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 and help 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 3

Nutrient Management

Voluntary Clean Water Guidance for Agriculture

Prepared by:
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Water Quality Program

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[2] https://ecology.wa.gov/about-us/accessibility-equity/accessibility

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Recommendations for Nutrient Management to Protect Water Quality

Introduction

Nutrient management is an essential component of production agriculture and involves careful budgeting and application of crop nutrients. The goals of nutrient management are to optimize crop utilization of applied fertilizers and organic amendments to enhance crop yield, quality and health, and soil fertility and health while minimizing negative impacts to the environment.

Managing agricultural nutrients involves controlling their source, timing, rate, and placement, and adaptively adjusting soil nutrient levels so they are efficiently used by crops and not lost to the environment. Limiting losses to the environment is primarily achieved through management and application practices that improve nutrient utilization by crops thus limiting residual nutrients in the soil, and practices that reduce the transport of nutrients through processes such as runoff, erosion, leaching, volatilization and denitrification.

This guidance includes practices that can be used to promote the efficient use of applied nutrients by crops and limit losses to surface water, groundwater and the air.

Scope of Guidance

Best management practices recommendations included in this guidance are primarily source control practices intended to prevent pollutants from entering surface or groundwater through runoff, leaching or being emitting to the atmosphere and later deposited. Adaptive management is key for any nutrient management approach; thus, this guidance also includes recommendations and resources for adaptive management and guidance and resources for soil testing and organic nutrient source testing.

While nutrient management techniques can limit losses to the environment, agricultural systems are inherently leaky and cannot fully protect water quality in isolation. Therefore, effective nutrient management relies upon making good, agronomy-based decisions and using complementary conservation practices that maximize in-field nutrient retention and edge-of-field capture to fully protect water quality. Examples of these types of practices include tillage and residue management, cover crops, grassed waterways, field borders, filter strips, riparian buffers, and irrigation management. Information about these practices can be found in companion chapters of the Clean Water Guidance for Agriculture.

Definitions Used in the Guidance

- **Aerial application** - fertilizer is applied using aircraft, such as airplanes or drones.
- **Agronomic rate** –application amounts that provide sufficient nutrients for optimal crop yield while simultaneously ensuring that excess nutrients are not left in the soil or lost to the environment.
- **Banding** - nutrients are applied in a concentrated band near the root zone for more efficient uptake, particularly in areas where nutrient leaching or loss is a concern.
- **Buffer capacity** – the ability of soils to resupply cations for those in soil water that were removed by plant roots or leached. The higher the cation exchange capacity, the greater the ability to resupply additional cations.
- **Broadcast application** - fertilizer is spread evenly across the surface of the soil.
- **Cation exchange** – process where adsorbed cations exchange with other cations in soil solution.
- **Cation exchange capacity (CEC)** – a measure of the total negative charges within the soil and relative ability to adsorb plant nutrient cations such as calcium magnesium, potassium, ammonium and sodium. CEC is a property of a soil that describes its capacity to supply plant nutrient cations for plant uptake.
- **Deep placement** - fertilizer is placed several inches below the surface near the plant roots, often using specialized equipment.
- **Denitrification** – a process where nitrite and/or nitrate are converted to gaseous forms of nitrogen including nitrous oxide (N_2O), nitrogen oxides (NO and NOx) and dinitrogen gas (N_2).
- **Fertigation** - fertilizer is dissolved in irrigation water and applied through the irrigation system.
- **Foliar application** - liquid fertilizer is applied directly to plant leaves or the soil.
- **Groundwater** – saturated underground zones where water has infiltrated below the land surface and is retained in the pores and fractures of materials such as sand, gravel or rock.
- **Growing season** - period of the year where environmental conditions such as temperature, day length, and moisture are suitable for plant growth and crop development.
- **Leaching** – downward movement of dissolved nutrients through the soil profile via percolating water.
- **Mulching** - using organic fertilizers as a mulch material which naturally breaks down and adds nitrogen and other nutrients to the soil.
- **Macronutrients -** elements used by plants in large quantities. Macronutrients can be further defined as primary or secondary.

- **Micronutrients** – nutrients needed in very small quantities but are essential for plant survival. Micronutrients include iron (Fe), boron (B), copper (Cu), chlorine (Cl), Manganese (Mn), molybdenum (Mo), zinc (Zn), cobalt (Co), and nickel (Ni).
- **Mineralization** – process of converting organic soil nutrients (from decomposed plants and applied organic fertilizers like manure) into inorganic, plant-available forms.
- **Nitrification** – process of converting ammonium to nitrate.
- **Nitrogen fixation** – process where atmospheric nitrogen (N_2) is converted to ammonia (NH_3) or ammonium (NH_4^+) via specific types of nitrogen-fixing bacteria or by lightning.
- **Nitrogen immobilization** - process where soil microorganisms convert plant available, inorganic nitrogen into organic forms making it temporarily unavailable.
- **Nutrient use efficiency (NUE)** - the ability of a crop to utilize available nutrients in the most effective way for growth and development. NUE is commonly used as a tool to assess how well a crop or crop system uses a given amount of nutrient inputs relative to yield or other desired outcomes.
- **Pre-planting** - where nutrients are applied during soil preparation or before planting. It is usually via incorporation or a subsurface method.
- **Percent base saturation** - the proportion of a soil's cation exchange capacity (CEC) that is occupied by acid cations (H^+ and Al^{3+}) and basic cations, primarily calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), and sodium (Na^+). The relative proportion of acids and bases determines a soil's pH
- **Primary nutrients** – macronutrients including nitrogen (N), phosphorus (P), and potassium (K).
- **Realistic yield goal** - an anticipated amount of crop production (e.g. weigh or volume) that is achievable based site-specific factors such as such climate, crop variety and genetics, water availability, soil fertility and crop management.
- **Secondary nutrients** – nutrients needed in medium quantities in comparison to macronutrients and micronutrients and include calcium (Ca), magnesium (Mg), and sulfur (S).
- **Side-dress** - applied during the growing season to meet nutrient demands as plants grow, especially for crops that require additional nutrients.
- **Volatilization** - a process where ammonium (NH_4^+) is chemically reduced and converted to ammonia gas (NH_3) which is released to the atmosphere.
- **Top-dress** - spreading fertilizer on the surface of the soil around plants.

