCRs that include cover cropping—especially outside the primary growing season—are more likely to reduce N losses compared to continuous monoculture or rotations without cover crops.

Data for P loss reduction by CCR is inconsistent. While some research has shown reductions in TP loss under some rotations, other studies have shown no significant effect or even an increase in P loss, especially in the dissolved form (Koropeckyj-Cox et al., 2021a, 2021b). Hanrahan et al. (2023), for example, reported greater dissolved and TP losses under a corn-soybean-wheat rotation vs. a corn-soybean rotation. Reports of sediment reduction for CCR have also been mixed; crop rotation effects on soil loss are predominantly driven by factors of crop cover, elimination of fallow, and tillage practices, particularly level of soil disturbance and residue management. Soil characteristics beyond the effects of short-term studies such as organic matter content, soil texture, and infiltration rates also affect sediment loads. However, the effectiveness of cover crops at reducing sediment losses are applicable to CCR when the rotation includes cover crops.

Contour Farming

Contour farming creates soil surface roughness patterns that are perpendicular rather than parallel to the slope. This alteration in surface roughness patterns reduces surface runoff and soil erosion by slowing runoff velocity and detaining runoff in micro-depressions, thereby increasing opportunities for infiltration of precipitation. The net result can be a significant reduction of sediment, nitrogen (N), and phosphorus (P) transport and delivery in surface runoff (Farahani et al., 2016; Mondaca et al., 2024; Stevens et al., 2009).

Research examining soil erosion on cropland with contour tillage indicates that contour farming should be implemented as part of a system of soil and water conservation practices (Farahani et al., 2016; Puertes et al., 2021; Regasa & Nones, 2024). Contour farming with conventional tillage (CT) is less effective than contour farming with conservation tillage (no-till or minimum till) at controlling erosion in areas with relatively steep slopes (e.g., where slopes may locally exceed 10%) and rainfall intensities may be high during the growing season (Farahani et al., 2016). Modeling of semi-arid watersheds with ephemeral streams in Spain suggests that coupling grassed field borders or hedgerow field borders with contour farming can improve sediment and N load reductions to surface waters (Puertes et al., 2021). The potential for contour farming alone to reduce sediment and N loads was estimated to be 6.5% and 8.7%, respectively. Contour farming coupled with grassed field borders was estimated to have the potential to reduce sediment and N loads by 8.3% and 13.3%, respectively. Contour farming and hedgerow field borders had the greatest potential sediment and N load reductions at 12.1% and 20.2%, respectively.

Tang et al. (2022) studied factors influencing ephemeral gully formation on cropland with contour tillage in China. Ephemeral gullies were observed to form localized areas of steep slopes coincided with relatively large drainage areas. They also found evidence that much of the erosion associated with ephemeral gullies can be attributed to less frequent, high intensity rainfall events. Ridges formed by the contour tillage reduce the drainage areas that contribute to ephemeral gullies. However, when row slopes exceeded roughly 3.5%, ridges were eroded and overtopped by runoff. These findings provide support for NRCS design considerations that row slopes need to be no more than 4%.

In Ethiopia, Regasa and Nones (2024) used Soil and Water Assessment Tool (SWAT) modeling to predict the effectiveness of contour farming at reducing watershed–scale sediment yields. The authors estimated that contour farming could reduce sediment yields by 75% to 80%; however given the high rate of existing soil erosion, it was concluded that additional best management practices (BMPs) would be needed to achieve a tolerable rate of soil loss below 5 t/ac.

In summary, because contour farming does not fully control surface runoff and soil erosion (Fajeriana et al., 2024; Kurothe et al., 2014), it should not be considered a sole or stand-alone practice to achieve goals for soil loss reduction. Rather, contour farming should be implemented in concert with other practices that address the generation, transport, interception, and treatment of pollutants in surface runoff, such as conservation tillage, nutrient management, contour buffer strips, cover crops, field borders, grassed waterways, riparian buffers, terraces, and water and sediment control basins.

There are relatively few studies on the effectiveness of contour farming, with most of the findings arising from research outside the United States. Of the studies reviewed, nearly all focus upon sediment and/or P reductions, with only one study examining N reductions, and no studies examining pathogens or pesticide effectiveness.

Table 1 below summarizes literature findings on the effectiveness of contour farming at reducing sediment, N, and P in surface runoff. Following the table are subsections on sediment and nutrients that provide further detail about the studies with findings related to water quality protection.

It is important to recognize that experimental findings at the plot-scale may not be an accurate estimate of effectiveness at greater spatial or temporal scales. For example, plot-scale pollutant reduction estimates will underestimate hillslope to field scale reductions if a proportion of the pollutants (e.g., sediment) transported in surface runoff do not leave a field. Conversely, plot-scale studies may not accurately reflect the potential influence of concentrated flows upon pollutant generation and transport at the hillslope to field scale. As slope length increases, there is an increasing likelihood for the generation of concentrated flows which may accelerate erosion and pollutant transport through the formation of rills and gullies. This is because shallow overland flow typically becomes concentrated flow after a maximum slope length of roughly 100 ft to 300 ft (IADNR, 2023; USACE, 2024). According to NRCS (2017b), the volume and velocity of overland flows on slopes longer than 400 ft will exceed the capacity for contour ridges to contain the flow (and this again supports the conclusion that contour farming should be implemented in concert with additional complementary BMPs). Finally, data based on plot studies that measure one or a few storm events—especially using simulated rainfall—will tend to underestimate the effects of a practice over a full seasonal cycle or calendar year. Thus, effectiveness estimates for contour farming may be overestimated for field- or watershed-scales.

Table 1. Changes in surface runoff and pollutant loads attributed to contour cultivation.

Location	Study type	Technique	Runoff reduction (%)	Sediment reduction (%)[1]	Total N reduction (%)	Total P reduction (%)	Source
Ethiopia	Watershed Modeling—Soil and Water Assessment Tool (SWAT)	Cultivation effects simulated by adjusting curve number (CN) and practice support factor (P) in SWAT	>40	75 to 80	===	===	Regasa and Nones (2024)
Indonesia	Experimental—plot scale, natural rainfall	Embankments (EM) Bench terraces (BT)	24 (EM) 25 (BT)	8 (EM) 8 (BT)	===	===	Fajeriana et al. (2024)
India	Experimental—plot scale, natural rainfall	Ridge tillage (RT) Mulch tillage (MT) No-till (NT)	69.4 (RT) 59.6 (MT) 16.2 (NT)	78 (RT) 71 (MT) 37 (NT)	===	===	Kurothe et al. (2014)
China	Experimental—plot scale, natural rainfall	Ridge tillage (RT) Flat tillage (FT)	===	84 (RT) 77 (FT)	===	===	Zhang et al. (2004)
United Kingdom	Experimental—hillslope scale, natural rainfall	Unspecified	64 to 76	45 to 79	63 to 71	48 to 79	Deasy et al. (2010)
Brazil	Experimental—plot scale, simulated rainfall	Unspecified	===	===	===	28	Barbosa et al. (2009)
England	Experimental—plot scale, natural rainfall	Flat tillage with buffer strips (FT-B) Minimum flat tillage with buffer strips (MT-B)	72	(64, 88)[2] (+236, +9)[2]	===	(93,78)[2] (66, +10)[2]	Stevens et al. (2009)
Philippines	Experimental—plot scale, natural rainfall	Ridge tillage (RT) Flat tillage with buffer strips (FT-B) Ridge tillage with buffer strips (RT-B)	===	45 (RT) 30 (FT-B) 53 (RT-B)	===	===	Thapa et al. (1999)

[1] The results are relative to up- and downslope tillage, except the results from Thapa et al. (1999), which are relative to flat contour tillage alone.

[2] Results are relative to conventional up- and down slope tillage and minimum up- and downslope tillage, respectively. A “+” symbol indicates an increase in sediment loss.

Sediment

Most studies have concluded that contour farming reduces runoff volumes and sediment loss in comparison to tillage/cultivation that is not performed along slope contours (Fajeriana et al., 2024; Farahani et al., 2016; Kurothe et al., 2014; Stevens et al., 2009).

In India, Kurothe et al. (2014) evaluated contour farming relative to CT in a semi-arid, sub-tropical climate with non-irrigated, continuous cropping. The soil was a very deep sandy loam with a 1% to 2% slope. Four different cropping treatments were used for this plot scale experiment, which varied as follows:

- CT: two passes of cultivation followed by planking to smooth the surface. Crops were sown down-slope and residue removed from field after harvest.
- Ridge Farming Tillage (RFT): ridges with a roughly 6–inch height formed 18–inches apart on the contour without additional soil manipulation. Wet season crops were sown on ridges, dry season crops were sown in furrows, and residues were removed from the field after harvest.
- Stubble Mulch Farming Tillage (SMFT): one pass with a moldboard plow on the contour followed by one pass with cultivation, surface roughness maintained (no planking). Crops were sown on the contour, with 2 t/ha chopped pearl millet straw mulch spread on the surface.
- No Tillage (NT): no seedbed preparation, minimal soil disturbance for seed, and fertilizer placement using only a hand hoe. Crops were sown on the contour, and residues were removed from field after harvest.

Runoff and soil loss (based on sediment concentrations in runoff samples) were measured over two time periods totaling nine years of measurements. NT, SMFT, and RFT reduced runoff by 16%, 60%, and 69%, respectively, in comparison to CT. The average annual soil loss under CT was between 3 and 5 times greater than RFT and SMFT and 1.6 times greater than NT. Reductions in annual soil loss for RFT, SMFT, and NT were 78%, 71%, and 37%, respectively.

In England, Stevens et al. (2009) evaluated runoff and sediment losses from several treatments on sloping clay soils (slope range: 3.5% to 10.5%) involving: conventional or minimum tillage; contour flat tillage, up-downslope flat tillage, or mixed direction flat tillage (plowing and planting in an up- and down slope direction but rolling and other operations conducted on the contour); and the inclusion/exclusion of contour buffer strips. Contour tillage cultivation reduced surface runoff by a mean of 72% (range 9%–98%) compared to upslope and downslope cultivation in both the conventional and minimum tillage treatment areas, but the differences were not statistically significant. Contour conventional tillage with contour buffer strips was found to reduce sediment loss by 64% relative to conventional upslope-downslope cultivation and 88% relative to upslope-downslope minimum tillage. In contrast, contour minimum tillage with contour buffer strips increased sediment losses by 236% compared to conventional upslope-downslope cultivation and by 9% relative to upslope-downslope minimum tillage. The authors did not discuss potential reasons for why contour minimum tillage resulted in increased sediment loss, but it may have been related to a lack of contour-aligned surface roughness given the large reductions in erosion observed for contour conventional tillage. The addition of contour strips to contour tillage treatments further reduced sediment losses, but only by a small amount. Mixed direction operations were associated with increased runoff and increased sediment losses.

In the Philippines, Thapa et al. (1999) compared soil erosion rates on fields with slopes of 16%–22% following four different contour cropping methods: (1) contour moldboard plowing in the open field (MP-open); (2) contour ridge tillage in the open field (RT-open); (3) contour moldboard plowing with contour natural grass barrier strips (MP-strip); and (4) contour natural grass barrier strips plus ridge tillage (RT-strip). The contour buffer strips were 1.6 ft in width. Relative to the mean annual soil loss for MP-open, soil erosion was reduced by 30%, 45%, and 53% for the MP-strip, RT-open, and RT-strip systems, respectively. The results indicate that implementation of ridge tillage and contour buffer strips within a contour farming system further reduce soil losses.

In Indonesia, Fajeriana et al. (2024) evaluated differences in soil erosion on cropland plots with a 23% slope planted with kale. The three treatments were: upslope-downslope tillage; contour tillage with “soil bunds” (embankments along the downslope edge of the row); and contour tillage with flat terraces along the contour. Over the course of the four-week study, the two contour practices reduced runoff amounts by 24% to 25% and reduced soil erosion by 8% to 11%.

In the United Kingdom, Deasy et al. (2010) found that contour farming of clay soils reduced overwinter runoff by 64% to 76% and losses of sediment by 45% to 79% at the field scale. The addition of 6.6 ft wide elevated contour buffer strips resulted in additional total phosphorus (TP) and total nitrogen (TN) reductions of 16% to 94%.

In China, Zhang et al. (2004) compared soil erosion rates between ridge contour tillage vs. downslope ridge tillage and flat contour tillage vs. downslope flat tillage on plots with slopes ranging between 4% and 48%. Erosion rates for ridge contour tillage and flat contour tillage were 84% and 77% lower, respectively, compared to the downslope tillage methods.

Nitrogen and Phosphorus

Studies indicate that contour farming can lead to nitrogen (N) and phosphorus (P) reductions at plot and field scales relative to farming that does not follow hillslope contours (Deasy et al., 2010; Stevens et al., 2009). In a simulated rainfall experiment in Brazil, Barbosa et al. (2009) found that contour farming reduced plot-scale TP losses during cultivation of oats and vetch crops by 28% in comparison to upslope-downslope cultivation. At the field scale (slope length range: 230 ft to 886 ft) in the United Kingdom, Deasy et al. (2010) found that contour farming of clay soils reduced overwinter losses of TP and TN in surface runoff by 48% to 79% and 63% to 71%, respectively. Including contour buffer strips reduced TP and TN by an additional 9% to 97% and 30% to 97%, respectively.

In England, Stevens et al. (2009) found that the intensity of tillage influenced the effectiveness of contour cultivation at reducing plot-scale P losses on slopes of 3.5% to 10.5%. Contour conventional tillage with contour buffer strips was found to reduce TP loss by 93% relative to conventional upslope-downslope cultivation and by 78% relative to upslope-downslope minimum tillage. Contour minimum tillage with contour buffer strips decreased TP loss by 66% compared to conventional upslope-downslope cultivation, yet increased TP loss by 10% relative to upslope-downslope minimum tillage. It is unclear why contour minimum tillage with contour buffer strips resulted in greater P loss than upslope and downslope minimum tillage. One potential reason is that a lack of contour-aligned surface roughness may have facilitated increased movement of soil-adsorbed P. This seems plausible when considering that contour conventional tillage with contour buffer strips had lower sediment and TP loss relative to both conventional and minimum upslope-downslope tillage.

Pathogens and Pesticides

No studies were located that examined reductions in pathogens and pesticides resulting from contour farming. However, reductions in loads of pathogens in surface runoff are likely to occur due to documented reductions in surface runoff volumes for contour farming. In this regard, it is likely that pathogen reductions are similar to those of sediment and nutrients, whose reductions are also correlated with infiltration of runoff into soils. For highly mobile pesticides (i.e., those that have a lower organic carbon-water partition coefficient (K_{oc})), reductions are likely to be strongly correlated with reductions in surface runoff volumes and similar to observed reductions for dissolved N and P in runoff. The effectiveness of contour farming for pesticides with low mobility (i.e., those that have a higher K_{oc}) is likely to be similar to the observed practice effectiveness for sediment reductions because these pesticides tend to adsorb to sediment and organic matter particles.

Conclusions

- Contour farming of annual and perennial crops can be effective at reducing surface runoff, and the sediment, N, and P loads associated with low to moderate intensity precipitation events.
- Contour farming is most appropriate on moderately sloped (2% to 10%) lands with slope lengths of less than 400 ft.
- There is some evidence that during high intensity storms, contour farming may result in increased soil erosion in comparison to downslope farming. The erosion risk increases as slope length, slope steepness, and slope irregularity increases.
- There is some evidence that contour ridge tillage may reduce runoff and pollutant transport more than contour flat tillage, particularly in regions that experience higher intensity storms.
- The addition of contour buffer strips may improve the effectiveness of contour farming, with the benefit likely varying according to the width of the strip, the density of the vegetation, and whether or not soils in the strip are mounded.
- To obtain best performance, contour farming should be combined with other practices such as conservation tillage, contour buffer strips, cover crops, field borders, grassed

waterways, riparian buffers, terraces, and water and sediment control basins. By itself, contour farming is unlikely to be effective at protecting surface water quality.