Best Management Practices

The following are recommendations for managing the rate, timing, source and placement of nutrient applications. Also included are recommendations and guidance for the management of secondary- and micro-nutrients, soil monitoring and organic nutrient source testing along with adaptive management strategies that should be used when soil sampling demonstrates adjustments are needed.

This guidance includes additional information about aspects of nutrient management that affect effectiveness if not properly managed. Topics covered include ammonia volatilization, soil pH, nitrogen immobilization and denitrification, fertilizer types and the management of secondary and micronutrients. More information about these topics can be found in Part A of the Appendix.

Application Rates

Every crop has its own distinct nutrient demands in terms of the types of nutrients needed, amounts needed, when they are most needed, and these nutrient requirements will vary based on site-specific factors. The goals of applying nutrients at proper rates are to ensure there are adequate nutrients for optimal crop yield and quality while simultaneously ensuring that excess nutrients are not left in the soil after a growing season. Residual, unused soil nutrients are susceptible to many processes that transport nutrients to groundwater, surface water and the atmosphere via runoff, erosion, leaching, volatilization and denitrification.

The following are recommendations to help ensure nutrients are applied at proper rates.

- Use Pacific Northwest land grant university fertilizer guidelines to determine crop-specific application rates and optimal times for applying nutrients.
    - When land-grant university recommendations are unavailable (e.g., new crops or varieties, or specific growing conditions), use industry or out-of-region guidance as necessary. Guidance used should include nutrient utilization information.
- Application rates for nitrogen, phosphorus and potassium must be based on crop and/or crop sequence, current soil samples, nutrient content of organic sources (when used), realistic yield goals, and not exceed land grant university recommendations. Plant tissue or stem testing may also be used to develop applications rates.
    - A realistic yield goal is the anticipated amount of crop production (e.g. weigh or volume coupled with nutrient content by weight or volume) that is achievable based on site-specific factors such as climate, crop variety and genetics, water availability, soil fertility and crop management.
    - At a minimum, yield goals should be realistic and based on historical yield data, soil productivity information, climatic conditions, nutrient test results, level of management, and incorporate factors that may limit yield such as poor soil quality,

    - drainage, pH, soil salinity, current nutrient imbalances, irrigation availability, and available soil moisture.
- Application rates must not exceed the annual amount of nitrogen and phosphorus needed to meet a realistic yield during a growing season, accounting for soil test values and anticipated amounts from in-soil sources.
    - See the Nitrogen Fertilizer and Phosphorus Fertilizer sections in Part A of the Appendix for more information about estimating mineralization.
- Manage secondary and micronutrients to maintain crop health and support nitrogen and phosphorous use efficiency. Land grant extension service soil interpretation guides should be used to evaluate the need for supplemental nutrients.

Nutrient Budgets

A nutrient budget is a plan used to determine the amount of nutrients that will be applied to a specific crop each year. Crop budgets account for nutrients currently available in the soil, nutrients that will become available (mineralization) and additional sources including starter fertilizer, fixed nitrogen from legumes, and nitrate from irrigation. Budgets are based on a realistic yield goal, the amount of nutrients needed to meet the yield goal (minus credits), and the type and nutrient content of fertilizer(s) to be used.

Information needed to create a nutrient budget includes:

- Crop type (annual, biennial, perennial),
- Realistic yield goal and crop removal rates,
- Total amount of nitrogen (N), phosphorus (P) and potassium (K) needed to meet the yield goal,
- Current soil nutrient analysis – at a minimum, N and P content from the most recent soil sampling taken in the spring, prior to planting,
- Soil organic matter and estimation of N supplied by soil organic matter via mineralization,
- Estimation of nitrogen and phosphorus provided by additional sources (e.g., irrigation or atmospheric deposition of nitrogen),
- Types of nutrients that will be used (inorganic or organic sources), their nutrient content, and other nutrient credits such as nitrogen provided by legumes,
- Estimation of nitrogen losses from the source and application method used (primarily volatilization of nitrogen from surface applied manure, urea or other ammonium-based fertilizers),
- Determination of the net nutrient balance (surplus or deficit) for N, P and K.

- Soil series description for each field.
    - Soil properties influence how nutrients are released, retained and become plant available.
    - The Natural Resources Conservation (NRCS) has online tools that can be used to obtain this information.

The NRCS Field Office Technical Guide (FOTG) for nutrient management includes templates that can be used to develop a nutrient budget and includes tools to estimate nitrogen credits from legumes and crop removal rates for nitrate, phosphorus and potassium. A certified crop advisor can also help develop nutrient budgets.

Nutrient Sources

- There are many forms of inorganic and organic sources of crop nutrients, and each has its unique characteristics, applications, and benefits. It's critical for agricultural producers to assess their needs and plan accordingly when choosing which nutrient source to use.
- Different types (organic and inorganic) and forms of fertilizers can be used in complementary ways depending on crop needs and soil health goals.
- The type of fertilizer used for a given crop or cropping system will vary depending on factors such as land aspect, fertilizer composition, crop type, tillage and application methods, soil conditions, climate, and economic and environmental considerations.
- Inorganic and organic fertilizers sources can both be used to effectively supply plant nutrients, but they differ in several important ways.
    - See the Nitrogen Fertilizer and Phosphorus Fertilizer sections in Part A of the Appendix for more information about the types and forms (organic and inorganic) of nitrogen and phosphorus fertilizers, their nutrient content, estimating mineralization, common application methods, and benefits and challenges of each.
    - See the Soil Nitrogen Immobilization section in Part A of the Appendix for information about factors that affect nitrogen immobilization including the use of organic sources of nutrients.
    - Use tools like the Organic Fertilizer and Cover Crop Calculators[3] which can be used to estimate nutrients supplied by cover crops and organic fertilizers and develop nutrient management budget.
- Ultimately, nutrient sources must be compatible with the tillage and planting system used, soil properties, crop, crop rotation, and the timing of crop needs.

[3] https://smallfarms.oregonstate.edu/calculator

- Whenever possible, measure irrigation water nutrient concentrations during the growing season, especially when irrigation water sources are known or expected to have substantial nutrient concentrations.

Application Timing

Proper nutrient application timing ensures nutrients are available when they are needed by growing plants. Well timed nutrient applications can support greater crop production and improved nutrient use efficiency, thus reducing the potential for residual nutrients to be left in the soil after a growing season. Timing also influences the potential for applied nutrient to be lost to the environment during and after the growing season through processes such as runoff, erosion, leaching, volatilization and denitrification.

The following are recommended practices for nutrient timing.

- Only apply nutrients during the growing season for the target crop.
- Nutrient applications should be timed for peak nutrient demand and completion of the crop in the season. This is typically from the early to mid-growing season for many crops.
    - When using organic nutrient sources, account for their nutrient concentration, release rates and release timing to ensure nutrients are plant-available when needed.
    - Avoid or reduce application rates if nutrients aren't plant-available during peak demand.
- Use split applications to best match nutrient demands when feasible for the crop.
- Use land grant university guidance to conduct a pre-sidedress nitrate test prior to fertilizing/side-dressing corn to ensure additional nitrogen is needed and to determine the appropriate application rate.
- Nutrients, especially nitrogen and phosphorus, should not be applied under the following conditions.
    - Frozen or snow-covered soil,
    - Saturated or near-saturated soil,
    - During precipitation events,
    - When field conditions and measurable precipitation are forecasted that is likely to cause runoff, erosion or cause soil water to enter subsurface tile drainage systems. This includes intense rain events or steady accumulations.
        - Check the 5-day weather forecast when planning nutrient applications, especially in the spring and fall.
- Avoid times when runoff, erosion, leaching to groundwater or subsurface drain tiles, or volatilization are likely.

    - See the Nitrogen Loss & Transport Mechanisms and Phosphorus Mobility & Phosphorus Transport sections in Part A of the Appendix for more information about field conditions that increase the potential for nutrient losses.
    - See the Ammonia Volatilization section in Part A of the Appendix more information about factors that affect ammonia volatilization and practices that can be used to limit volatilization from ammonia- and ammonium-based fertilizers including manure.
- Do not apply in or adjacent to direct conduits to surface or groundwater such as swales that convey runoff to surface waters, gullies, open tile line intake structures, sinkholes, agricultural or drinking water well heads, or other conduits to surface or groundwater.
- Also consider factors such as crop type, growth stage, fertilizer type, tillage methods and application equipment used, and irrigation availability and irrigation schedules when planning application timing.

Cool-season Forage & Hay Grasses

- Do not apply nitrogen to cool-season grasses from October 1 until after T-Sum 200 is reached (west of Cascades) or until T-Sum 360 is reached (east of Cascades) the following year.
- For spring applications to cool-season grass crops:
    - Use T-Sum 200 (west of Cascades) and T-Sum 360 or T-Sum 720 (east of Cascades) to time the first application of nitrogen.
        - See Nitrogen Management for Cool-Season Grasses in Part A of the Appendix for additional information including how to calculate T-Sum 200, T-Sum 360 and T-Sum 720.
    - Ensure field and crop conditions are conducive for early nitrogen applications.
    - Pastures and hayland with a poor stand are not suitable for early nitrogen applications.
    - Common application rates at T-Sum 200 and T-Sum 360 for grass dominated, higher yielding fields ranges from 40-60 lbs./acre for first nitrogen application. Lower yielding fields and/or fields with a mix of grass and legumes need less nitrogen.
        - Higher yielding grass hay and silage fields will be harvested more frequently (approximately four to six times per season) for both yield and quality, thus, nitrogen and other nutrients will likely need to be reapplied more often.
    - Avoid times when runoff, erosion, leaching or volatilization are likely.
- Late summer or early fall nitrogen applications to cool season grass crops.
    - Cool season grasses (pasture and hayland) may benefit from additional nitrogen applied in late summer or early fall.

    - Prior to applying nitrogen (including manure sources), test soils to determine if additional nitrogen is needed.
        - If additional nitrogen is needed, nitrogen should be applied from approximately mid-August through September based on location and weather conditions and no later than October 1.
    - Do not exceed plant nutrient needs. Excess nutrients applied during this time are more likely to be lost via runoff and leaching, and vigorously growing plants are more susceptible to winter damage.
    - Nitrogen applications should be coordinated with appropriate temperatures and moisture availability.
    - Do not apply nitrogen if adequate rain does not fall prior to October 1 or if irrigation is unavailable.
    - If organic sources such as manure are used to supply nitrogen, late season nitrogen applications should not result in the over application of phosphorus beyond crop need.
    - Avoid times when runoff, erosion, leaching or volatilization are likely.
- Consult Pacific Northwest Land Grant University guidance such as Nutrient Management for Pastures (EM 9224)[4], Pasture and Grazing Management in the Northwest (PNW 614)[5] , The Western Oregon and Western Washington Pasture Calendar (PNW 699)[6], and the Inland Pacific Northwest Pasture Calendar (PNW 708)[7]for application rate information.

Placement

Nutrient placement is the positioning of nutrients in the soil to ensure accessibility for plants and maximize plant uptake while minimizing the potential for losses. In general, proper placement involves determining the optimal depth, location, and method of nutrient application relative to the crop's root zone.

- At a minimum, nutrients must be placed outside of riparian core zones as outlined in Chapter 12 of the Clean Water Guidance (Riparian Areas and Surface Water Protection).
- Place nutrients in the soil in a manner that ensures plant accessibility and maximizes plant uptake while minimizing the potential for losses.
- Subsurface placement techniques or incorporation should be used whenever possible.

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[4] https://extension.oregonstate.edu/sites/extd8/files/documents/em9224.pdf
[5] https://www.uidaho.edu/-/media/uidaho-responsive/files/extension/publications/pnw/pnw0614.pdf?la=en&rev=86448e20502d463ea759694aff7fd26f
[6] https://extension.oregonstate.edu/sites/extd8/files/documents/pnw699.pdf
[7] https://wpcdn.web.wsu.edu/wp-ecommerce/uploads/sites/2/product-4768-sku-PNW708.pdf

- Placing nutrients below the soil surface or incorporating surface-applied nutrients into the soil can significantly reduce or prevent losses via runoff, erosion and volatilization.

- Use application methods that are most compatible with the crop and/or tillage system for the crop or crop rotation and are most likely to limit losses runoff, erosion, leaching and volatilization.
- When incorporation or subsurface placement aren't feasible, avoid conditions likely to lead to runoff, erosion, leaching and/or ammonia volatilization.
  - See the Ammonia Volatilization section in Part A of the Appendix for more information about factors that affect ammonia volatilization and practices that can be used to limit volatilization from ammonia- and ammonium-based fertilizers including manure.
- See the Nutrient Application Method & Placement section in Part A of the Appendix for more information about nutrient placement and methods including a brief description of common application practices and some advantages and disadvantages of each.
- Ensure application equipment is in good working order and well maintained.