Intercropping and Strip Cropping

Most estimates of pollutant reduction effectiveness associated with multi-species cropping have focused on intercropping rather than strip cropping, and their effectiveness for water quality protection may differ. No studies were found that compared the pollutant reduction effectiveness of strip cropping to that of intercropping.

Intercropping reduces sediment and nutrients in surface runoff through increased soil cover that inhibits runoff generation and soil erosion, and by promoting infiltration of water into soils (Nyawade et al., 2019, Siller et al., 2016). No studies were found that evaluated the effectiveness of strip cropping at reducing sediment and nutrients in surface runoff. Differences in the physical arrangement of species between strip cropping and intercropping may translate into differing effectiveness at reducing pollutant loads in surface runoff. Strip cropping is typically practiced on sloping land across the slope and filters runoff generated in the strips of erosion susceptible crops, for example in grass strips downgradient of row crop strips. Intercropping is not necessarily practiced on sloping land and may lack the runoff filtering functions of strip cropping; however, intercropping inhibits runoff generation and subsequent pollutant transport by increasing the amount of soil cover relative to monocropping (Nyawade et al., 2019).

Intercropping has also been found to reduce NO_3^- leaching (Nie et al., 2012), and may reduce the risk of P leaching (He et al., 2024). When intercropping with a legume, evidence suggests that the risk of N leaching is reduced when the fixation of N by the legume is sufficient to reduce N fertilizer requirements for the non-legume crop; concurrently, if the amount of available N (e.g., NO_3-N and NH_4-N) is not a limiting factor then crop yields on a land-equivalent ratio may be maintained or increased (Nasar et al., 2024; Stoltz & Nadeau, 2014). However, reductions in N leaching have also been observed in intercropping systems that do not incorporate legumes (Nie et al., 2012). Reductions in nitrate leaching in non-legume intercropping systems occur through enhanced plant uptake of N (Nie et al., 2012), as well as potentially through enhanced denitrification processes associated with soil conditions that are altered by the presence of multiple crops (Wang et al., 2024). Lastly, there is evidence that intercropping of certain crop combinations (e.g., wheat and fava bean) can draw down the pool of P in soils by increasing the bioavailability of less labile forms of P (He et al., 2024). This may decrease the risk of P losses in two ways—by reducing P fertilization requirements (He et al., 2024) and by decreasing the risk of P runoff in eroded soil and leaching associated with P saturation in soils (Djodjic et al., 2004).

Strip cropping may not be as effective as intercropping at reducing NO_3^- leaching. Reductions in nutrient leaching for intercropping systems are linked to the close proximity of differing crop species (He et al., 2024; Nasar et al., 2024; Stoltz & Nadeau, 2014). Nutrient leaching can be reduced in intercropping through improved nutrient use efficiency by the multi-species mixture

(Nie et al., 2012) or indirectly when legumes provide N to the other crop(s) within the system (Stoltz & Nadeau, 2014; Yan et al., 2024). In strip cropping, fertilizer–derived NO_3^- leaching below the strips of one crop type may be largely inaccessible to the roots of a crop in adjacent strips. Without comparative studies of the two practices, caution should be exercised in applying the effectiveness findings for one practice to the other practice.

The effectiveness of both intercropping and strip cropping at reducing pesticides loads remains largely unquantified due to a lack of research. A study by Rutkoski et al. (2024) found evidence that a practice analogous to strip cropping reduced the transport of a pesticide with moderate to high mobility; however, the value of the findings are limited due to the low rigor of the study. Other evidence indicates that intercropping and strip cropping may indirectly protect water quality from pesticides by reducing the need for pesticide applications (Alarcón-Segura et al., 2022; Yan et al., 2024). Reductions of pesticides with low mobility (i.e., those that have a higher K_{oc}) are likely to be similar to the practice effectiveness at reducing sediment loads because these pesticides tend to adsorb to soil particles (Long et al., 2005). Load reductions of highly mobile pesticides (i.e., those that have a lower K_{oc}) within surface runoff are likely to be strongly correlated with reductions in surface runoff volumes and similar to reductions for dissolved N and P. This is because infiltration of precipitation into soils is the primary means by which loading of dissolved pollutants in runoff to surface waters is prevented (see Chapter 12).

The effectiveness of intercropping and strip cropping at reducing pathogen loads is also uncertain because no relevant studies were located for this evaluation. However, reductions in pathogen loads in surface runoff are likely to be strongly correlated with reductions in surface runoff volumes because water infiltration into soils is the primary means by which small, suspended particles (e.g., clay or microorganisms) in surface runoff are prevented from reaching surface waters.

Table 2 provides pollutant reductions reported from several studies of intercropping and strip cropping. Summaries of effectiveness findings for individual studies follow the table.

Table 2. Summary of pollutant reductions associated with intercropping and strip cropping.

Location	Study type	Practice	Treatment	Evaluation type	Sediment reduction %	Nitrogen reduction %	Phosphorus reduction%	Pesticide reduction %	Author
China	Experimental	Intercropping	Corn with soybean, groundnut, ryegrass, or alfalfa	Leaching	===	12.5 to 76.3[1]	===	===	Nie et al. (2012)
Kenya	Experimental	Intercropping	Potatoes with legumes	Surface Runoff	51 to 70	41 to 82[2]	52 to 70[3]	===	Nyawade et al. (2019)
Wisconsin	Experimental	Intercropping	Corn, no-till planted into Kura clover	Surface Runoff	77	80[2]	80[4]	===	Siller et al. (2016)
Iowa	Observational: Paired Watershed	Strip cropping	Contour prairie strips within fields planted with corn	Surface Runoff	===	===	===	50.6[5]	Rutkoski et al. (2024)

[1] Nitrate
[2] Total nitrogen
[3] Plant-available phosphorus (e.g., ortho-phosphorus)
[4] Total phosphorus
[5] Clothianidin

Sediment

Literature on the effectiveness of intercropping and strip cropping at reducing sediment losses from cropland is very limited. Both studies reviewed for this evaluation indicate that intercropping can reduce sediment losses in surface runoff by more than 50%.

In Kenya, potatoes intercropping with legumes was found to reduce plot-scale sediment yield by 51%–70% compared to a mono-cropped potatoes (Nyawade et al., 2019). Most of the sediment loss occurred as potato shoots were emerging and after potato harvest, indicating that the effectiveness of intercropping at reducing pollutant transport depends on the level of soil cover. Intercropped legumes reduced soil erosion due to an emergence and growth rate that exceeded that of the potatoes, thereby providing more soil cover than in mono-cropped potatoes.

In Wisconsin, a simulated rainfall experiment was conducted to compare soil erosion and nutrient losses in surface runoff between mono-cropped corn and corn intercropped with Kura clover as a living mulch (Siller et al., 2016). Five simulated rainfall events were conducted over a one-year period with the intensity of each being equivalent to a storm event for southeast Wisconsin having a 1 hour duration and a 50 year return period (70 mm hr^{-1}). Averaged over the five events, the intercropping treatment displayed 50% less runoff and 77% less soil loss relative to monocropping.

Nitrogen and Phosphorus

Intercropping has been found to substantially reduce N and P export in surface runoff. Potatoes intercropped with legumes in Kenya reduced plot-scale losses of TN and plant-available P in surface runoff by 41%–82% and 52%–70%, respectively, in comparison to mono-cropped potatoes (Nyawade et al., 2019). As for sediment, nutrient losses were greatest early in the cropping period, after fertilizer application, while soil cover was minimal. Additionally, in Wisconsin, corn intercropped with clover resulted in an 80% reduction in both total N and total P lost in runoff compared to mono-cropped corn (Siller et al., 2016).

There is evidence that intercropping can also reduce NO_3^- leaching. In China, Nie et al. (2012) found that reductions in nitrate leaching in intercropping systems were not limited to grain-legume combinations. In this study, N fertilizer was over-applied (827 lb/ac) to plots that were either mono–cropped (corn) or intercropped (corn-soybean, corn-groundnut, corn-ryegrass, or corn-alfalfa) to assess the effect of intercropping upon nitrate leaching. All intercropping treatments reduced nitrate leaching relative to the sole corn, with reductions ranging from 12.5%–76.3%. The results therefore indicate that intercropping can reduce N leaching in fields where N fertilizer applications exceed uptake by conventional monocrops.

Intercropping may also indirectly reduce the potential for N leaching by reducing N fertilizer requirements. In France, Yan et al. (2024) examined whether intercropping led to reductions in N fertilizer use and found that it depended upon the crop type. Nitrogen fertilizer use was reduced by up to 38% for wheat intercrops, which was attributable to the incorporation of a legume in the system. There were no significant differences in N fertilizer use between the canola monocrops and intercrops. For pea-based intercrops, an increase in N fertilizer use was observed in comparison to peas monocrops. The reason for this is that mono-cropped peas do not require N fertilizer, whereas the pea intercrop contains cereal grain, which does require fertilizer.

In China, Nasar et al. (2024) found evidence that intercropping of corn and soybeans can reduce N fertilizer requirements while producing similar or greater total grain yields to monocropping. In comparison to corn-soybean rotation monocropping with 25% less N fertilizer than the conventional amount used, intercropping without N fertilizer resulted in a total grain yield that was roughly equal to monocropping. Intercropping yield with 25% less N fertilizer than the conventional amount used for monocropping exceeded that of monocropping. This suggests that intercropping may indirectly protect water quality by reducing N fertilizer requirements, resulting in less N available to be leached through soils or transported in surface runoff.

In Sweden, Stoltz and Nadeau (2014) found that corn intercropped with faba bean (fertilized with 60 kg N/ha) was associated with 40% less residual soil NO_3-N in the 0.0 m to 0.60 m soil depth relative to mono-cropped corn (fertilized with 120 kg N/ha). Although this result may be expected because twice as much N was applied to the mono-cropped corn, it is important to recognize that yields (based on a land equivalent ratio, i.e., the ratio of the area of sole cropping to the area of intercropping needed to produce the same yield) were greater in two of three fields with intercropping plots than in mono-cropped plots. The increased yield and reduced soil residual NO_3-N were found in the fields with relatively high amount of available N, but not in a field with lower N availability. Therefore, in contrast to the study by Nasar et al. (2024), this study was able to conclude that comparable yields could be attained though intercropping despite using half as much N.

Some research has compared the effects upon soil NO_3-N when a cover crop is terminated either before or after the planting of a main crop. In Nebraska, Stephens et al. (2023) found that in the first and wetter year of the experiment, termination of a cereal rye cover crop two weeks after planting of soybeans reduced soil NO_3-N levels by the same amount (48%) as termination of the cover crop two weeks prior to planting soybeans; this occurred despite the late-terminated cover crop attaining a biomass more than six times greater than the earlier-terminated cover crop. In the drier second year, soil nitrate increased under both treatments, which was thought to be a potential result of crops using less N in drier years and/or the addition of N to the soil by soybean residues. This study indicates that a short period of intercropping with a cover crop (e.g., two weeks) may not have any additional benefit on the soil nitrate leaching potential than growing cover crops and main crops without overlap in their periods of growth.

Intercropping may also indirectly reduce the potential for P losses in surface runoff and leaching by reducing P fertilizer requirements. In a multi-year intercropping experiment in China, He et al. (2024) observed that intercropping fava bean with wheat had greater P uptake than when either were grown as a single crop. This effect was primarily associated with an increase in the mobilization (i.e., increased biological availability) of P from the non-labile P pool within the intercropping treatment. In contrast, intercropping had almost no effect on the labile P pool relative to monocropping. These findings suggest that at least some types of intercropping systems can reduce the soil P saturation level, thereby reducing P fertilization requirements, and consequently reduce the risks of P loss in surface runoff or through leaching.

Other Pollutants

Research addressing the effects of intercropping and strip cropping on pesticide transport are very limited, and no studies were found that address effects upon pathogen transport. As described below, some studies indicate that intercropping and strip cropping may have direct or indirect effects on water quality protection from pesticides.

In Iowa, Rutkoski et al. (2024) evaluated whether the incorporation of contour prairie grass strips into catchments with grassed waterways used for corn-soybean rotations reduced the transport of the pesticide clothianidin (a neonicotinoid insecticide that has a moderate to high mobility in soils (APVMA, 2007)) relative to fields without prairie strips. In effect, this cropping system was analogous to strip cropping. The prairie strips were planted six years prior to the study, and corn was the crop grown during the study period. Clothianidin was not detected in any groundwater samples, and the highest levels of the pesticide were found in soil samples from the furthest downgradient location (footslope position) in both the treatment and control fields. Clothianidin concentrations in the surface layers of soils in the footslope position were 50.6% lower in the prairie strip treatment than in the control; however, the difference was not statistically significant. The authors cautioned that the study was conducted during drought conditions that resulted in minimal surface runoff and also that the grassed waterways in the fields may have facilitated the downslope transport of the pesticide. Nevertheless, the results provide evidence that strip cropping can reduce pesticide transport in surface runoff.

Intercropping and strip cropping may indirectly protect water quality from pesticides by reducing the need for pesticide applications (Alarcón-Segura et al., 2022; Yan et al., 2024). In Germany, Alarcón-Segura et al. (2022) found evidence that strip cropping of two crops (canola and wheat) that typically use high levels of synthetic pesticides resulted in greater biological control of insect pests through predation. The results suggest that synthetic pesticide usage may be decreased where intercropping and strip cropping facilitate biological pest control, thereby reducing the supply of pesticides available for transport off the field. Yan et al. (2024) used cropping data reported in a national database for French farms to conduct paired comparisons of pesticide use between monocrops and intercrops for multiple crop species (including winter wheat, winter barley, peas, and canola). Pesticide use was reduced on average 42% and 50% in the case of wheat- and barley-based intercrops compared with sole wheat and barley crops, respectively, due to reductions in herbicides and fungicides. Pea-based intercrops were the only system in which insecticide use was reduced—by an average 72%; the authors noted, however, that most insecticide use for cereal crops is through seed treatment, which was not addressed by the study. In contrast, no significant differences in pesticide use were observed between canola monocrops and intercrops.

Conclusions

- Intercropping and strip cropping have been shown to reduce sediment, N, P, and pesticides in surface runoff.
    - Studies of intercropping have found reductions in sediment, N, and P of 51%–77%, 41%–82%, and 52%–80%, respectively (Nyawade et al., 2019, Siller et al., 2016).
    - Strip cropping has been found to reduce the amount of a moderate to highly mobile pesticide by approximately 51%.
    - Reductions in pathogen transport are uncertain, although they are likely to be similar to reductions in sediment.
- Intercropping and strip cropping can reduce nutrient leaching of N.
    - NO_3-N leaching reductions of ~13%–76% have been observed for intercropping (Nie et al., 2012).
- Additional research on intercropping is needed to evaluate potential reductions in P leaching.
- There is evidence that intercropping and strip cropping can reduce N and P fertilizer requirements and pesticide requirements.
- The effectiveness at reducing fertilizer use, pesticide use, pollutants in runoff, and nutrient leaching are dependent upon site conditions as well as the mixture of crop species, cultivation sequencing, planting patterns, and crop rotations. Given wide variation in both site conditions and potential intercropping and strip cropping systems, the effectiveness for a specific combination of site conditions and a cropping system cannot be predicted.
- Beyond water quality benefits, intercropping and strip cropping may improve soil health, plant health, and plant productivity.
- In designing an intercropping or strip cropping system intended to reduce pollutants in surface runoff or subsurface flow, it is important to consider the following factors:
    - Site factors such as climate, topography, soil characteristics, and pests/disease.
    - Management factors such as tillage and residue management, fertilization requirements and methods, irrigation requirements, soil drainage systems, and pesticide use.
    - Resource concerns, for example what pollutants need to be addressed and how they are being generated and transported.