Secondary Nutrients, Micronutrients, and pH

Secondary, micronutrients and pH can play critical roles in crop development and their soil levels can significantly influence crop yield, quality, and resistance to diseases.

- Routinely test soils for secondary- and micro-nutrients and adjust their levels or soil conditions such as soil pH that are limiting their availability.
  - Use resources such as the Oregon State University Soil Test Interpretation Guide to determine if soil levels are in proper ranges and identify options for adjusting them.
  - See the Secondary & Micronutrient section in Part A of the Appendix for information about secondary and micronutrients and an overview of their roles in plant development.
- Regularly test soils for cation exchange capacity (CEC) and use results to determine the percent base saturation when planning nutrient applications.
  - CEC is a fundamental soil property used to predict plant nutrient availability and retention in the soil.
  - Soil CEC affects liming and fertilization practices.
  - Soils with high CEC generally retain more nutrients than low-CEC soils.
  - Ideal ratios of Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+} in the base saturation spectrum promote optimal plant growth which can enhance nutrient use efficiency of macronutrients.
  - Soils with high percent base saturation are generally more fertile.

- Managing soil pH is an important practice because it directly affects nutrient availability, microbial activity, soil and plant health.
    - Regularly test soil pH at the same time of year each year.
    - Keep soil pH at crop-specific optimal levels for the planned crop or crop rotation.
    - Use Pacific Northwest Land Grant University guidelines, when available, to determine optimal crop pH ranges and manage soil pH.
    - Certain ammonia- and ammonium-forming fertilizers can lead to soil acidification. Consider using alternative, non-acidifying nitrogen fertilizers when needed.
    - For acidic soils, agricultural lime (calcium carbonate), dolomitic lime (calcium magnesium carbonate), and other pH adjusting amendments can be used to increase soil pH.
    - For alkaline soils, adding organic matter such as compost or manure can help buffer soil pH. Amendments such as elemental sulfur can also be used to lower soil pH.

Secondary & Micronutrient Interpretation Guide Resources

- Sullivan, D. M., Horneck, D. A., Owen, J. S., & Hart, J. M. (2019). Oregon State University Extension Service Soil Test Interpretation Guide.
- Natural Resource Conservation Service Field Office Technical Guide for Nutrient Management (590)
- Marx, E. S., Hart, J., & Stevens, R. G. (1999). Soil test interpretation guide (EC 1478). Oregon State University Extension.
- Washington State University. (n.d.). Micronutrient functions in plants. Washington State University. https://smallgrains.wsu.edu/soil-and-water-resources/essential-nutrients/micronutrients/micronutrient-functions-in-plants/
- Peryea, F. J. (2019, February). *Micronutrients*. WSU Tree Fruit. https://treefruit.wsu.edu/micronutrients/

Soil pH Management Resources

- Anderson, N. P., Hart, J. M., Sullivan, D. M., Christensen, N. W., Horneck, D. A., & Pirelli, G. J. (2013). Applying lime to raise soil pH for crop production (Western Oregon) (EM 9057). Oregon State University Extension Service.
- Anderson, N. P., Hart, J. M., Sullivan, D. M., Christensen, N. W., Horneck, D. A., & Pirelli, G (2010) Evaluating Soil Nutrients and pH by Depth in Situations of Limited or No Tillage in Western Oregon (EM 9014). Oregon State University Extension Service.
- Carter, P. (n.d.). *Using a pH meter for in-field soil pH sampling* (FS205E). Washington State University Extension. https://wpcdn.web.wsu.edu/wp-ecommerce/uploads/sites/2/product-4263-sku-FS205E.pdf

- McFarland, C. R., Huggins, D. R., & Koenig, R. T. (2025). *Soil pH and implications for management: An introduction* (FS170E). Washington State University Extension.
- Oregon State University Extension Service. (2021). *Living on the Land: Managing soil pH* (EC 1657). https://extension.oregonstate.edu/sites/extd8/files/documents/ec1657.pdf
- Oregon State University Extension Service. (2013). *Soil acidity in Oregon: Understanding and using concepts for crop production* (EM 9061). https://extension.oregonstate.edu/sites/extd8/files/documents/em9061.pdf
- Sullivan, D. M., Horneck, D. A., & Wysocki, D. J. (2013). *Eastern Oregon liming guide* (EM 9060). Oregon State University Extension Service.
- Wortmann, C. S., Mamo, M., & Shapiro, C. A. (2015). *Management strategies to reduce the rate of soil acidification* (NebGuide G1503). Nebraska Extension, Institute of Agriculture and Natural Resources. https://extensionpubs.unl.edu/publication/g1503/2015/pdf/view/g1503-2015.pdf

Soil Monitoring & Organic Nutrient Source Testing

Routine Soil Monitoring for Nutrient Planning

- Routinely test soils for primary, secondary, and micronutrients to evaluate soil nutrient levels and develop nutrient budgets to ensure nutrients aren't over- or under-applied.
    - At a minimum, soil tests should include pH, sodicity and electrical conductivity (EC) where salts are a concern, soil organic matter, nitrogen (nitrate plus ammonia), phosphorus, potassium, and other nutrients recommended by appropriate Pacific Northwest land grant university crop production guidelines.
- Test for soil nitrogen (ammonium-N plus nitrate-N) each spring to finalize nutrient budgets ahead of the growing season. Soil testing in the spring should occur as close to fertilizer application as possible.
    - West of the Cascades, soil nitrate is evaluated within the first foot.
    - In arid regions east of the Cascades, soil nitrate is evaluated by measuring nitrate nitrogen (NO_3^-) in one-foot depth increments to a depth of 2 to 5 feet as necessary for the planned crop or crop rotation. Sampling depths may need to be adjusted for shallow rooting crops to avoid overestimating the amount of available nutrients.
    - Consult nutrient management guidelines for individual crops to determine sampling depth and method for crediting soil nitrogen.
- For phosphorus:
    - Use the Bray P1 method for acidic soils and the Olsen sodium bicarbonate ($NaHCO_3$) method for alkaline soils. If the soil pH baseline is unclear, include both tests so valid results are obtained. Phosphorus fertilizer recommendations are typically based on results from these methods.
    - Sample fields at least once every 3 years.