Alley Cropping

The rows of trees, shrubs, and/or other perennial vegetation in AC systems reduce pollutant transport in surface runoff through a number of interrelated effects (Kim & Isaac, 2022; Pavlidis & Tsihrintzis, 2018; Salceda-Gonzalez, 2023), including:

- **Intercepting precipitation**, which reduces raindrop impact upon soils and slows the development of runoff.
- **Increasing soil organic carbon (SOC)**, which increases soil water–holding capacity.
- **Increasing soil porosity**, which increases soil water–holding capacity.
- **Increasing soil hydraulic conductivity**, which increases the rate at which soils drain.
- **Increasing infiltration**, which reduces runoff volumes.
- **Increasing surface roughness**, which reduces runoff velocities and increases physical trapping of sediment.

Additionally, the rows of perennial plants within AC systems can reduce leaching of dissolved N and P below through:

- **Uptake of water and nutrients by trees and shrubs** (Andrianarisoa et al., 2016; Gikas et al., 2016; Salceda-Gonzalez, 2023).
- **Drying of deeper soil** layers by trees and shrubs (Allen et al., 2004; O'Connor et al., 2023).
- **Enhancement of conditions for denitrification** (Kim & Isaac, 2022; Pavlidis & Tsihrintzis, 2018).
- **Microbial transformation of nitrate (NO_3) into less-mobile ammonium (NH_4)** (Andrianarisoa et al., 2016).

Deep rooted trees serve as a nutrient pump by translocating N and P into their above ground tissues from soil layers below the crop rooting zone; nutrients are eventually deposited onto the alley cropped soil surface via litterfall as well as in the upper soil profile via root death and decay (Gikas et al., 2016; Kim & Isaac, 2022; O'Connor et al., 2023). O'Connor et al. (2023) found evidence that as trees within an AC system age, they develop fine root systems within deeper soil layers, which dries the soil below the crop rooting zone, thereby increasing the volume and depth of soil able to store precipitation during the non-growing season. Additionally, there is evidence that exudates from tree roots in AC systems facilitate the microbial transformation of negatively charged nitrate (NO_3-) into positively charged NH_4; NH_4 is less susceptible to leaching because of it has a tendency to adsorb to negatively charged soil particles (Andrianarisoa et al., 2016; O'Connor et al., 2023). Inputs of carbon associated with tree roots and litter can enhance denitrification which removes N from the system through the transformation of nitrate-N (NO_3-N) in the soil into N gas (N_2) that is emitted into the atmosphere (Kim & Isaac, 2022; Pavlidis & Tsihrintzis, 2018; Salceda-Gonzalez, 2023). For dissolved P, the primary means for reducing leaching is through tree/shrub uptake (Gikas et al., 2016).

A key aspect to the effectiveness of AC systems is that the strips of perennial vegetation can remove pollutants from runoff and subsurface leaching during periods of time before and after the alley crops are actively growing and providing soil cover (Dougherty et al., 2009; Pavlidis & Tsihrintzis, 2018). However, it is important to note that because AC can increase infiltration of precipitation (Pavlidis & Tsihrintzis, 2018) there may be potential for increased subsurface drainage and leaching of nutrients and pesticides; for example, leaching may be increased following fertilizer applications that occur prior to the growing season for annual or perennial alley crops and while the trees/shrubs are dormant.

Literature specific to the effectiveness of AC systems is somewhat limited. Most studies of AC effectiveness have examined its influence on N losses through leaching or surface runoff. In contrast, few studies have examined the effectiveness of AC systems for controlling pesticides, P, sediment, and pathogens (e.g., *E. coli*). Study findings on pollutant reductions in surface runoff and subsurface transport (e.g., leaching, shallow subsurface flow) are depicted in Table 3 and Table 4. This is followed by sub-sections that summarize AC effectiveness findings for individual pollutant types. Some of the findings summarized below include relevant effectiveness information for similar agroforestry practices (e.g., riparian buffers) relevant because AC systems are a type of agroforestry. Also, because the perennial vegetation rows in AC systems are essentially narrow vegetated buffers, effectiveness findings for riparian buffers and vegetative soil stabilization practices are also relevant to the consideration of AC effectiveness. See chapters 5 and 12 for more information.

Table 3. Alley cropping pollutant reduction effectiveness for surface runoff[1]

Location	Study type	Sediment reduction (%)	Total suspended solids reduction (%)	Nitrate reduction (%)	Total N reduction (%)	Total P reduction (%)	Dissolved P reduction (%)	Pesticide reduction (%)	Author
Missouri	Observational: paired watersheds	===	62	25[2]	64	23	===	===	Salceda-Gonzalez (2023)
Missouri	Observational: paired watersheds	===	30	===	11	26	===	===	Udawatta et al. (2011)
Missouri	Observational: paired watersheds	===	+35	24[3]	20[4]	17	===	===	Udawatta et al. (2002)
Italy	Observational: upgradient–downgradient	===	88 to 94	===	74	80 (approximately)	7[5]	===	Borin et al. (2010)
North America	Meta-analysis: silvoarable agroforestry	62	===	===	===	===	===	===	Zhu et al. (2020)
Global	Meta-analysis: linear tree plantings	24 to 80	===	===	===	===	===	===	Zhu et al. (2020)
Global	Global Review	===	===	===	===	===	===	40 to 100	Pavlidis & Tsihrintzis (2018)

[1] Values with a + indicate an increase in pollutant transport.
[2] Result is for NO_3 + NO_2-N.
[3] Result is from the third year of implementation (April –May 1999). There was no reduction in NO_3 during years 1 and 2 of the study.
[4] Reported result is from a single large runoff event during April 1999, in the third year of the study. No reduction in total nitrogen (TN) was observed in years 1 and 2 of the study, and the overall reduction for year 3 was not reported.
[5] Result is for PO_4–P.

Table 4. Alley cropping pollutant reduction effectiveness for subsurface transport.

Location	Study type	Pollutant pathway	Nitrate reduction (%)	Dissolved P reduction (%)	Pesticide reduction (%)	Pathogen reduction (%)	Author
Italy	Observational: upgradient–downgradient	Shallow subsurface flow	100 (approximately)	100[1] (approximately)	55 to 90	===	Borin et al. (2010)
Florida	Experimental: control–treatment	Leaching	72	===	===	===	Allen et al. (2004)
Greece	Observational: plot comparison	Leaching	===	15 to 50[1]	===	===	Gikas et al. (2016)
Canada	Observational: plot comparison	Tile drainage	5 to 46	===	===	NS[2]	Dougherty et al. (2009)

[1] Result is for PO_4–P.
[2] Differences in *E. coli* concentrations within tile drain effluent were not significantly different.

Sediment

Studies indicate that AC systems can effectively reduce the loss of sediment in runoff from cropland (Borin et al., 2010; Salceda-Gonzalez, 2023; Udawatta et al., 2011). However, the literature suggests that several years of growth may be needed for the perennial vegetation to become effective at promoting infiltration of runoff and trapping of sediment (Udawatta et al., 2021; Udawatta et al., 2011; Udawatta et al., 2002).

In a paired watershed study in Missouri, Udawatta et al. (2002) found that annual total suspended solids (TSS) loads increased by 35% in a corn-soybean AC system in the first three years following implementation before trees and grass in the 15 ft wide vegetated strips (containing three species of oak trees, perennial grasses, and a legume (Birdsfoot trefoil)) had become fully established. Roughly one decade later, after the tree/grass buffers were fully established in the same AC system, Udawatta et al. (2011) reported that annual TSS loads had been reduced by 30%. Using the same paired watersheds in Missouri by Udawatta et al. (2002), Salceda-Gonzalez (2023) found that annual TSS loads in the AC system after 25 years of implementation were 62% lower than loads from the control watershed. The greater decrease in sediment loads relative to the previous studies was attributed to the development of mature stands of trees that reduced runoff velocities and facilitated water infiltration while also increasing soil hydraulic conductivity and soil porosity. It was also suggested that water use by trees and an associated increase in soil water–storage capacity (i.e., via drying of soils through tree evapotranspiration) may also have contributed to the sediment load reduction. The ability of trees in agroforestry systems to increase infiltration capacity and soil water–storage capacity by reducing soil moisture content has been observed in a prior study by Anderson et al. (2009) at this same experimental site in Missouri.

In two experiments in Italy over 3 and 4 years, Borin et al. (2010) evaluated the effects of narrow vegetated buffers on TSS in surface runoff from crop fields used for corn, soybean, and sugar beet rotations. The buffer strips in these studies were analogous to a vegetation strip in an AC system. Two sites were evaluated: a >20–year old, 6m wide hedgerow of trees/shrubs, with trees periodically harvested for wood and a 4–year old, single row of trees adjacent to a strip of grass (4 m total width). TSS reductions of 88% were observed in the younger 4 m buffer and 94% in the older 6 m buffer.

A meta-analysis of data from 119 studies comparing soil erosion and runoff between multiple agroforestry practices (including alley cropping) and monocropping in humid and sub-humid tropical climates found that soil erosion and runoff in agroforestry systems were reduced by 50% and 57%, respectively, and infiltration rates were 75% greater than in monocropping systems (Muchane et al., 2020). Although this effectiveness information is associated with locations of ecological conditions very different from those of Washington, the underlying physical processes by which AC in tropical climates reduce sediment transport are comparable. However, because the study did not separately evaluate the effectiveness of AC, the findings for this evaluation are of limited value. Similarly, Zhu et al. (2020) performed a global meta-analysis of 83 studies on the effectiveness of agroforestry practices for water quality protection.

One analysis evaluated global findings for linear tree plantings, a practice analogous to AC. Sediment reductions for linear tree plantings ranged from 24% to 80%. Another analysis evaluated “silvoarable agroforestry” which included combined effects for two practices: (1) AC and (2) agroforests combined with perennial shade tolerant crops. Mean runoff and sediment reductions for North American studies of silvoarable agroforestry were 28% and 62%, respectively.

Nitrogen

The following subsections summarize the findings of studies that have evaluated the effectiveness of AC at reducing the amount of N lost in surface runoff or through subsurface leaching. Additionally, trees and shrubs in AC systems theoretically can capture N (ammonia (NH_3) and nitrous oxide (N_2O) from the air associated with atmospheric emissions from inorganic fertilizer and livestock manure (Kim and Isaac, 2022). However, no studies were reviewed that quantified the reductions associated with this effect.

Surface Runoff

The available literature on the effects of AC systems suggests that reduction of N transport in surface runoff is likely to vary according to site-specific conditions and management factors such as soil characteristics (e.g., soil hydrologic group), slope, precipitation patterns and variability, tillage, crop types, age of the system, and presence of other best management practices (BMPs) that affect runoff velocities and volumes such as cover crops and nutrient management.

In Missouri, Udawatta et al. (2002) initiated a long-term paired watershed study to examine the effectiveness of AC at reducing nutrients in surface runoff from corn-soybean rotations. AC did not reduce annual total nitrogen (TN) loss during the first two years of the implementation as tree rows were becoming established, but did lead to a 20% reduction in TN load during a large precipitation event in the third year of the study. Similarly, NO_3-N loads did not decrease in the AC system during the first two years, although there was a 24% reduction in NO_3-N loss during the third year of the experiment. At the same study sites roughly ten years after initial implementation of the AC system, Udawatta et al. (2011) observed an annual TN load reduction of 11%.

Returning to the same paired watersheds in Missouri studied by Udawatta et al. (2002), Salceda-Gonzalez (2023) found that NO_3-N + nitrate as nitrogen (NO_2-N) and TN loads in a corn-soybean AC system were 25% and 64% lower, respectively, than loads from the control watershed after 25 years of implementation. The AC system had N losses in runoff corresponding to 13% of the total applied from fertilizer. The results of all three studies (see Table 3) suggest that the effectiveness of the AC system at reducing N in surface runoff increased as the tree rows matured (Salceda-Gonzalez, 2023; Udawatta et al., 2011; Udawatta et al., 2002).

Leaching

A consensus in the literature indicates that AC systems can significantly reduce NO_3^- leaching. The magnitude of NO_3^- leaching reductions can vary with a number of factors including: the number, age, and species of trees/shrubs in the buffer rows; interannual-variability in precipitation; soil characteristics; geology; N fertilizer application rates; and crop uptake of N (Bergeron et al., 2011; Salceda-Gonzalez, 2023). One key factor is that uptake of water by trees/shrubs in the buffers needs to coincide with times when the majority of NO_3- leaching occurs (Dougherty et al., 2009). In temperate climates, most NO_3- leaching occurs between November and May (Andrianarisoa et al., 2016). If substantial NO3- leaching occurs during time periods when while deciduous trees and shrubs are dormant, then the trees/shrubs will neither uptake NO_3^- nor will they reduce NO_3^- mobility by drying out soil layers. Similarly, although AC can facilitate denitrification through the addition of organic C to soils (Kim & Isaac, 2022; Pavlidis & Tsihrintzis, 2018), the rate of denitrification is inversely proportional to the temperature (Addy et al., 2016; Hoover et al., 2016). In this regard, there may be misalignment between time periods when denitrification potential is at a maximum and time periods during which the majority of nitrate movement through soils occurs.

In Greece, Gikas et al. (2016) compared NO_3-N concentrations through soil profiles in cultivated fields and adjacent to poplar stands that bordered the cultivated fields. In cultivated fields NO_3-N concentrations were observed to increase with soil depth, while in the areas of fields adjacent to poplar stands, NO_3-N concentrations were found to decrease with soil depth. Depth-averaged NO_3-N concentrations were 36% to 54% lower in areas of the fields adjacent to poplar stands than at greater distances in the fields.

In southern France, Andrianarisoa et al. (2016) evaluated the effectiveness of an AC system at reducing N leaching involving hybrid walnut and wheat/canola rotations receiving fertilizer at a rate of 134 lb N/ac annually. After 14 years of tree growth, mineral N in soils at 0.2 m, 1.0 m, and 2.0 m depths were 64%, 58%, and 51% lower, respectively, compared to the conventional wheat/canola crop system serving as the control. In a similar study of a pecan-cotton AC system in Florida, Allen et al. (2004) observed that NO_3-N leaching was reduced by 72% at a soil depth of 0.9 m below the cotton alleys.

In Quebec, Canada, Bergeron et al. (2011) evaluated the effect of hybrid poplar trees in AC systems at two sites (site 1: soybean crops on clay loam soils; site 2: a canola/white clover rotation on sandy soils) upon N leaching. Over a two year period, cumulative tree uptake of NO_3^- on the clay loam soils was estimated to be 229 lb N/ac. The total N uptake exceeded the cumulative amount of N fertilizer (119 lb N/ac) applied during the two years. DON, which was only sampled in year 2, was reduced by 139 lb N/ac; the reduction in DON leaching was thought to be caused by enhanced utilization of DON in the vicinity of tree roots. The trees reduced NO_3-N leaching more in year 1, in which greater precipitation occurred, and concentrations were greater in the soil solution. In contrast, the overall reduction of N leaching was insignificant at the site with sandy soils. The authors suggested that younger trees on this site

(6–year old trees on the clay loam soils vs. 2–year old trees on the sandy soils) and N leaching rates that exceeded root N uptake rates accounted for the lack of an effect upon N leaching.

In Ontario, Canada a study of a mixed AC system involving hybrid poplar, silver maple, winter wheat or corn, and canola found reductions in NO_3-N leaching of 5% and 46% for two consecutive years (Dougherty et al., 2009). The main differences between the two years were that winter wheat was grown in 2005, while corn was grown in 2006 (e.g., a fall planted crop vs. a spring planted crop). In 2006, there was more NO_3- in the soil available that could be leached or taken up by plants; precipitation was greater in 2006 (especially during spring and fall) which increased the duration of tile drain flow. The authors concluded that AC can significantly reduce NO_3-N leaching when site conditions that promote leaching occur, such as high N availability in soils during spring when N uptake by alley crops is not occurring.

In Illinois, Wolz et al. (2018) evaluated differences in plot-scale NO_3^- leaching involving either conventional corn-soybean (MSR) cropping or AC systems containing six different food-producing tree and shrub species and alleys in which grass-clover hay was grown. Grass-clover alleys, rather than row-crop alleys, were included in this study because this is the approach most commonly used by farmers adopting AC in the region. Over the four–year study period, NO_3-N leaching (at 20 inch soil depth) constituted 29.6% and 5.5% of annual N inputs to MSR and AC, respectively, and leaching was reduced by 82%–91% in AC. However, because the alley crops were different among treatments, the results are limited to demonstrating that conversion of conventional MSR systems to AC systems with hay production reduces NO_3-N leaching, i.e., the results do not demonstrate that corn-soybean AC systems have lower NO_3-N leaching than conventional MSR systems. Another weakness of the study is that the NO_3-N samples were taken at a depth representing two-thirds of the rooting zone of the corn-soybean, ignoring the possibility that additional NO_3-N uptake or other changes in conditions affecting leaching may have occurred below this depth.

In Missouri, Salceda-Gonzalez (2023) examined the effects upon N in shallow groundwater by 15 m edge-of-field agroforestry buffers (containing grass and deep-rooted poplar trees) within catchments used for pasture underlain by deep loess soils. The buffers reduced dissolved nitrogen (DN) and TN concentrations in shallow groundwater by 99% (5.36 mg/L to 0.06 mg/L) and 85% (9.04 mg/L to 1.37 mg/L). Although the study was conducted on a site grazed by livestock rather than a row cropping system, the results suggest that trees can also substantially reduce concentrations of N leached from cropland or hay land into shallow groundwater. The author suggested that variation in N reductions among different sites may be attributable to tree species, tree age, buffer width, soil characteristics, and geology.

It should be noted that the use of some tree species in AC systems can increase N inputs on a site. Leguminous trees in AC systems contribute tens to hundreds of pounds of new N per acre annually (global average roughly 220 lb N/ac/yr) through their symbiotic association with N fixing bacteria in their root tissue; however, this can vary considerably based on soil characteristics, soil biology, and management factors (such as tree density and fertilizer inputs) (Kim & Isaac, 2022). This may result in a reduced need for crop fertilization if the alley crops are able to access N inputs associated with the trees. Therefore, when using leguminous trees in an AC system, their potential influence on N availability for alley crops should be considered relative to fertilizer inputs, for example as part of a nutrient management BMP (NRCS 590). This is because maintaining conventional fertilization rates in an AC system containing leguminous trees may increase the total amount of N inputs to the system, which, depending on site conditions, may also increase the risk of N export through leaching or surface runoff. According to Kim and Isaac (2022) the cumulative N inputs to agroforestry systems from leguminous trees (via subsurface N_2 fixation, tree litter deposition, pumping of subsoil N by tree roots, and aerosol ammonia capture) can far exceed N inputs from organic amendments and inorganic fertilizers. Therefore, the additional presence of non-leguminous trees in the tree rows may be warranted to manage potential N leaching (Bergeron et al., 2011).

Phosphorus

Relatively few studies have examined the influence of AC systems on P transport. The following subsections summarize results of available research that has examined the influence of AC upon surface and subsurface transport of P.

Surface Runoff

In Missouri, Udawatta et al. (2002) initiated a long-term paired watershed study which included examination of the effectiveness of AC at reducing P loads in surface runoff from corn-soybean rotations. AC reduced annual total phosphorus (TP) loads by 17% during the first three years of implementation, relative to the control. At the same study sites roughly ten years after initial implementation of the AC system, Udawatta et al. (2011) observed annual TP load reductions of 26%. Returning to the same paired watersheds in Missouri studied by Udawatta et al. (2002), Salceda-Gonzalez (2023) found that TP loads in a corn-soybean AC system were 23% less than loads from the control watershed after 25 years of implementation. The AC system had P losses in runoff corresponding to 24% of the total applied from fertilizer. Overall, TP reductions displayed little change over the entire span of time that the AC system was studied.

In Italy, Borin et al. (2010) found that a 6 m wide narrow buffer strip (composed of tree/shrub and analogous to vegetation strips in AC systems) along crop fields used for corn, soybean, and sugar beet rotations reduced total P and PO_4–P in surface runoff by 80% and 7%, respectively. The authors explained that the observed TP reduction could be attributed to sediment trapping by the buffer strip since most of the TP was in a sediment-bound form, which suggests that most of the PO_4-P was in a dissolved form.

Leaching and Subsurface Transport

AC systems can also reduce excess P in soils. Although most P loss tends to occur via surface runoff, P leaching can be significant and is influenced by factors including the amount of P in the soil, the capacity of the soil minerals to adsorb P, the rate of vertical movement of water through the soil, the depth to groundwater, and tillage practices (Djodjic et al., 2004, Pan et al., 2023). Gikas et al. (2016) observed that PO_4–P concentrations at locations in cultivated fields both adjacent to and distant from poplar stands declined with soil depth (indicating low-mobility); however, depth-averaged PO_4–P concentrations were 15% to 50% lower in crop soils adjacent to the poplar stands. In Italy, Borin et al. (2010) found that a 6 m wide narrow buffer strip (composed of 1 m of trees and 5 m of grass and analogous to vegetation strips in AC systems) along crop fields used for corn, soybean, and sugar beet rotations reduced PO_4–P in shallow groundwater by nearly 100%.

Pesticides

There has been very limited research on the effectiveness of AC systems at reducing pesticide losses through either surface runoff or leaching. In Italy, Borin et al. (2010) found that a 20–year old vegetated buffer (1 m width of trees and 5 m of grass) along a crop field with corn, soybean, and sugar beet rotations reduced several pesticides in shallow groundwater by 55% to 90%. The pesticides that had lower reduction rates (alachlor and nicosulfuron) were those with a high mobility in soils (i.e., a lower organic carbon-water partition coefficient (K_{oc})), while those with greater reduction rates (linuron, pendimethalinin, and terbuthylazine) have a low mobility in soils (i.e., a high K_{oc}). In a global review of the effectiveness of multiple agroforestry practices, the range in reductions of various pesticides in surface runoff was reported to be from 40% to 100% (Pavlidis & Tsihrintzis, 2018).

Pathogens

Research addressing reductions in pathogens in AC systems is even more limited than that examining pesticide transport. In Ontario Canada, Dougherty et al. (2009) compared *E. coli* counts in tile drain effluent from monocropping and AC systems during spring in two consecutive years. Mean *E. coli* counts were lower in tile drainage from the AC system in comparison to the monocropping system (11.5% and 16.5% lower for the two years), yet the differences were not statistically significant. There is a lack of evidence that AC systems reduce the transport of pathogens in surface runoff. However, AC can be expected to reduce pathogen transport because it has been observed to increase infiltration of runoff (Zhu et al., 2020). In this regard, pathogens reductions in surface runoff are likely to be similar to those observed for sediment and nutrients, whose reductions in surface runoff are also correlated with infiltration.

Conclusions

- The strips of perennial vegetation in an AC system act as in-field buffers, helping to prevent surface runoff and associated pollutants from leaving fields.
- AC systems can reduce sediment, TN, TP, and pesticide losses in surface runoff from fields and may also reduce pathogen transport.
    - The limited study data suggest that AC can be effective at reducing P and N associated with sediment and organic particles transported in surface runoff, but that reductions in dissolved P and NO_3^- in runoff require infiltration of runoff into soils. This difference has been observed in studies of other BMPs that influence erosion and soil/particulate losses.
- AC can reduce losses of NO_3^- and dissolved P from a field that occur through leaching or subsurface transport, although the effectiveness may display seasonal variation.

    - AC can reduce N leaching when the period(s) of greatest N leaching coincide with periods of high water and N uptake by trees and shrubs. The same is likely to be true for leaching of dissolved P.
    - Reductions in N and P leaching by the tree/shrub rows associated with uptake of water and nutrients are unlikely when conditions that promote leaching (e.g., wet soils that have been fertilized in between cropping periods) coincide with tree/shrub dormancy; however, reductions may still occur if the tree/shrub rows lead to enhanced subsurface denitrification (e.g., resulting from increased levels of SOC).
- AC may reduce the transport of airborne N (e.g., NH_3, N_2O) associated with agricultural activities (e.g., atmospheric emissions from manure and inorganic fertilizer applications).
- The effectiveness of AC for water quality protection on a given site is likely to vary by several site, seasonal, and management factors:
    - Important site and seasonal factors likely include soil characteristics, slope, climate variables such as precipitation patterns and amounts, dormancy periods for tree/shrub species, and depth to groundwater.
    - Important management factors likely include alley widths, buffer widths, crop types, tree/shrub species, the presence of tile drains, and implementation of other BMPs that address pollutant generation and transport including, but not limited to, conservation tillage, cover crops, nutrient management, and pesticide management.
- Key circumstances that enhance the effectiveness of AC at reducing sediment, N, and P losses in surface runoff include:
    - Tree and/or shrub rows are positioned along a contour to intercept overland flow.
    - Tree/shrub rows are well established.
    - Soils are unsaturated.
    - Concentrated flow does not exit the tree/shrub rows.
- Key circumstances that enhance the effectiveness of AC at reducing N and P losses through leaching or shallow subsurface flow include:
    - Trees/shrubs grown in the buffer strips are deep-rooting species.
    - Tree/shrub rows are well established.
    - The period(s) in which trees/shrubs in the buffer strips are actively taking up water and nutrients coincides with the period(s) in which most nutrient leaching or subsurface flow occurs.
    - Trees/shrub rows are positioned to intercept subsurface flow.
    - There is adequate coverage of a field by the tree/shrub rows, e.g., the quantity, dimensions, and spacing of the tree/shrub rows are proportional to the field size.

Cover Crops

Cover crops can effectively address issues of erosion and soil loss, nutrient (N and P) losses in surface runoff, and nutrient (N) leaching to groundwater. Research has consistently demonstrated the effectiveness of cover crops in controlling N losses both in surface runoff and in water leaching; reports of P loss reduction are less consistent but have also been shown. From an agronomic point of view, reductions in N losses can mean less need for supplemental N fertilizers. The following sections discuss the scientific findings on the effectiveness of cover crops at protecting water quality as well as complementary environmental benefits.

Water Quality Benefits

The effects of cover crops on pollutant reductions reported from selected published scientific literature are summarized in Tables 5 and 6 below as reduction efficiencies in percent. Efficiencies for surface runoff and for leaching losses are reported separately.

Table 5. Changes in surface runoff quantity and pollutant load attributed to cover cropping.

Location	Conditions[1]	Runoff reduction (%)	Runoff Pollutant Load Reduction (%)[2] TSS	TN	NO_3-N	TP	Diss P	Source
Ohio	Mixed watershed; SWAT	< 2	28	18	17	16	12	Bosch et al. (2013)
Global	Meta-analysis	18	≤ 75	===	28	+5	===	Daryanto et al. (2018)
Global	Meta-analysis	16	51	===	39	===	===	Fioratti Junod et al. (2024)
New Jersey	Ag watershed; SWAT	ns	1–3	===		3–14	===	Giri et al. (2020)
Ohio	Corn-soybean-wheat	ns	===	ns	ns	ns	ns	Hanrahan et al. (2021)
Missouri	Corn-soybean		===	===	===	70	73	Kaur et al. (2024a)
Missouri	NT corn-soybean	12–16	0–50	===	0–68	===	===	Kaur et al. (2024b)
Austria	Potato	68	50	===	===	===	===	Konzett et al. (2024)
Iowa	NT corn-soybean	65	68	===	===	83	84	Korucu et al. (2018)
Chesapeake Bay watershed	CC1 NT commercial crop	===	===	<1	===	===	===	CBP (2017); EPA (2023)
Chesapeake Bay watershed	CC 2 High till row crop; normal plant	===	10	20	===	7	===	CBP (2017); EPA (2023)

Location	Conditions[1]	Runoff reduction (%)	Runoff Pollutant Load Reduction (%)[2] TSS	TN	NO_3-N	TP	Diss P	Source
Chesapeake Bay watershed	CC 3 High till row crop; early plant	===	20	20	===	15	===	CBP (2017); EPA (2023)
Missouri	NT corn-soybean	30	29	ns	ns	69	75	Salceda-Gonzalez (2023)
Global	Meta-analysis	50	97	===	===	===	===	Scholberg et al. (2010)
Illinois	Mixed watershed; corn-soybean	34	33	===	+ ~51	+ ~6	===	Singh et al. (2018)
Iowa	Corn-soybean	===	===	23–39	43	===	===	Waring et al. (2024)
Austria	Winter wheat	17	===	===	===	===	===	Yu et al. (2016)

[1] Some studies include subsurface drainage with surface water measurement.
[2] Positive values indicate a decrease; "ns" indicates no significant effect.

Table 6. Changes in leaching quantity and pollutant load attributed to cover cropping.

Location	Conditions	Flow change (%)	Leaching Pollutant Load Reduction (%)[1] TN	NO_3-N	TP	Diss P	Source
South Dakota	NT corn-soybeans	===	$\leq$ -16	$\leq$ -20	===	===	Bawa et al. (2023)
Global	Meta-analysis	===	===	41	===	===	Fioratti Junod et al. (2024)
Ohio	Corn-soybean-wheat	ns	50	50	ns	ns	Hanrahan et al. (2021)
Illinois	Corn-soybean plots	===	48	60	===	===	Johnson et al. (2024)
Various	Review	===	===	17–80	===	===	Meisinger et al. (1991)
Global	Meta-analysis	ns	===	69	===	===	Nouri et al. (2022)
Various	Meta-analysis	===	===	70	===	===	Scholberg et al. (2010)
Global	Meta-analysis	===	===	56	===	===	Thapa et al. (2018)
Global	Meta-analysis	===	===	40–70	===	===	Tonitto et al. (2006)

[1] Positive values indicate a decrease; "ns" indicates no significant effect.

The flow and pollutant reduction efficiencies cited in Tables 5 and 6 illustrate the high degree of variability in the documented effectiveness of cover cropping. Reported reductions in surface runoff due to cover crops have ranged from negligible to 68%. None of the studies included in this summary reported significant changes in leaching volume, although with significant reductions in surface runoff, increased leaching might be expected. It is possible that this apparent discrepancy is because most reported studies have focused on either leachate or runoff, but not both. In addition, studies that combined surface runoff with captured subsurface drainage (e.g., Johnson et al. (2024); Kaur et al. (2024a); Kaur et al. (2024b)) included changes in upper soil leaching in their reported water budgets. Finally, increases in leaching volume are accounted for in the load reductions reported in Table 2, suggesting that pollutant concentrations were lower under cover cropping.