        - Increase the frequency to every 1-2 years on sandy, low organic matter soils, fields that receive regular manure or compost applications, intensive cropping systems, or when there is a history of deficiencies.
        - When sampling soil for phosphorus, it's important to be aware of previous phosphorus management.
        - Avoid fertilizer bands when collecting soil samples.
    - Conduct a post-harvest soil test at least once every three years and use results to adaptively manage soil phosphorus.
        - Increase the frequency to every 1-2 years for soils with low cation exchange capacity, regular manure or compost applications, intensive cropping systems or when there is a history of deficiencies.
        - See the adaptive management section below for additional information.
- For secondary nutrients (calcium, magnesium and sulfur):
    - Test for secondary nutrients every 1-3 years.
    - Sulfur and boron are typically evaluated every 2 - 3 years; however, each is prone to leaching. Increase the frequency to every 1-2 years if leaching is an issue.
    - Calcium and magnesium are commonly evaluated every 2-3 years.
- For micronutrients,
    - Soil micronutrients are typically evaluated every 2-4 years or as needed.
    - Which micronutrients to test for will likely vary based on crop or crop rotation, history of management and soil properties.
    - Certified crop advisors can help identify which micronutrient to test for.
- Plant tissue or stem testing may also be used to support nutrient management planning.
- Follow Pacific Northwest Land Grant University sampling, handling and testing procedures that are regional and crop appropriate. Below are examples of available resources.
- Consult the Natural Resource Conservation Service (NRCS) Field Office Technical Guide (FOTG) for Nutrient Management (590) for additional information and resources when needed.

Soil Sampling & Testing Resources

- Halbleib, M., Ellsworth, J. W., Sullivan, D. M., Horneck, D. A., Brown, B. D., & Stevens, R. G. (2024). Monitoring soil nutrients using a management unit approach (PNW 570). Oregon State University Extension Service. https://extension.oregonstate.edu/sites/extd8/files/catalog/auto/PNW570.pdf

- Hart, J., Strik, B., & Rempel, H. (2023, May). Cranberries: Nutrient management guide. Washington State University Extension (EM 8903-E) https://wpcdn.web.wsu.edu/wp-extension/uploads/sites/2056/2023/05/Cranberries-Nurtient-Management-Guide.pdf
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- Sullivan, D. M., Cogger, C. G., Bary, A. I., Bittman, S., & Brewer, L. J. (2021). Postharvest soil nitrate testing for manured grass and silage corn (west of the Cascades) (EM 8832). Oregon State University Extension Service. https://extension.oregonstate.edu/sites/extd8/files/documents/em8832.pdf
- Horneck, D. A., Sullivan, D. M., Owen, J. S., & Hart, J. M. (2019). Soil test interpretation guide (EC 1478). Oregon State University Extension Service. https://extension.oregonstate.edu/sites/extd8/files/catalog/auto/EC1478.pdf
- Marx, E. S., Hart, J., & Stevens, R. G. (1999). *Soil test interpretation guide* (EC 1478). Oregon State University Extension Service. https://piercecd.org/DocumentCenter/View/670/OSU-Soil-Test-Interpretation-002?bidId
- Natural Resource Conservation Service Field Office Technical Guide for Nutrient Management (590)

Soil Monitoring for Adaptive Management

- Soil nitrogen should be tested each year in the fall (ammonium-N plus nitrate-N) after harvest to evaluate nutrient budget effectiveness and/or to determine application rates for fall planted crops.
  - West of the Cascades, soil nitrate is evaluated within the first foot.
  - In arid regions east of the Cascades, soil nitrate is evaluated by measuring NO_3-N in one-foot depth increments to a depth of 2 to 5 feet.
- Soil phosphorus should be tested in the fall to evaluate nutrient budgets and make necessary adjustments.
  - Samples must be taken at least once every 3 years.
  - West of the Cascades, soil phosphorus is typically evaluated within the first foot.
  - In arid regions east of the Cascades, phosphorus is typically evaluated within the first two feet.
- For post-harvest sampling (nitrogen and phosphorus):
  - Samples should be collected as soon as possible after crop harvest.
  - Samples should be taken before heavy rain.

- Avoid sampling fields where manure has been applied within the past 30 days.

Manure & Other Organic Sources

- Nutrient values of manure, organic by-products and biosolids must be determined prior to land application.
- Analyses of manure or other organic nutrient sources should include total nitrogen (N), ammonium (N), total phosphorus (P) or phosphate (P_2O_5), total potassium (K) or potassium oxide (K_2O), and percent solids. Proper conversion between phosphorus (P) and phosphate (P_2O_5), nitrate and nitrate as nitrogen, as well as between potassium (K) and potassium oxide (K_2O), where appropriate, is important to avoid accidental over- or under-application.
- Manure, organic by-products, and biosolids samples must be collected and analyzed at least annually, or more frequently if needed to account for operational changes (feed management, animal type, manure handling strategy, etc.) that impact manure nutrient concentrations.
    - If no operational changes occur, less frequent manure testing is allowable where operations can document a stable level of nutrient concentrations for the preceding three consecutive years, unless federal, State (Washington State Department of Ecology or Washington State Department of Agriculture), or local regulations require more frequent testing.
- Samples must be collected, prepared, stored, and shipped according to land-grant university guidance or industry standards.
- Biosolids application must follow Washington State Department of Ecology guidelines.
- Use Pacific Northwest land grant university guidance for nutrient source sampling and estimating the nutrient content and nutrient availability from organic sources. Below are examples of available resources.

Organic Source Testing and Nutrient Estimation Resources

- Sullivan, D. M. (2023). Estimating plant-available nitrogen from manure (EM 8954-E). Oregon State University Extension Service. https://extension.oregonstate.edu/catalog/pub/em-8954-estimating-plant-available-nitrogen-manure
- Bary, A. I., Cogger, C. G., & Sullivan, D. M. (2016). Fertilizing with manure and other organic amendments (PNW 533). Oregon State University Extension Service. https://extension.oregonstate.edu/catalog/pub/pnw-533-fertilizing-manure-other-organic-amendments

Adaptive Management for Nitrogen & Phosphorus

Of all plant nutrients, nitrogen, potassium and phosphorus are used in the greatest amounts. Of these, nitrogen and phosphorus have the greatest impact on water quality. Therefore, it is critically important that post-harvest soil levels remain low because residual soil nitrogen and phosphorus are most susceptible to losses to surface and groundwater which can result in many negative impacts to water quality.