Reported reductions in soil loss (measured as total suspended solids (TSS)) have also been variable, ranging from negligible to 97%. Experimental design and methods may explain some of this variability. Results from watershed-scale modeling (e.g., SWAT) are difficult to compare to edge-of-field studies. Some reported reductions have been derived from short-term plot studies, some using only a few events of simulated rainfall. It is often observed that overland flow, erosion, and transport processes in small plots vary with plot design and may not be fully representative of field-scale processes. Furthermore, runoff and soil loss observed in a few runoff events may not represent long-term behavior over a full seasonal cycle. Other sources of variability in the reported effectiveness of cover crops on reductions in soil loss include soil type and texture, tillage level, extent of crop cover, biomass of the cover crop and the timing or method of cover crop termination. These and other issues of cover crop design and management are discussed in more detail below. Regardless of the variability in performance of cover crops in specific settings, it is widely accepted that cover cropping can significantly reduce soil erosion and soil loss from cropland. For example, in a county-scale analysis in U.S. Midwestern states, Chen et al. (2022) reported that counties with higher cover crop acreage had statistically lower water and wind soil erosion levels.

Cover crop reductions in N and P losses from cropland have been variable as well. Part of this variability is based on transport mechanism and pollutant chemistry. For example, Hanrahan et al. (2021) reported that N loads in tile discharge and surface runoff were significantly reduced by cover crops but that P loads were either unaffected or increased under cover crops. As shown in Table 2, reductions in N leaching (principally nitrate-N (NO_3-N)) of >50% are frequently reported, whereas cover crops appear to have a negligible effect on dissolved P leaching. This pattern is likely due to the mobility of soluble NO_3-N in soils vs. the tendency of P to be strongly adsorbed to the soil. Furthermore, N uptake by the growing cover crop is a major component of N reduction in soil water, especially in situations where excess N from commercial fertilizers or legume crops remains in the soil after crop harvest. Significant reductions in both N and P loss in surface runoff have been observed due to cover cropping (Table 5); again, some of the variability may be explained by soil type, tillage level, cover crop species used, and the extent of crop cover (see Tables 7, 8, and 9 for ranges of effectiveness).

Data on cover crop effects on other pollutants are scarce. In Maryland, Reed-Jones et al. (2016) concluded that although cover crops may have an impact on bacterial population dynamics in soils, they were not the only or most influential driving force. The utilization of cover crops and green manures as possible biocontrol strategies against foodborne pathogens did not appear to be promising. However, in Kansas, Zhao et al. (2023) reported on the potential for three cover crop species to reduce the load of *E. coli* bacteria in contaminated agricultural soils. Mustard, hemp, and buckwheat cover crops significantly reduced the population of *E. coli* compared to the control. Buckwheat resulted in the highest reduction (3.92 log CFU/g). An inhibitory effect on microbial growth was also observed in soils containing mustard greens and sunn hemp.

As a general principle, most of the scientific literature supports the use of cover crops to reduce both runoff and leaching losses of sediment and nutrients from cropland. To infer cover crop performance on a specific site, however, managers must consider the soil type and texture, climate, tillage, cover crop species, and other factors of cover crop design and management as discussed below. If a specific reduction efficiency value must be selected (e.g., for use in modeling), managers should consult the details of the particular study cited to ensure applicability to the situation.

Other Environmental Benefits

Beyond water quality improvement, cover crops may offer several other environmental benefits. NRCS (2014b) states that the cover crop practice 340 can be applied to support one or more of the following purposes:

- Reduce erosion from wind and water.
- Maintain or increase soil health and organic matter content.
- Reduce water quality degradation by utilizing excessive soil nutrients.
- Suppress excessive weed pressures and break pest cycles.
- Improve soil moisture use efficiency.
- Minimize soil compaction.

In modeling of corn-soybean rotations in a Mid-Atlantic climate, Schipanski et al. (2014) estimated that cover crops could increase 8 of 11 ecosystem services without negatively influencing crop yields: crop yield, biomass product, nitrogen mineralization, nitrous oxide (N_2O) reduction, soil carbon (C) storage, erosion control, mycorrhizal fungi, and weed suppression.

Daryanto et al. (2018) discussed some ecosystem services of cover crops based on a meta-analysis of global data:

- Cover crops increase the concentration of soil organic carbon, total nitrogen, and total phosphorus.
- Cover crops increase soil microbial biomass carbon, nitrogen, phosphorus, and colonization by arbuscular mycorrhizal fungi.
- Cover crops reduce the bulk density of soil.

- Cover crops reduce weed, but not plant-parasitic nematode incidence.
- Cover crops increase yields of the subsequent cash crop.

The authors noted, however, that cover crops tend to increase greenhouse gasses flux compared to fallow.

In Minnesota, Gutknecht et al. (2023) noted that farmers reported soil health improvements including increases in earthworm counts, improvements in apparent soil structure, earlier planting dates, and consistent crop growth across fields after several years of cover cropping. Although actual field and laboratory assessments did not always support these observations due to high variability across sites, the authors concluded that adding a diverse annual cover crop mix to increase continuous cover can improve characteristics associated with soil health.

Table 7. Traditional cover crop effectiveness values for total N (TN), total P (TP), and sediment (TSS) (CBP, 2022)[1].

	Coastal Plain/Piedmont Crystalline/Karst						Mesozoic Lowlands/Valley and Ridge Siliciclastic					
	Low-till land uses			High-till land uses			Low-till land uses			High-till land uses		
Cover crop type[2]	TN (%)	TP (%)	TSS (%)	TN (%)	TP (%)	TSS (%)	TN (%)	TP (%)	TSS (%)	TN (%)	TP (%)	TSS (%)
Rye, early, drilled	45	0	0	45	15	20	34	0	0	34	15	20
Rye, early, other	38	0	0	38	15	20	29	0	0	29	15	20
Rye, early, aerial	25	0	0	25	15	20	19	0	0	19	15	20
Rye, standard, drilled	41	0	0	41	7	10	31	0	0	31	7	10
Rye, standard, other	35	0	0	35	7	10	27	0	0	27	7	10
Rye, late, drilled	19	0	0	19	0	0	15	0	0	15	0	0
Rye, late, other	16	0	0	16	0	0	12	0	0	12	0	0
Wheat, early, drilled	31	0	0	31	15	20	24	0	0	24	15	20
Wheat, early, other	27	0	0	27	15	20	20	0	0	20	15	20
Wheat, early, aerial	17	0	0	17	15	20	13.5	0	0	13.5	15	20
Wheat, standard, drilled	29	0	0	29	7	10	22	0	0	22	7	10
Wheat, standard, other	24	0	0	24	7	10	19	0	0	19	7	10
Wheat, late, drilled	13	0	0	13	0	0	10	0	0	10	0	0
Wheat, late, other	11	0	0	11	0	0	9	0	0	9	0	0

[1]Only rye and wheat cover crops are listed.

[2]Early/standard/late refers to planting date. Early means the cover crop is planted more than two weeks before the average frost date. Standard or normal is when the cover crops is planted between the average frost date and two weeks before that date. Late is when the cover crop is planted within three weeks after the average frost date. Aerial/drilled/other refers to seeding method. Aerial includes seeding by airplane and other broadcast methods where the seed is not incorporated into the soil (including broadcast only and broadcast/stalk-chopped). Drilled involves planting with a seed drill, whether no-till or conventional till conditions apply. Other includes any non-drilled seeding method where the seed is incorporated into the soil, e.g., broadcast and disked

Table 8. Commodity cover crop TN reductions. (CBP, 2022)[1]: Coastal Plain, Piedmont Crystalline and Karst Hydrogeomorphic Regions

Cover crop type[2]	Low-till land uses TN (%)	High-till land uses TN (%)
Commodity cover crop, early	5	5
Commodity cover crop, standard	10	10
Commodity cover crop, late	15	15

[1]There are no TP or TSS reductions associated with this BMP.
[2]Early/standard/late refers to planting date. Early means the cover crop is planted more than two weeks before the average frost date. Standard or normal is when the cover crops is planted between the average frost date and two weeks before that date. Late is when the cover crop is planted within three weeks after the average frost date.

Table 9. Commodity cover crop TN reductions. (CBP, 2022)[1]: Mesozoic Lowlands, Valley and Ridge Siliciclastic Hydrogeomorphic Regions

Cover crop type[2]	Low-till land uses TN (%)	High-till land uses TN (%)
Commodity cover crop, early	4	4
Commodity cover crop, standard	8	8
Commodity cover crop, late	12	12

[1]There are no TP or TSS reductions associated with this BMP.
[2]Early/standard/late refers to planting date. Early means the cover crop is planted more than two weeks before the average frost date. Standard or normal is when the cover crops is planted between the average frost date and two weeks before that date. Late is when the cover crop is planted within three weeks after the average frost date

Conclusions

Cover cropping is a BMP that offers wide applicability and promises significant effectiveness in reducing sediment and nutrient losses from cropland to both surface and groundwaters. The practice also provides important agronomic and ecosystem services including improvements in soil quality and increases in soil C storage. While implementation of cover crops into a cropping system is subject to some challenges, research has demonstrated that there are generally significant net benefits to integrating cover crops into agricultural management.

Bibliographies

Conservation Crop Rotation

Aggarwal, S., Magner, J., Srinivas, R., & Sajith, G. (2022). Managing nitrate-nitrogen in the intensively drained upper Mississippi River Basin, USA under uncertainty: a perennial path forward. Environmental Monitoring and Assessment, 194(10), Article 704. https://doi.org/10.1007/s10661-022-10401-4

Fioratti Junod, M., Reid, B., Sims, I., & Miller, A. J. (2024). Cover crops in cereal rotations: A quantitative review. Soil and Tillage Research, 238, 105997. https://doi.org/https://doi.org/10.1016/j.still.2023.105997

Gonzalez, J. M., Dick, W. A., Islam, K. R., Watts, D. B., Fausey, N. R., Flanagan, D. C., Batte, M. T., VanToai, T. T., Reeder, R. C., & Shedekar, V. S. (2023). Cover crops, crop rotation, and gypsum, as conservation practices, impact Mehlich-3 extractable plant nutrients and trace metals. International soil and water conservation research. https://doi.org/https://doi.org/10.1016/j.iswcr.2023.11.001

Hanrahan, B., King, K., Rumora, K., & Stinner, J. (2024). Nitrogen balances and losses in conservation cropping systems across a tile-drained landscape in Ohio, United States. Journal of Soil and Water Conservation, 79(3), 145-154.

Hanrahan, B. R., King, K. W., Rumora, K. R., & Stinner, J. H. (2023). Contrasting the influence of crop rotation on phosphorus balances and losses in agricultural fields across a tile-drained landscape in Ohio, USA. Journal of Great Lakes Research, 49(6), 102232. https://doi.org/https://doi.org/10.1016/j.jglr.2023.09.003

Her, Y., Chaubey, I., Frankenberger, J., & Smith, D. (2016). Effect of conservation practices implemented by USDA programs at field and watershed scales. Journal of Soil and Water Conservation, 71(3), 249-266.

IDALS. (2017). IOWA NUTRIENT REDUCTION STRATEGY. A science and technology-based framework to assess and reduce nutrients to Iowa waters and the Gulf of Mexico.

Iheshiulo, E. M.-A., Larney, F. J., Hernandez-Ramirez, G., St. Luce, M., Chau, H. W., & Liu, K. (2024). Crop rotations influence soil hydraulic and physical quality under no-till on the Canadian prairies. Agriculture, Ecosystems & Environment, 361, 108820. https://doi.org/https://doi.org/10.1016/j.agee.2023.108820

Iheshiulo, E. M.-A., Larney, F. J., Hernandez-Ramirez, G., St. Luce, M., Liu, K., & Chau, H. W. (2023). Do diversified crop rotations influence soil physical health? A meta-analysis. Soil and Tillage Research, 233, 105781. https://doi.org/https://doi.org/10.1016/j.still.2023.105781

Jiang, F., Drohan, P. J., Cibin, R., Preisendanz, H. E., White, C. M., & Veith, T. L. (2021). Reallocating crop rotation patterns improves water quality and maintains crop yield. Agricultural Systems, 187, 103015. https://doi.org/https://doi.org/10.1016/j.agsy.2020.103015

Jones, C., Seeman, A., Kyveryga, P., Schilling, K., Kiel, A., Chan, K.-S., & Wolter, C. (2016). Crop rotation and Raccoon River nitrate. Journal of Soil and Water Conservation, 71(3), 206-219.

Karlen, D. L., Hurley, E. G., Andrews, S. S., Cambardella, C. A., Meek, D. W., Duffy, M. D., & Mallarino, A. P. (2006). Crop rotation effects on soil quality at three northern corn/soybean belt locations. Agronomy Journal, 98(3), 484-495.

Koropeckyj-Cox, L., Christianson, R. D., & Yuan, Y. (2021a). Effectiveness of conservation crop rotation for water pollutant reduction from agricultural areas. Transactions of the ASABE, 64(2), 691-704.

Koropeckyj-Cox, L., Christianson, R. D., & Yuan, Y. (2021b). Effectiveness of conservation crop rotation for water pollutant reduction from agricultural areas. Transactions of the ASABE, 64(2), 691-704.

Lago-Olveira, S., Rebolledo-Leiva, R., Garofalo, P., Moreira, M. T., & González-García, S. (2023). Environmental and economic benefits of wheat and chickpea crop rotation in the Mediterranean region of Apulia (Italy). Science of the Total Environment, 896, 165124. https://doi.org/https://doi.org/10.1016/j.scitotenv.2023.165124

Li, A., Wu, Y., Tai, X., Cao, S., & Gao, T. (2023). Effects of Alfalfa Crop Rotation on Soil Nutrients and Loss of Soil and Nutrients in Semi-Arid Regions. Sustainability, 15(20), 15164.

McDaniel, M. D., Bird, J. A., Pett-Ridge, J., Marin-Spiotta, E., Schmidt, T. M., & Grandy, A. S. (2023). Diversifying and perennializing plants in agroecosystems alters retention of new C and N from crop residues. Ecological Applications, 33(2), e2784.

NRCS. (2014a). Conservation Crop Rotation (No.) (328) Conservation Practice Standard. In: United States Department of Agriculture.

NRCS. (2023a). CPS E328E Soil health crop rotation. In U.-W. NRCS (Ed.), Conservation Enhancement Activity, Conservation Stewardship Program.

NRCS. (2023b). CPS E328J Improved crop rotation to provide benefits to pollinators. In U.-W. NRCS (Ed.), Conservation Enhancement Activity, Conservation Stewardship Program.

NRCS. (2023c). CPS E328L Leaving tall crop residue for wildlife. In U.-W. NRCS (Ed.), Conservation Enhancement Activity, Conservation Stewardship Program.

Pease, L. A., King, K. W., Williams, M. R., LaBarge, G. A., Duncan, E. W., & Fausey, N. R. (2018). Phosphorus export from artificially drained fields across the Eastern Corn Belt. Journal of Great Lakes Research, 44(1), 43-53.

Schillinger, W. F. (2020). New winter crops and rotations for the Pacific Northwest low-precipitation drylands. Agronomy Journal, 112(5), 3335-3349.

Shah, K. K., Modi, B., Pandey, H. P., Subedi, A., Aryal, G., Pandey, M., & Shrestha, J. (2021). Diversified crop rotation: an approach for sustainable agriculture production. Advances in Agriculture, 2021(1), 8924087.

Shipitalo, M. J., Owens, L. B., Bonta, J. V., & Edwards, W. M. (2013). Effect of no-till and extended rotation on nutrient losses in surface runoff. Soil Science Society of America Journal, 77(4), 1329-1337.

Silva, L. d. C. M. d., Avanzi, J. C., Peixoto, D. S., Merlo, M. N., Borghi, E., Resende, Á. V. d., Acuña-Guzman, S. F., & Silva, B. M. (2021). Ecological intensification of cropping systems enhances soil functions, mitigates soil erosion, and promotes crop resilience to dry spells in the Brazilian Cerrado. International soil and water conservation research, 9(4), 591-604. https://doi.org/https://doi.org/10.1016/j.iswcr.2021.06.006

Simão, L. M., Cruppe, G., Michaud, J. P., Schillinger, W. F., Ruiz Diaz, D., Dille, A. J., Rice, C. W., & Lollato, R. P. (2024). Chapter Two - Beyond grain: Agronomic, ecological, and economic benefits of diversifying crop rotations with wheat. In D. L. Sparks (Ed.), Advances in Agronomy (Vol. 186, pp. 51-112). Academic Press. https://doi.org/https://doi.org/10.1016/bs.agron.2024.02.007

WSU. (2012). Winter Canola Feasibility in Rotation with Winter Wheat. In: Washington State University Extension.