Adaptive Management for Nitrogen Using Post-Harvest Soil Monitoring

Residual (post-harvest) soil nitrate-nitrogen is a useful measurement to evaluate nutrient (nitrogen) management. Excess soil nitrate in the fall can result from the over-application of nitrogen, mistimed nitrogen application, soil nutrient imbalances, nitrogen mineralization after crop uptake ceases, or poor growing conditions such as drought, pests or lack of adequate irrigation or rainfall.

When post-harvest nitrate levels are elevated, management decisions including nutrient budgets (and yield goals), application timing and method, nutrient sources used, and soil nutrient imbalances should be evaluated and adjusted to prevent excessive post-harvest soil nitrate-nitrogen in subsequent years.

Post-harvest nitrogen testing is conducted in the fall to evaluate nutrient budget effectiveness. The following is a description of soil nitrate levels along with actions that should be taken based on soil nitrogen concentrations.

Table 1: Adaptive management actions for nitrogen using post-harvest soil monitoring.

Soil Nitrate-nitrogen (NO_3^--N) (ppm)	Description	Actions Needed
<10*	Low	• Continue to follow nutrient budgets and yield goals. • Continue to test soils for primary, secondary and micronutrients (as needed) and manage nutrients to appropriate levels. • Maintain soil pH at crop-specific optimal levels for the planned crop or crop rotation. • Continue to use spring soil sample results to establish application rates. • Continue to use post-harvest soil sampling to evaluate nutrient management practices. • Consider planting cover crops wherever possible.
10-20*	Medium	• Reduce application rates for fall-planted crops. • Consider planting cover crops wherever possible. • Revaluate nutrient budget assumptions including yield goals, soil mineralization, nitrogen volatilization, and other sources of nutrients e.g., legumes, irrigation water or atmospheric/precipitation deposition. • Verify application rates and recalibrate land application equipment when necessary. • Ensure plant available nitrogen applications occur prior to peak crop uptake. • Reduce nutrient applications to the field when other factors affecting soil nitrate levels aren't determined. • Continue to test soils for primary, secondary and micronutrients (as needed) and manage nutrients to appropriate levels. • Continue to use spring soil sample results to establish application rates. • Continue to use post-harvest soil sampling to evaluate nutrient management practices.

Soil Nitrate-nitrogen (NO_3^--N) (ppm)	Description	Actions Needed
		• Maintain soil pH at crop-specific optimal levels for the planned crop or crop rotation. • Maintain nutrient balances between macronutrients, secondary and micronutrients. • Consider hiring a professional/consultant to evaluate nutrient budget assumptions, application methods and timing to develop revised annual nutrient budgets and application rates.
20-30*	High	• Reduce application rates for fall-planted crops. • Plant cover crops wherever possible. • Consult a professional crop advisor to evaluate nutrient budget assumptions, application methods and timing to develop revised annual nutrient budgets and application rates. • Reestablish nutrient budget assumptions including yield goals, soil mineralization, nitrogen volatilization, and other sources of nutrients e.g., legumes, irrigation water or atmospheric/precipitation deposition. ○ Reduce future nitrogen application rates. • Verify application rates and recalibrate land application equipment when necessary. • Adjust land application timing so nutrient availability aligns with peak crop uptake. • Enhance nutrient removal via crop management. • Ensure plant available nitrogen is applied as close as possible to peak crop uptake. • Continue to test soils for primary, secondary and micronutrients (as needed) and manage nutrients to appropriate levels. • Continue to use spring soil tests for nitrogen to adjust application rates.

Soil Nitrate-nitrogen (NO_3^--N) (ppm)	Description	Actions Needed
		• Continue to use post-harvest soil sampling to evaluate nutrient management practices. • Maintain nutrient balances between macronutrients, secondary and micronutrients. • Maintain soil pH at crop-specific optimal levels for the planned crop or crop rotation.
>30*	Very High	• Significantly reduce application rates for fall-planted crops. • Plant cover crops wherever possible. • Consult a professional crop advisor to evaluate nutrient budget assumptions, application methods and timing to develop revised annual nutrient budgets and application rates. • Reestablish nutrient budget assumptions including yield goals, soil mineralization, nitrogen volatilization, and other sources of nutrients e.g., legumes, irrigation water or atmospheric/precipitation deposition. ○ Significantly reduce future nitrogen application rates. • Verify application rates and recalibrate land application equipment when necessary. • Enhance nutrient removal via crop management. • Ensure plant available nitrogen is applied as close as possible to peak crop uptake. • Continue to test soils for primary, secondary and micronutrients (as needed) and manage nutrients to appropriate levels. • Continue to use spring soil tests for nitrogen to adjust application rates. • Continue to use post-harvest soil sampling to evaluate nutrient management practices.

Soil Nitrate-nitrogen (NO_3^--N) (ppm)	Description	Actions Needed
		• Maintain nutrient balances between macronutrients, secondary and micronutrients. • Maintain soil pH at crop-specific optimal levels for the planned crop or crop rotation.

* When converting from parts per million (ppm) to lbs./acre, soil bulk density must be considered. For medium to fine textured soils, multiply ppm by 3.5 to estimate lbs./acre. Multiple by ppm by 4 when the soil is more than 60% sand (Horneck et al., 2019). Conversions may need to be adjusted based on site specific soil conditions, especially soils with low bulk densities.

Adaptive Management for Phosphorus Using Post-Harvest Soil Monitoring

Phosphorus soil test results are an index of phosphorus availability but can't be used to predict plant phosphate availability (lbs./acre) given the many site-specific soil factors that affect phosphorus availability such as pH and soil concentrations of minerals such as calcium, aluminum and iron. Nevertheless, soil phosphorus test results do provide an indication of the amount of plant available, soluble phosphorus likely to be available given the relationship between the forms of phosphorus (organic, adsorbed, and labile phosphorus) and soluble phosphorus.

In general, as soil test phosphorus increases, so does the amount of soluble phosphorus that can be used by crops or transported to surface water or leached. As soil phosphorus concentrations increase, so does the potential for losses of soluble phosphorus. Further, phosphorus is strongly bound to soil particles, so fields with elevated soil phosphorus that are also prone to erosion pose a higher risk of contributing larger amounts of phosphorus if eroded soils reach surface water.

Whether eroded, leached or transported via runoff, phosphorus can significantly impact water quality. Therefore, crop fields must be properly managed to prevent the buildup of soil phosphorus; and if buildup occurs, steps must be taken to reduce levels and the subsequent risk to water quality.

The following is a description of soil phosphorus levels along with actions that should be taken should they become elevated.

Table 2: Adaptive management actions for phosphorus using post-harvest soil monitoring.

Bray P1 test) (ppm P)	Olsen test (ppm P)	Description	Actions Needed
<20*	<10*	Low	• Continue to follow nutrient budgets and yield goals and apply phosphorus at crop removal rates. • Continue to test soils for primary, secondary and micronutrients (as needed) and manage nutrients to appropriate levels. • Maintain soil pH at crop-specific optimal levels for the planned crop or crop rotation. • Continue to use post-harvest soil sampling to evaluate nutrient management practices. • Monitor crops for signs of phosphorus deficiencies.
20-40*	10-25*	Medium	• Consider reducing application rates and apply only at crop removal rates. • Use banded applications when possible. • Revaluate nutrient budget assumptions including yield. • Verify application rates and recalibrate application equipment when necessary • Consider adjusting application timing so nutrient availability aligns with peak crop uptake. • Continue to test soils for primary, secondary and micronutrients (as needed) and manage nutrients to appropriate levels. • Maintain soil pH at crop-specific optimal levels for the planned crop or crop rotation.

Bray P1 test) (ppm P)	Olsen test (ppm P)	Description	Actions Needed
			• Continue to use post-harvest soil sampling to evaluate nutrient management practices. • For fields routinely used for manure application, consider additional approaches such increasing acres available for spreading and/or selling manure or identifying other marketable uses. • Evaluate fields for their potential to erode and for eroded soils to reach surface waters. • Consider using NRCS' Phosphorus Index to evaluate fields that may require additional practices to prevent phosphorus transport to surface water via runoff, erosion, leaching and through subsurface tile drainage. • Consider planting cover crops especially on field with tile drainage and/or higher potential for erosion and excessive runoff.
40-100	25-50*	High	• Stop applying phosphorus until medium or low phosphorus levels are reached. • Plant crops with high phosphorus uptake. • Continue to test soils for primary, secondary and micronutrients (as needed) and manage nutrients to appropriate levels. • Maintain soil pH at crop-specific optimal levels for the planned crop or crop rotation. • Continue to use post-harvest soil sampling to evaluate nutrient management practices. • For fields regularly used for manure applications, consider additional approaches such increasing acres available

Bray P1 test) (ppm P)	Olsen test (ppm P)	Description	Actions Needed
			for spreading and/or selling manure or identifying other marketable uses. • Evaluate fields for their potential to erode and for eroded soils to reach surface waters. • Plant cover crops especially on fields with tile drainage and/or higher potential for erosion and excessive runoff. • Consider using NRCS' Phosphorus Index to evaluate fields that may require additional practices to prevent phosphorus transport to surface water via runoff, erosion, leaching and through subsurface tile drainage.
>100*	>50*	Very High	• Stop applying phosphorus until a medium or low phosphorus level is reached. • Plant crops with high phosphorus uptake. • Continue to test soils for primary, secondary and micronutrients (as needed) and manage nutrients to appropriate levels. • Maintain soil pH at crop-specific optimal levels for the planned crop or crop rotation. • Continue to use post-harvest soil sampling to evaluate nutrient management practices. • For fields regularly used for manure applications, consider additional approaches such increasing acres available for spreading and/or selling manure or identifying other marketable uses. • Evaluate fields for their potential to erode and for eroded soils to reach surface waters.

Bray P1 test) (ppm P)	Olsen test (ppm P)	Description	Actions Needed
			• Plant cover crops especially on fields with tile drainage and/or higher potential for erosion and excessive runoff. • Consider using NRCS' Phosphorus Index to evaluate fields that may require additional practices to prevent phosphorus transport to surface water via runoff, erosion, leaching and through subsurface tile drainage.

* When converting from parts per million (ppm) to lbs./acre, soil bulk density must be considered. For medium to fine textured soils, multiply ppm by 3.5 to estimate lbs./acre. Multiple by ppm by 4 when the soil is more than 60% sand (Horneck et al., 2019). Conversions may need to be adjusted based on site specific soil conditions, especially soils with low bulk densities.

Related NRCS Practices

- Nutrient Management (590)
- Salinity and Sodic Soil Management (610)
- Amending Soil Properties with Lime (805)
- NRCS's Agricultural Waste Management Field Handbook[8] (AWMFH)

Commonly Associated Practices

- Chapter 1: Tillage & Residue Management
- Chapter 2: Crop Systems
- Chapter 5: Soil Stabilization & Sediment Capture (Vegetative)
- Chapter 7: Irrigation Management
- Chapter 8: Field Drainage & Subsurface Drainage Management
- Chapter 11: Animal Confinement & Manure Handling & Storage
- Chapter 12: Riparian Areas and Surface Water Protection

[8] https://directives.sc.egov.usda.gov/viewerFS.aspx?hid=21430

Chapter 3 Appendix Part A: Effectiveness Synthesis for Nutrient Management

Agricultural Nutrients: Water & Air Quality

Nitrogen and phosphorus are essential inputs for agricultural production and are also significant sources of water pollution associated with agriculture. When unused by plants, these nutrients can accumulate in the soil and enter the environment as a pollutant through multiple soil, hydrologic and meteorological processes. Common ways nitrogen and phosphorus are lost to the environment are through soil erosion, runoff, and leaching which can cause numerous negative effects to soil quality, ground water and surface water quality. Nitrogen can also be lost via gaseous emissions.

Nutrient losses negatively affect soil quality by reducing their balanced fertility, increase nutrient concentrations in ground and surface water, and induce numerous physical, biological and chemical changes that negatively affect the health and function of aquatic ecosystems (Del Rossi et al., 2023, Shroder et al., 2003). Common environmental impacts of nitrogen and phosphorus losses to surface water include eutrophication, hypoxia, harmful algae blooms, drinking water contamination, and changes to ecological and species composition in aquatic ecosystems. (Del Rossi et al., 2023, Howarth et al., 2002). Nitrogen leaching can also contaminate groundwater, which is a major source of the states' drinking water.