Yuan, Y., Book, R. S., Mankin, K. R., Koropeckyj-Cox, L., Christianson, L., Messer, T., & Christianson, R. (2022). An overview of the effectiveness of agricultural conservation practices for water quality improvement. Journal of the ASABE, 65(2), 419-426.

Contour Farming

Barbosa, F., Bertol, I., Luciano, R., & González, A. P. (2009). Phosphorus losses in water and sediments in runoff of the water erosion in oat and vetch crops seed in contour and downhill. Soil and Tillage Research, 106(1), 22-28.

Cerdà, A., Morera, A. G., & Bodí, M. B. (2009). Soil and water losses from new citrus orchards growing on sloped soils in the western Mediterranean basin. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group, 34(13), 1822-1830.

Deasy, C., Quinton, J. N., Silgram, M., Bailey, A. P., Jackson, B., & Stevens, C. J. (2010). Contributing understanding of mitigation options for phosphorus and sediment to a review of the efficacy of contemporary agricultural stewardship measures. Agricultural Systems, 103(2), 105-109.

Fajeriana, N., Ali, A., & Rini, R. P. (2024). Soil Tillage and Planting Along the Contour on Sloping Land to Minimize the Potential for Erosion and Surface Runoff [Article]. Sarhad Journal of Agriculture, 40(1), 93-182. https://doi.org/10.17582/journal.sja/2024/40.1.82.93

Farahani, S. S., Fard, F. S., & Asoodar, M. A. (2016). Effects of contour farming on runoff and soil erosion reduction: a review study. Elixir Agriculture, 101(1), 44089-44093.

IADNR. (2023). Iowa Stormwater Management Manual.

Kurothe, R. S., Kumar, G., Singh, R., Singh, H. B., Tiwari, S. P., Vishwakarma, A. K., Sena, D. R., & Pande, V. C. (2014). Effect of tillage and cropping systems on runoff, soil loss and crop yields under semiarid rainfed agriculture in India. Soil and Tillage Research, 140, 126-134. https://doi.org/https://doi.org/10.1016/j.still.2014.03.005

Mondaca, P., Lebuy, R., Rojas, S., Aguas, J., Celis-Diez, J. L., & Díaz-Siefer, P. (2024). Contour furrowing reduces erosion and enhances soil moisture on semiarid hillslopes. Geoderma Regional, e00826. https://doi.org/https://doi.org/10.1016/j.geodrs.2024.e00826

NRCS. (2015). Contour Orchard and Other Perennial Crops (No.) (331) Conservation Practice Standard. In: United States Department of Agriculture.

NRCS. (2017b). Contour Farming (No.) (330) Conservation Practice Standard. In: United States Department of Agriculture.

Puertes, C., Bautista, I., Lidón, A., & Francés, F. (2021). Best management practices scenario analysis to reduce agricultural nitrogen loads and sediment yield to the semiarid Mar Menor coastal lagoon (Spain). Agricultural Systems, 188, 103029. https://doi.org/https://doi.org/10.1016/j.agsy.2020.103029

Regasa, M. S., & Nones, M. (2024). Modeling best management practices to reduce future sediment yield in the Fincha watershed, Ethiopia. International Journal of Sediment Research. https://doi.org/https://doi.org/10.1016/j.ijsrc.2024.04.010

Stevens, C. J., Quinton, J. N., Bailey, A., Deasy, C., Silgram, M., & Jackson, D. (2009). The effects of minimal tillage, contour cultivation and in-field vegetative barriers on soil erosion and phosphorus loss. Soil and Tillage Research, 106(1), 145-151.

Tang, J., Xie, Y., Liu, C., Dong, H., & Liu, G. (2022). Effects of rainfall characteristics and contour tillage on ephemeral gully development in a field in Northeastern China. Soil and Tillage Research, 218, 105312. https://doi.org/https://doi.org/10.1016/j.still.2021.105312

Thapa, B., Cassel, D., & Garrity, D. P. (1999). Ridge tillage and contour natural grass barrier strips reduce tillage erosion. Soil and Tillage Research, 51(3-4), 341-356.

USACE. (2024). HEC-HMS Technical Reference Manual. Retrieved 11/21/24 from https://www.hec.usace.army.mil/confluence/hmsdocs/hmstrm

Wallis, J., Schaefer, M., Barker, B., & Taylor, G. (2007). Regional precipitation-frequency analysis and spatial mapping for 24-hour and 2-hour durations for Washington State. Hydrology and Earth System Sciences, 11(1), 415-442.

Zhang, J., Frielinghaus, M., Tian, G., & Lobb, D. A. (2004). Ridge and contour tillage effects on soil erosion from steep hillslopes in the Sichuan Basin, China. Journal of Soil and Water Conservation, 59(6), 277-284.

Intercropping and Strip Cropping

Alarcón-Segura, V., Grass, I., Breustedt, G., Rohlfs, M., & Tscharntke, T. (2022). Strip intercropping of wheat and oilseed rape enhances biodiversity and biological pest control in a conventionally managed farm scenario. Journal of applied ecology, 59(6), 1513-1523.

APVMA. (2007). Public Release Summary on Evaluation of the new active Clothianidan in the products: Sumitomo Shield Systemic Insecticide; Sumitomo Samurai Systemic; Insecticide Sumitomo Stealth Systemic Insecticide. A. P. a. V. M. Authority. https://www.apvma.gov.au/sites/default/files/publication/13641-prs-clothianidin.pdf

Djodjic, F., Börling, K., & Bergström, L. (2004). Phosphorus leaching in relation to soil type and soil phosphorus content. Journal of Environmental Quality, 33(2), 678-684.

He, J., He, J., Li, H., Yu, Y., Qian, L., Tang, L., Zheng, Y., & Xiao, J. (2024). Continuous Intercropping Increases the Depletion of Soil Available and Non-Labile Phosphorus. Agronomy, 14(6), 1121.

Long, R., Gan, J., & Nett, M. (2005). Pesticide choice: Best management practice (BMP) for protecting surface water quality in agriculture.

Nasar, J., Ahmad, M., Gitari, H., Tang, L., Chen, Y., & Zhou, X. B. (2024). Maize/soybean intercropping increases nutrient uptake, crop yield and modifies soil physio-chemical characteristics and enzymatic activities in the subtropical humid region based in Southwest China [Article]. BMC Plant Biology, 24(1), Article 434. https://doi.org/10.1186/s12870-024-05061-0

Nie, S.-W., Eneji, A. E., Chen, Y.-Q., Peng, S., Huang, J.-X., & Huang, S.-M. (2012). Nitrate leaching from maize intercropping systems with N fertilizer over-dose. Journal of Integrative Agriculture, 11(9), 1555-1565.

NRCS. (2017c). Stripcropping (No.) (585) Conservation Practice Standard. In: United States Department of Agriculture.

NRCS. (2021). E328N. Intercropping to improve soil health.

Nyawade, S. O., Gachene, C. K., Karanja, N. N., Gitari, H. I., Schulte-Geldermann, E., & Parker, M. L. (2019). Controlling soil erosion in smallholder potato farming systems using legume intercrops. Geoderma Regional, 17, e00225.

Rutkoski, C. E., Schulte, L. A., & Evans, S. E. (2024). Neonicotinoid retention and transport in a maize cropping system with contour prairie strips. Agriculture, Ecosystems & Environment, 373, 109111. https://doi.org/https://doi.org/10.1016/j.agee.2024.109111

Sahoo, U., Malik, G. C., Maitra, S., Banerjee, M., Masina, S., Nath, S., & Suvadra, J. S. (2024). Intercropping system: A climate-smart approach for sustaining food security. Journal of Applied Biology and Biotechnology, 12(4), 30-36. https://doi.org/10.7324/JABB.2024.170871

Siller, A. R., Albrecht, K. A., & Jokela, W. E. (2016). Soil erosion and nutrient runoff in corn silage production with Kura clover living mulch and winter rye. Agronomy Journal, 108(3), 989-999.

Stephens, T., Blanco-Canqui, H., Knezevic, S., Rees, J., Koehler-Cole, K., & Jhala, A. J. (2023). Impact of planting green on soil properties under irrigated no-till soybean. Agrosystems, geosciences & environment, 6(4), e20443.

Stoltz, E., & Nadeau, E. (2014). Effects of intercropping on yield, weed incidence, forage quality and soil residual N in organically grown forage maize (Zea mays L.) and faba bean (Vicia faba L.). Field Crops Research, 169, 21-29.

Wang, Y., Zhang, Y., Yang, Z., Fei, J., Zhou, X., Rong, X., Peng, J., & Luo, G. (2024). Intercropping improves maize yield and nitrogen uptake by regulating nitrogen transformation and functional microbial abundance in rhizosphere soil. Journal of Environmental Management, 358, 120886. https://doi.org/https://doi.org/10.1016/j.jenvman.2024.120886

Yan, E., Munier-Jolain, N., Martin, P., & Carozzi, M. (2024). Intercropping on French farms: Reducing pesticide and N fertiliser use while maintaining gross margins. European Journal of Agronomy, 152, 127036.

Alley Cropping

Addy, K., Gold, A. J., Christianson, L. E., David, M. B., Schipper, L. A., & Ratigan, N. A. (2016). Denitrifying bioreactors for nitrate removal: A meta-analysis. Journal of Environmental Quality, 45(3), 873-881.

Allen, S. C., Jose, S., Nair, P., Brecke, B. J., Nkedi-Kizza, P., & Ramsey, C. L. (2004). Safety-net role of tree roots: evidence from a pecan (Carya illinoensis K. Koch)–cotton (Gossypium hirsutum L.) alley cropping system in the southern United States. Forest ecology and management, 192(2-3), 395-407.

Anderson, S. H., Udawatta, R. P., Seobi, T., & Garrett, H. E. (2009). Soil water content and infiltration in agroforestry buffer strips. Agroforestry systems, 75, 5-16.

Andrianarisoa, K. S., Dufour, L., Bienaimé, S., Zeller, B., & Dupraz, C. (2016). The introduction of hybrid walnut trees (Juglans nigra× regia cv. NG23) into cropland reduces soil mineral N content in autumn in southern France. Agroforestry systems, 90, 193-205.

Bergeron, M., Lacombe, S., Bradley, R. L., Whalen, J., Cogliastro, A., Jutras, M.-F., & Arp, P. (2011). Reduced soil nutrient leaching following the establishment of tree-based intercropping systems in eastern Canada. Agroforestry systems, 83, 321-330.

Borin, M., Passoni, M., Thiene, M., & Tempesta, T. (2010). Multiple functions of buffer strips in farming areas. European Journal of Agronomy, 32(1), 103-111.

Dougherty, M. C., Thevathasan, N. V., Gordon, A. M., Lee, H., & Kort, J. (2009). Nitrate and Escherichia coli NAR analysis in tile drain effluent from a mixed tree intercrop and monocrop system. Agriculture, Ecosystems & Environment, 131(1-2), 77-84.

Garrett, H. G., & Buck, L. (1997). Agroforestry practice and policy in the United States of America. Forest ecology and management, 91(1), 5-15.

Gikas, G. D., Tsihrintzis, V. A., & Sykas, D. (2016). Effect of trees on the reduction of nutrient concentrations in the soils of cultivated areas. Environmental Monitoring and Assessment, 188, 1-19.

Hoover, N. L., Bhandari, A., Soupir, M. L., & Moorman, T. B. (2016). Woodchip denitrification bioreactors: Impact of temperature and hydraulic retention time on nitrate removal. Journal of Environmental Quality, 45(3), 803-812.

IADNR. (2023). Iowa Stormwater Management Manual.

Kim, D.-G., & Isaac, M. E. (2022). Nitrogen dynamics in agroforestry systems. A review. Agronomy for Sustainable Development, 42(4), 60.

Muchane, M. N., Sileshi, G. W., Gripenberg, S., Jonsson, M., Pumariño, L., & Barrios, E. (2020). Agroforestry boosts soil health in the humid and sub-humid tropics: A meta-analysis. Agriculture, Ecosystems & Environment, 295, 106899.

NRCS. (2009). Alley Cropping.

NRCS. (2017a). Alley Cropping (No.) (311) Conservation Practice Standard. In: United States Department of Agriculture.

O'Connor, C., Zeller, B., Choma, C., Delbende, F., Siah, A., Waterlot, C., & Andrianarisoa, K. S. (2023). Trees in temperate alley-cropping systems develop deep fine roots 5 years after plantation: What are the consequences on soil resources? Agriculture, Ecosystems & Environment, 345, 108339. https://doi.org/https://doi.org/10.1016/j.agee.2022.108339

Pavlidis, G., & Tsihrintzis, V. A. (2018). Environmental benefits and control of pollution to surface water and groundwater by agroforestry systems: a review. Water Resources Management, 32, 1-29.

Salceda-Gonzalez, M. (2023). Agroforestry and Cover Crops for Improving Surface Water and Groundwater Quality University of Missouri-Columbia].

Udawatta, R. P., Garrett, H. E., Jose, S., & Lovell, S. T. (2021). Water Quality and Quantity Benefits of Agroforestry and Processes: Long-Term Case Studies from Missouri, USA. Agroforestry and ecosystem services, 113-139.

Udawatta, R. P., Garrett, H. E., & Kallenbach, R. (2011). Agroforestry buffers for nonpoint source pollution reductions from agricultural watersheds. Journal of Environmental Quality, 40(3), 800-806.

Udawatta, R. P., Krstansky, J. J., Henderson, G. S., & Garrett, H. E. (2002). Agroforestry practices, runoff, and nutrient loss: a paired watershed comparison. Journal of Environmental Quality, 31(4), 1214-1225.

USACE. (2024). HEC-HMS Technical Reference Manual. Retrieved 11/21/24 from https://www.hec.usace.army.mil/confluence/hmsdocs/hmstrm

Wolz, K. J., Branham, B. E., & DeLucia, E. H. (2018). Reduced nitrogen losses after conversion of row crop agriculture to alley cropping with mixed fruit and nut trees. Agriculture, Ecosystems & Environment, 258, 172-181. https://doi.org/https://doi.org/10.1016/j.agee.2018.02.024

Zhu, X., Liu, W., Chen, J., Bruijnzeel, L. A., Mao, Z., Yang, X., Cardinael, R., Meng, F.-R., Sidle, R. C., & Seitz, S. (2020). Reductions in water, soil and nutrient losses and pesticide pollution in agroforestry practices: a review of evidence and processes. Plant and Soil, 453, 45-86.

Cover Crops

Bawa, A., MacDowell, R., Bansal, S., McMaine, J., Sexton, P., & Kumar, S. (2023). Responses of leached nitrogen concentrations and soil health to winter rye cover crop under no-till corn–soybean rotation in the northern Great Plains. Journal of Environmental Quality, 52(3), 422-433.

Bosch, N. S., Allan, J. D., Selegean, J. P., & Scavia, D. (2013). Scenario-testing of agricultural best management practices in Lake Erie watersheds. Journal of Great Lakes Research, 39(3), 429-436.

CBP. (2017). Cover Crops Practices for Use in Phase 6.0 of the Chesapeake Bay Program Watershed Model. In C. B. Program (Ed.).

CBP. (2022). Chesapeake Bay Program Quick Reference Guide for Best Management Practices (BMPs): Nonpoint Source BMPs to Reduce Nitrogen, Phosphorus and Sediment Loads to the Chesapeake Bay and its Local Waters. In (Second edition ed.).

Chen, L., Rejesus, R. M., Aglasan, S., Hagen, S. C., & Salas, W. (2022). The impact of cover crops on soil erosion in the US Midwest. Journal of Environmental Management, 324, 116168. https://doi.org/https://doi.org/10.1016/j.jenvman.2022.116168

Daryanto, S., Fu, B., Wang, L., Jacinthe, P.-A., & Zhao, W. (2018). Quantitative synthesis on the ecosystem services of cover crops. Earth-Science Reviews, 185, 357-373.

EPA. (2023). Best Management Practice Efficiency References for the Pollutant Load Estimation Tool. In O. o. W. U.S. Environmental Protection Agency, Oceans and Watersheds (Ed.). Washington, DC.

Fioratti Junod, M., Reid, B., Sims, I., & Miller, A. J. (2024). Cover crops in cereal rotations: A quantitative review. Soil and Tillage Research, 238, 105997. https://doi.org/https://doi.org/10.1016/j.still.2023.105997

Giri, S., Lathrop, R. G., & Obropta, C. C. (2020). Climate change vulnerability assessment and adaptation strategies through best management practices. Journal of Hydrology, 580, 124311.

Gutknecht, J., Journey, A., Peterson, H., Blair, H., & Cates, A. (2023). Cover crop management practices to promote soil health and climate adaptation: Grappling with varied success from farmer and researcher observations. Journal of Environmental Quality, 52(3), 448-464.

Hanrahan, B. R., King, K. W., Duncan, E. W., & Shedekar, V. S. (2021). Cover crops differentially influenced nitrogen and phosphorus loss in tile drainage and surface runoff from agricultural fields in Ohio, USA. Journal of Environmental Management, 293, 112910. https://doi.org/https://doi.org/10.1016/j.jenvman.2021.112910

IDALS. (2017). IOWA NUTRIENT REDUCTION STRATEGY. A science and technology-based framework to assess and reduce nutrients to Iowa waters and the Gulf of Mexico.

Johnson, F. E., Roth, R. T., Ruffatti, M. D., & Armstrong, S. D. (2024). Cover crop impacts on nitrogen losses and environmental damage cost. Agriculture, Ecosystems & Environment, 363, 108859. https://doi.org/https://doi.org/10.1016/j.agee.2023.108859

Kaspar, T., Jaynes, D., Parkin, T., Moorman, T., & Singer, J. (2012). Effectiveness of oat and rye cover crops in reducing nitrate losses in drainage water. Agricultural Water Management, 110, 25-33.

Kaur, H., Nelson, K. A., Singh, G., Kaur, G., & Davis, M. P. (2024a). Spring applied phosphorus loss with cover crops in no-till terraced field. Journal of Environmental Management, 355, 120431. https://doi.org/https://doi.org/10.1016/j.jenvman.2024.120431

Kaur, H., Nelson, K. A., Singh, G., & Udawatta, R. P. (2024b). Cover crop impacts water quality in a tile-terraced no-till field with corn-soybean rotation. Agriculture, Ecosystems & Environment, 360, 108794. https://doi.org/https://doi.org/10.1016/j.agee.2023.108794

Konzett, M., Strauss, P., & Schmaltz, E. M. (2024). The not-so-micro effects of in-furrow micro-dams and cover crops on water and sediment retention in potato fields. Soil and Tillage Research, 235, 105911. https://doi.org/https://doi.org/10.1016/j.still.2023.105911

Korucu, T., Shipitalo, M. J., & Kaspar, T. C. (2018). Rye cover crop increases earthworm populations and reduces losses of broadcast, fall-applied, fertilizers in surface runoff. Soil and Tillage Research, 180, 99-106. https://doi.org/https://doi.org/10.1016/j.still.2018.03.004

Meisinger, J., Hargrove, W., Mikkelsen, R., Williams, J., & Benson, V. (1991). Effects of cover crops on groundwater quality. Cover crops for clean water, 57-68.

Nouri, A., Lukas, S., Singh, S., Singh, S., & Machado, S. (2022). When do cover crops reduce nitrate leaching? A global meta-analysis. Global Change Biology, 28(15), 4736-4749. https://doi.org/10.1111/gcb.16269

NRCS. (2014b). Cover Crop (No.) (340) Conservation Practice Standard. In: United States Department of Agriculture.

Reed-Jones, N. L., Marine, S. C., Everts, K. L., & Micallef, S. A. (2016). Effects of cover crop species and season on population dynamics of Escherichia coli and Listeria innocua in soil. Applied and Environmental Microbiology, 82(6), 1767-1777.

Roberts, D. E. (2018). Cover cropping and companion cropping for the Inland Northwest: an initial feasibility study.

Salceda-Gonzalez, M. (2023). Agroforestry and Cover Crops for Improving Surface Water and Groundwater Quality University of Missouri-Columbia].

Schipanski, M. E., Barbercheck, M., Douglas, M. R., Finney, D. M., Haider, K., Kaye, J. P., Kemanian, A. R., Mortensen, D. A., Ryan, M. R., & Tooker, J. (2014). A framework for evaluating ecosystem services provided by cover crops in agroecosystems. Agricultural Systems, 125, 12-22.

Scholberg, J. M., Dogliotti, S., Leoni, C., Cherr, C. M., Zotarelli, L., & Rossing, W. A. (2010). Cover crops for sustainable agrosystems in the Americas. Genetic Engineering, biofertilisation, soil quality and organic farming, 23-58.

Singh, G., Schoonover, J. E., & Williard, K. W. J. (2018). Cover Crops for Managing Stream Water Quantity and Improving Stream Water Quality of Non-Tile Drained Paired Watersheds. Water, 10(4), 521. https://www.mdpi.com/2073-4441/10/4/521

Srivastava, S., Basche, A., Traylor, E., & Roy, T. (2023). The efficacy of conservation practices in reducing floods and improving water quality [Review]. Frontiers in Environmental Science, 11. https://doi.org/10.3389/fenvs.2023.1136989

Thapa, R., Mirsky, S. B., & Tully, K. L. (2018). Cover crops reduce nitrate leaching in agroecosystems: A global meta-analysis. Journal of Environmental Quality, 47(6), 1400-1411.

Tonitto, C., David, M. B., & Drinkwater, L. E. (2006). Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: A meta-analysis of crop yield and N dynamics. Agric. Ecosyst. Environ., 112(1), 58-72. https://doi.org/doi:10.1016/j.agee. 2005.07.003

Waring, E. R., Pederson, C., Lagzdins, A., Clifford, C., & Helmers, M. J. (2024). Water and soil quality respond to no-tillage and cover crops differently through 10 years of implementation. Agriculture, Ecosystems & Environment, 360, 108791. https://doi.org/https://doi.org/10.1016/j.agee.2023.108791

Yu, Y., Loiskandl, W., Kaul, H.-P., Himmelbauer, M., Wei, W., Chen, L., & Bodner, G. (2016). Estimation of runoff mitigation by morphologically different cover crop root systems. Journal of Hydrology, 538, 667-676. https://doi.org/https://doi.org/10.1016/j.jhydrol.2016.04.060

Zhao, Y., Haley, O. C., Xu, X., Jaberi-Douraki, M., Rivard, C., Pliakoni, E. D., Nwadike, L., & Bhullar, M. (2023). The Potential for Cover Crops to Reduce the Load of Escherichia coli in Contaminated Agricultural Soil. Journal of Food Protection, 86(7), 100103. https://doi.org/https://doi.org/10.1016/j.jfp.2023.100103

Chapter 2 Appendix Part B: Implementation Considerations (Crop Systems)

Adoption of Crop Systems in Washington State

Climatic Conditions

Regional climate conditions are an important consideration when planning crop system BMPs. The climatic differences between eastern and western Washington can have a large impact on the species selected for various crop system practices as well as the accompanying management plan.

Soil Type

Soil types vary naturally across the state of Washington, and can be further impacted by the history of landuse at individual sites. Soil type, soil health, and soil erosion potential are several factors that should be considered when planning and implementing crop system BMPs, and it is recommended to incorporate site-specific soil conditions when planning and adaptively managing crop system practices. Carefully selected plant species that are implemented as a part of a crop system practice can help to improve soil health and retain topsoil.

Cost and Benefits Associated with Crop System BMPs

The costs of implementing crop system BMPs can vary, depending on the plant species and the method of planting implemented. Though there are additional costs in plant procurement, and additional time, energy, and resources invested in incorporating these BMPs into a management plan, there are benefits that may not be immediately evident. For example, in addition to protecting water resources, these practices can improve soil health and reduce soil loss, reducing costs in the long term.

Often there are resources available to support the planning and implementation of BMPs that provide co-benefits of protecting and/or restoring water quality. Local conservation districts, NRCS offices, and/or county programs may be able to provide cost-free technical assistance and even financial support for implementation. For example, NRCS' Conservation Technical Assistance (CTA) can help with resource assessments and monitoring, practice design, and the development of conservation plans, which can be implemented using financial assistance from other local, state, and/or federal funding sources. There are several federal funding sources that may support the implementation of subsurface drainage management, such as NRCS' Environmental Quality Incentives Program (EQIP), that provides both technical and financial assistance to address a variety of natural resource concerns, including improved water quality, conserved ground and surface water, and increased soil health, among others. Additionally, the Conservation Stewardship Program (CSP) provides support for improving operation enhancement and stewardship improvement. See NRCS' information on the [Washington State Programs and Initiatives][3] webpage to learn more and find a local field office.

Implementation Considerations and Costs

This section includes considerations for implementation of conservation crop rotation, contour farming, intercropping and strip cropping, alley cropping, and cover crops. Decisions regarding the design, planning, and implementation of these practices are dependent upon site-specific characteristics.

Conservation Crop Rotation

Use Cases

Conservation Crop Rotation (CCR) can be applied to all cropland where there is at least one annually planted crop. There are several different purposes for which CCR may be implemented, to address a variety of concerns and to protect water quality. The NRCS standard for 328 CCR (NRCS, 2014a) outlines several considerations for specific purposes:

- **Reduce sheet, rill, and wind erosion:** Select crops, a tillage system, and a cropping sequence that will produce sufficient and timely quantities of biomass or crop residue to be used in conjunction with other practices, to reduce erosion according to the planned soil loss objective.
- **Reduce water quality degradation due to excess nutrients**: To recover excess nutrients from the soil profile, use crops with quick germination and root system formation, a rooting depth sufficient to reach the nutrients not removed by the previous crop, and that have nutrient requirements that readily use the excess nutrients present. Include legume crops in the rotation to provide N for the non-legume crops, especially in fields where manure applications are restricted by high soil P levels.
- **Reduce the concentration of salts and other chemicals from saline seeps:** Select crops to be grown in the recharge area of saline seeps that have rooting depths and water requirements adequate to fully use all available soil water. Select crops with a tolerance to salinity that matches the salinity of the discharge area.

Benefits

Conservation crop rotation reduces water quality degradation from sediment and other field pollutants. Additionally, CCR can increase the diversity of the cropping system, support maintaining residue cover throughout the year, keeping a living root in the soil, and minimize chemical, physical, and biological disturbance to the soil, thereby improving soil health. When legumes are a part of the conservation crop rotation, an N credit can reduce the quantity of N fertilizer the producer needs to purchase and apply to the following crop, providing monetary savings on fertilizer purchase and application.

[3] https://www.nrcs.usda.gov/state-offices/washington

According to NRCS, additional variations of conservation crop rotation can also provide benefits to pollinators and wildlife, by making management changes to utilize pollinator-friendly crops on a certain percentage of cropland each year, limiting the use of insecticides, and leaving crop residue through winter and into spring. Conservation crop rotation can improve soil moisture efficiency, reduce plant pest pressures, and provide feed and forage for domestic livestock.

The benefits of CCR may be amplified or augmented through the co-implementation of other conservation practices, such as cover crops, nutrient management, residue and tillage management, as well as other practices discussed in this chapter, such as strip cropping and contour farming practices.

Table 10. Implementation considerations for Conservation Crop Rotation

Considerations	Details
Costs	**Implementation costs-** costs below are estimates from NRCS Washington Practice Scenarios for Fiscal Year 2025 • For growing basic crops, cost estimates of $17.79/acre incorporates the producer's time to plan and implement the logistics of changing the rotation and assumes no foregone income from this change in management practices. This cost represents typical situations for both conventional and organic producers. • For specialty crops, the cost estimate for the NRCS practice is $47.45 per acre, which accounts for the time to acquire the technical knowledge and skills to effectively implement a conservation crop rotation on a specialty crop farm, and assumes no foregone income. See Appendix B of Chapter 5 (Vegetative Sediment Control) for additional cost considerations. **Financial planning** • This practice may be compatible with existing federal and state cost-share programs.
Operational and Maintenance Requirements	• Crop rotation must include a minimum of two different crops; a cover crop is considered a different crop. Select crops, a tillage system, and cropping sequence that will produce sufficient and timely quantities of crop residue to reduce soil loss due to sheet, rill, and wind erosion. • Consider including perennial sod crops with deep or extensive root systems to build organic matter throughout the soil profile.

Considerations	Details
Operational and Maintenance Requirements, continued	• Consider lengthening the rotation to include several years of perennial cover to break pest life cycles and consider including plant species that will perform biological pest control. • Implementation planning should include field number and acres, purpose of the crop rotation, sequence of crops to be grown, crop types to be grown, tillage type and times, length of time each crop will be grown in the rotation, and total length of rotation. • Select plant species which are well suited to the local climate and field soil characteristics. Select plants which will provide the needed amounts of crop residue and that will appropriately address site-specific soil nitrogen concerns. • When cover crops are incorporated into conservation crop rotation, native species are preferred. **Monitoring/adaptive management** • Monitor soil health and adjust crops as needed- i.e. soil compaction can be reduced by adding deep rooting crops, legumes can provide nitrogen, etc. • It is recommended to include pre-planning for suitable crop substitutions to address weather, soil conditions, and other situations that may prevent the primary crops from being planted.
Technical Requirements	• Technical design standards can be found in NRCS' Field Office Technical Guide Practice 328. • Determine the amount of crop residue needed by using current erosion prediction technology, such as NRCS' Water Erosion Prediction Program[4].
Lifespan	This is a management practice, which can be implemented annually, with adjustments to plant species made to achieve desired outcomes over time.
Other Implementation Factors	Consider the use of other land management practices, such as crop selection and application of complementary BMPs such as cover crops, conservation tillage systems, nutrient management, and pest management. This practice is also

[4] https://www.nrcs.usda.gov/resources/tech-tools/water-erosion-prediction-project

Considerations	Details
	frequently applied in concert with strip cropping, contour farming, contour buffer strips, and terraces. **Considerations to improve wildlife habitat** • Consider leaving tall crop residue through the winter and into spring, to provide winer cover and forage for wildlife. • Plant pollinator-friendly crops on at least 5% of all acreage and limit insecticides.
Resources	NRCS Practice Scenario cost estimate for Washington, Fiscal Year 2025[5] See Cover Crop section below and Chapter 5: Vegetative Sediment Control, for additional considerations for selecting crop species and implementation of conservation cover.

Contour Farming

Use Cases

Contour farming can be applied to either perennial or annual cropping operations. For operations with appropriate hillslope patterns, soil hydrologic group, slope steepness, slope length, and precipitation intensity, contour farming can act to reduce pollutant transport from agricultural fields (NRCS, 2017b).

Benefits and Implementation Considerations

Contour farming can act to reduce erosion and trap sediment from running off agricultural fields. By creating soil surface patterns that are perpendicular rather than parallel to the slope, contours can act to reduce surface runoff and soil erosion, which can increase precipitation infiltration and help to retain soil moisture within fields. Slowing precipitation runoff reduces the sediment runoff from farm fields, supporting soil retention for producers.

Site specific conditions can create challenges in implementing this BMP. Fields that are cut by gullies or have strongly undulating topography may not be well suited for this practice, as gullies could provide pathways for flow to bypass the contour ridges. Additional considerations related to this practice include treating the runoff that may be produced from contour rows. The contour row runoff should be delivered to a stable outlet, and additional, complementary practices, such as filter strips, riparian buffers, and/or saturated riparian buffers may be recommended (NRCS, 2015).

[5] https://www.nrcs.usda.gov/sites/default/files/2024-11/fy25-wa-scenarios.pdf

Contour farming is most successful in supporting both water quality and retaining soil for producers when implemented in concert with other BMPs, such as conservation tillage, cover crops, field borders, grassed waterways, and riparian buffers. On its own, contour farming is unlikely to be sufficient to protect surface water quality. Consider the addition of contour filter strips to increase pollutant retention and reduce runoff from the field.

Changing precipitation patterns may add complexity to planning contour rows, and producers should consider how contour rows will accommodate future local conditions and precipitation patterns.

Table 11. Implementation considerations for Contour Farming

Considerations	Details

Costs	**Implementation costs-** costs below are estimates from NRCS Washington Practice Scenarios for Fiscal Year 2025
	• Annual crops (NRCS Practice 330)
	  ○ For a 30acre field with field slope averaging 6% while slope length averages 160 feet, the estimated cost is $12.76 per acre. This results in soil erosion rates that are reduced by nearly half.
	• Perennial crops (NRCS Practice 331)
	  ○ For a 10acre field with field slope averaging 6% while slope length averages 160 feet, the estimated cost is $38.27 per acre. This results in soil erosion rates reduced to tolerable soil loss levels.
	Financial planning
	• This practice may be compatible with existing federal and state cost-share programs.

Operational and Maintenance Requirements	**Installation and operation**
	• Develop a planning document that includes, at a minimum:
	  ○ Percent land slope.
	  ○ Minimum and maximum allowable row grades for the contour system.
	  ○ Sketch or map of the field showing the approximate locations of the baselined used to establish the system and the location of stable outlets (additional BMPs may be needed to treat outletted water).

Considerations	Details

Operational and Maintenance Requirements, continued	• Annual Crops
	  ○ Matching the grade of a contour row to the true contour will increase the operational efficiency of the practice.
	• Perennial Crops
	  ○ Fields with excessive slopes can have slope length shortened using diversions, terraces, or other structures.
	  ○ Inward-sloping berms may be used along crop rows to improve infiltration.
	• For annual crops, perform tillage and planting parallel to contour lines.
	• Periodic inspection and repairs to runoff water outlets.

Technical Requirements	• Technical design standards can be found in NRCS' Field Office Technical Guide Practices 330 and 331. • Consider using the Revised Universal Soil Loss Equation, Version 2 (RUSLE2) when planning contour specifications. • Producers may benefit from consultation with a technical assistance provider such as a local conservation district and/or NRCS office.
Lifespan	This is a management practice, which can be implemented annually, with adaptive management over time to ensure that the correct row grades are in place.

Land Area Requirements	• Annual crops
	  ○ Slopes should be between 2-10% and slope lengths between 100-400 feet. Fields cut by gullies or with strong undulating topography are not well suited to this practice.
	  ○ The 10-year, 24-hour rainfall events should be below 6.5 inches.
	• Perennial crops
	  ○ For perennial crops, field borders may be needed to accommodate farm implement operation and to address erosion along the field edge.

Considerations	Details
Other Implementation Factors	Consider the implementation of complementary BMPs, such as riparian buffers, saturated riparian buffers, filter strips, cover crops, and conservation tillage practices.
Resources	NRCS Practice Scenario cost estimate for Washington, Fiscal Year 2025[6] Soil erosion prediction tools, such as those available on NRCS' Soil Erosion Tools website[7] See Chapter 5: Vegetative Sediment Control for implementation considerations for contour filter strips.

Intercropping and Strip cropping

Use Cases

Intercropping and strip cropping are recommended for use in areas where conventional monocropping does not adequately prevent polluted runoff and soil erosion. These practices are beneficial in areas where winter and spring soil erosion is prevalent.

Strip cropping practices can be applied to all cropland, and can be especially beneficial when applied to sloping croplands. Strip cropping is often most appropriate for grain, seed, vegetable, hay, and silage production, on either side of the Cascade Range in Washington. In Western Washington, strip cropping is particularly recommended for low-residue crops (e.g. potatoes) that are susceptible to erosion during storm events before a cover crop can be established.

Intercropping is slightly more limited than strip cropping in its application, and is not applicable for annual hay or silage crops, though it is an appropriate practice for grain, seed, and vegetable production.

Benefits

Both strip cropping and intercropping are valuable BMP options for the source control of pollutants from agricultural fields. In situations where winter and/or spring soil erosion is a concern, inter- and strip cropping can help to prevent polluted runoff from agricultural fields. In western Washington, winter rains can cause polluted runoff to enter surface water and cause downgrade of shellfish beds in Puget Sound and other Pacific coast bays. The Palouse region in eastern Washington is characterized by hills and soils that are prone to runoff. These practices

[6] https://www.nrcs.usda.gov/sites/default/files/2024-11/fy25-wa-scenarios.pdf
[7] https://www.nrcs.usda.gov/resources/tech-tools/soil-erosion-tools

can be implemented to support addressing these runoff sources, preventing pollution from reaching surface water.

A monoculture can be replaced with a combination of strips of perennial species that can be used for forage, grown with strips of cash crops, effectively providing soil cover, reducing runoff and nutrient transport, and promoting soil moisture retention beyond the cultivation period of a single erosion-prone crop. Additionally, inter- or strip cropping with N-fixing plants such as legumes can reduce the amount of fertilizer that producers must add to fields. If a cover crop is used and the main crop is planted into it, producers can retain soil, compared to the loss that can result from conventional tillage practices.

Table 12. Implementation considerations for Intercropping and Strip Cropping

Considerations	Details
Costs	**Implementation costs-** the costs below are estimates from NRCS Washington Practice Scenarios for Fiscal Year 2025: • Installation of a strip cropping system that includes strips of water erosion resistant crop species parallel to non-water erosion resistant crop species, with widths determined using water erosion prediction technology is estimated at $2.64 per acre. **Financial planning** • This practice may be compatible with existing federal and state cost-share programs.
Operational and Maintenance Requirements	**Installation and operation** • Strip widths should be determined using a current erosion prediction tool. • Strip widths should be multiples of the width of the planting equipment. • Erosion-susceptible strips should not be adjacent to one another, though erosion-resistant strips may be. • Strips should be oriented perpendicular to wind and water erosion vectors, or as close as is practical. • Consider the soil infiltration rate when determining the row grades; see NRCS’ Field Office Technical Guide Practice 585 for additional considerations regarding row grades. • In a given year, at least 50% of the crop rotation should consist of erosion-resistant crops. • Fields with steep contours may need additional planning and maintenance considerations.

Considerations	Details
	○ Sod turn strips may be needed **Monitoring/adaptive management** • Monitor fields for preferential flow paths or areas of erosion; additional BMPs may be needed. • Sediment accumulations along strip edges may need to be smoothed or redistributed to maintain practice effectiveness. • Consider a crop rotation of at least three years and including at least three crop species from different families. • Depending on local climate conditions, consider managing the height of standing residue to maximize snow trapping potential.
Technical Requirements	• It is recommended to utilize erosion prediction technology to determine the necessary strip widths.
Lifespan	This is a management practice, which can be implemented annually, with adjustments to plant species made to achieve desired outcomes over time.
Other Implementation Factors	To reduce the amount of nutrients and pesticides available to leach into water, consider the use of other land management practices, such as crop selection and application of cropping BMPs like cover crops, conservation crop rotation, nutrient management, and pest management. In areas where runoff may result in concentrated flow erosion, stable outlets may be necessary, and may include grassed waterways, field borders, filter strips, and/or water and sediment control basins.
Resources	NRCS Practice Scenario cost estimate for Washington, Fiscal Year 2025[8] Soil erosion prediction tools, such as those available on NRCS' Soil Erosion Tools website[9]

[8] https://www.nrcs.usda.gov/sites/default/files/2024-11/fy25-wa-scenarios.pdf
[9] https://www.nrcs.usda.gov/resources/tech-tools/soil-erosion-tools

Alley Cropping

Use Cases

Alley cropping is an appropriate practice on all cropland and hayland where the climate, precipitation, and/or management practices will support trees, shrubs, forage, and crops growing in combination.

Benefits

The NRCS (2018) practice information for alley cropping outlines many benefits to implementing alley cropping, including:

- Enhanced microclimate conditions, which can improve crop quality and quantity.
- Reduced soil loss due to erosion and reduced surface water runoff.
- Improved soil health by increasing and cycling nutrients, further reducing the leaching of dissolved nutrients.
- Increased crop diversity and enhanced wildlife and beneficial insect habitat.
- Combinations of annual and perennial plants can yield differing products and profits at different times throughout the year, increasing the effective use of space and resources.

Table 13. Implementation considerations for Alley Cropping

Considerations	Details
Costs	**Implementation costs-** the costs below are estimates from NRCS Washington Practice Scenarios for Fiscal Year 2025: • Tree seedlings are installed into a field area that has previously been cropped in perennial grass; estimated costs of \$36.33 - \$47.27/planted seedling. Costs will vary depending on the crops added and method of installation. **Financial planning** • This practice may be compatible with existing federal and state cost-share programs.
Operational and Maintenance Requirements	**Installation and operation** • Careful consideration is recommended when choosing plant combinations, to ensure that crop or forage and woody plants are compatible and complementary. ○ Consider the nutrient balance when selecting plant species, to ensure maximized utilization and cycling of nutrients and soil organic matter. • Ensure that all plants are adapted to the climate and on-site soil conditions. Supplemental watering may be necessary, especially to establish tree species.

Considerations	Details
	• When possible, select pest-resistant varieties. **Monitoring/adaptive management** • Monitor fields for preferential flow paths or areas of erosion; additional BMPs may be needed. • Sediment accumulations along strip edges may need to be smoothed or redistributed to maintain practice effectiveness.
Technical Requirements	• Analysis of required spacing between tree/shrub sets to achieve the desired outcome and continue to allow the use of machinery and equipment. • Develop a planting plan which includes how many rows of trees/shrubs and the species in each row, as well as the type of erosion being treated and any areas of preferential flow.
Lifespan	This is a management practice, which can be implemented annually, with adaptive management over time to ensure use of appropriate plant species and spacing.
Other Implementation Factors	To reduce the amount of nutrients and pesticides available to leach into water, consider the use of other land management practices, such as nutrient management and pest management. Additional BMPs, such as filter strips and/or riparian buffers may be needed to address areas of preferential flow.
Resources	NRCS Practice Scenario cost estimate for Washington, Fiscal Year 2025[10]

Cover Cropping

Use Cases

Cover crops of grasses, legumes, and other forbs planted for seasonal vegetation can be implemented on all lands that would benefit from seasonal vegetative cover to address negative water quality impacts, such as can result from runoff of excess nutrients and/or sheet, rill, and wind erosion. Cover crops can be added to field management in all cropping systems that can support establishment and growth of cover crops and requires an adequate growing season for the establishment of a cover crop stand that can sufficiently protect soil during spring and winter conditions. Cover crops may perform differently on different soils, in different

[10] https://www.nrcs.usda.gov/sites/default/files/2024-11/fy25-wa-scenarios.pdf

climates, and under different tillage conditions. Cover crops can be combined with other cropping BMPs, which may enhance nutrient removal efficiency.

Benefits

When planted for seasonal vegetative cover, cover crops can act to reduce sheet, rill, and wind erosion, as well as reduce the amount of nitrogen that is leached from a field. Additionally, cover crops can improve soil health by maintaining or increasing soil organic matter, improving habitat for soil organisms, improving moisture management, and reducing soil compaction. The use of a cover crop during the winter season can also reduce weed and pest pressure, and, depending on the crop type utilized, can supply nitrogen to the subsequent cash crop. Cover crop species can also be chosen to provide additional benefits, such as improving habitat for pollinators, beneficial organisms, and/or natural enemies of crop pests.

Challenges

To successfully utilize cover crops, there must be an adequate growing season following harvest of the cash crop, to support the growth of a cover crop. Adverse weather conditions can result in varied levels of success for cover crops. Cover crops should be carefully selected, to avoid contamination of the primary cash crop.

Table 14. Implementation considerations for Cover Cropping

Considerations	Details
Costs	**Implementation costs-** the costs below are estimates from NRCS Washington Practice Scenarios for Fiscal Year 2025 • In this scenario, fields are planted within 30 days of crop harvest, with a small legume or grain cover crop, that is seeded with a drill. No additional fertilizer is used and the cover crop is terminated using an accepted herbicide. Estimated $84.07/acre. • For a multi-species cover crop, which may include a small grain, a legume, forage sorghum, radish, turnip, etc., seeded immediately after the harvest of a row crop, but may be inter-seeded into a row crop using a broadcast seeder or drill, and terminated using herbicide or tillage, the estimated cost per acre is $103.82. • In this scenario on an organic operation, a small organic grain or grain/legume mix is planted immediately after harvest and terminated using a mechanical method within weeks prior to planting the next crop. Estimated cost per acre is $128.22. • For a smaller-scale field, with a production bed of ~4,000sqft, with a multi-species cover crop planted

Considerations	Details
	immediately after harvest of a crop and implementation via hand labor, with the cover crop mechanically terminated, the estimated cost is $31.62 per acre. **Financial planning** • This practice may be compatible with existing federal and state cost-share programs. • Cover crops may be applicable for crop insurance.
Operational and Maintenance Requirements	**Installation and operation** • Consider your crop and harvest needs, as well as seeding method to determine whether to interseed cover crops into production crops or to plant cover crops following harvest of production crops. • When selecting appropriate cover crop species: ○ Consider interactions between cover crops and the production crop. ○ Select cover crop species that do not harbor unmanageable pests or diseases of subsequent production crop. ○ For weed suppression and additional erosion prevention, leave terminated cover crop on the soil surface when appropriate. Consider the soil moisture in your area when determining timing of cover crop termination and the appropriate amount of soil moisture removal. ○ Consider soil compaction and select species which can penetrate compacted soil layers. • Leave cover crop residue on field to maximize mulching benefits, weed control, and erosion reduction.
Technical Requirements	• Determine the method and timing of cover crop termination to meet the objective and NRCS Cover Crop Termination Guidelines. • Use current erosion prediction technology to determine the amount of cover needed to achieve soil erosion reduction.
Lifespan	This is a management practice, which can be implemented annually, with adaptive management over time to ensure use of appropriate plant species and spacing.

Considerations	Details
Other Implementation Factors	Additional BMPs, such as filter strips and/or riparian buffers may be needed to address runoff from high erosion areas and/or areas of preferential flow.
Resources	NRCS Practice Scenario cost estimate for Washington, Fiscal Year 2025[11] NRCS Cover Crop Termination Guidelines, 2019[12] Soil erosion prediction tools, such as those available on NRCS' Soil Erosion Tools website[13]

[11] https://www.nrcs.usda.gov/sites/default/files/2024-11/fy25-wa-scenarios.pdf
[12] https://www.nrcs.usda.gov/sites/default/files/2022-09/Termination_Guidelines_Designed_6.28_10.24am_%28002%29.pdf
[13] https://www.nrcs.usda.gov/resources/tech-tools/soil-erosion-tools