Excess nutrients in aquatic ecosystems can lead to eutrophication and its associated negative effects including hypoxia and harmful algal blooms. Eutrophication occurs when there are too many nutrients in a waterbody, mainly nitrogen and phosphorus which leads to excessive growth of aquatic plants and algae. Significant increases in algae and aquatic vegetation harm water quality, food resources and habitats, and decrease dissolved oxygen that fish and other aquatic life need to survive. When these algae and aquatic plants die, bacteria consume large amounts of dissolved oxygen as part the decomposition process which can lead to hypoxia, a condition where dissolved oxygen is severely diminished to a point where a waterbody can't fully support aquatic life. Persistently low dissolved oxygen harms aquatic animals resulting in chronic stress or even mortality. Large growths of algae, called algal blooms, can block sunlight and lead to severely depleted dissolved oxygen leading to aquatic life illness or even death in large numbers.

Eutrophication can also cause harmful algal blooms. Harmful algal blooms are algal blooms that produce elevated toxins and bacterial growth that can make people and animals sick or even cause death if they come into contact with polluted water, drink contaminated water or consume tainted fish or shellfish (Environmental Protection Agency, 2021). The impacts of nutrient loading and eutrophication is substantial and has led to increases in the number of nutrient-impaired water bodies and decreases in the number of high-quality water bodies across the United States, indicating poor biological health of the nation's rivers and streams (Del Rossi et al., 2023).

Crop production and fertilization can also negatively impact air quality as these activities generate nitrous oxide and several other air pollutants such as ammonia and nitrogen oxides (NO and NO2). Fertilizer application is directly associated with high emission of nitrous oxide accounting for approximately 68% to 75% of emissions in the United States. Nitrous oxide is a potent greenhouse gas with 300 times more global warming implications than carbon dioxide. (Follett and Delgado, 2002, Singh et al., 2018, Environmental Protection Agency, 2025).

Water and air pollution associated with agricultural sources of nitrogen and phosphorus is understandably a significant concern in the United States and globally. According to the Environmental Protection Agency (EPA), excess nutrients is one of the most common pollution problems affecting waterbodies in the United States. EPA's 2018-2019 National Rivers and Streams Assessment Report found less than one-third of national river and stream miles (28%) had healthy biological communities and only 35% had healthy fish communities. This report found phosphorus and nitrogen to be the most prevalent stressors with 42% of rivers and streams in poor condition due to elevated phosphorus and 44% in poor condition due to nitrogen. Further, the report determined that poor biological conditions were more likely when rivers and streams had poor conditions for nutrients, and 20% of river and stream miles in poor biological condition could be improved if nutrient conditions changed from poor to fair or good (Environmental Protection Agency, 2023).

Causes of Agricultural Nutrient Pollution

Agricultural nutrient pollution, primarily caused by excess nitrogen and phosphorus in the soil and water, has significant and lasting effects on both water quality and human health. The primary causes of agricultural nutrient pollution are rooted in modern farming practices and the intensification of crop production which includes widespread over- or mis-use of synthetic fertilizers, animal manure, and other agricultural practices which introduce large amounts of nutrients into the soil, water, and air when they are not efficiently used by crops or properly managed.

Nutrient pollution occurs when phosphorus and nitrogen enter surface and groundwater through processes such as soil erosion, runoff, leaching, the direct discharge of waste, and indirect pathways such as atmospheric deposition, many of which are the result of excessive use of fertilizers, mismanagement of fertilizers, and poor manure handling and application practices. Nutrient losses to surface and ground water are especially pronounced if nutrients are applied when field or weather conditions are conducive to runoff and erosion or when excess nutrients remain in the soil after a growing season (Howarth et al., 2002).

The nature in which nutrients enter surface and ground water highlights the importance of implementing agricultural best management practices that both prevent over- or mis-use of fertilizer and limit erosion, leaching, runoff and atmospheric deposition. Reducing nutrient pollution ultimately requires a multi-faceted approach beginning with nutrient management.

Fertilizer Use Trends, Cropland & Water Quality

One of the greatest changes in agriculture has been the dramatic increase in the use of inorganic fertilizers beginning in the 1950s (Howarth et al., 2002). This growth inorganic fertilizer use is largely attributed to the increased demand for crop and animal production to meet population demands after the end of World War II and a changing landscape of agricultural in the United States. As production demand increased so did mechanization and usage of inorganic fertilizers, particularly nitrogenous fertilizers which led to significant increases in productivity and strong export markets for domestically produced agricultural goods (Del Rossi et al., 2023, Howarth et al., 2002). During this time, developed countries also built large processing plants to manufacture nitrogenous fertilizers and convert rock phosphate into various water-soluble and partially water-soluble phosphorous fertilizer products (Howarth et al., 2002).

The use of commercial fertilizer has expanded dramatically since the 1950s. From 1950 to 2017 the overall use of commercial nitrogen fertilizer increased from about 1 million metric tons per year to nearly 13 million metric tons per year. Much of this exponential increase in usage occurred from 1950 to the early 1980s when annual commercial nitrogen fertilizer use reached 10 million metric tons. Since then, increases in commercial nitrogen use has followed a steadier and more gradual pattern (Del Rossi et al., 2023). Trends of commercial phosphorus fertilizer use followed a similar pattern during this timeframe but differed in magnitude. From 1950 to 2017, commercial phosphorus fertilizer use increased from approximately 1 million metric tons to 2 million metric tons. The differences in magnitude between nitrogen and phosphorus are due to nutrient requirements of crops where nitrogen is typically applied in greater amounts than phosphorus as nitrogen often favors crop yield (Del Rossi et al., 2023, Howarth et al., 2002). For livestock manure, the annual increase in total nitrogen is moderate and increased from 4.7 million metric tons to 6.7 million metric tons from 1950 to 2017 (Del Rossi et al., 2023). By 2017, phosphorus from commercial fertilizer was roughly equal to livestock total phosphorus.

The amount of land planted in row crops in the United States has varied considerably since the 1950s. Acreage planted with row crops began to decrease beginning in the 1950s and were less than 300 million by 1965, then rebounded by the early 1980s to approximately 360 million acres. Row crop acreage dropped again in the 1980s as the U.S. Department of Agriculture rolled out its Conservation Reserve Program that paid farmers to take vulnerable or marginal cropland out of production for environmental benefits. Since then, row crop acreage gradually decreased and was approximately 320 million acres by 2017 (Del Rossi et al., 2023).

Along with changes to the type and amount of fertilizer used, agricultural production systems in the U.S. have become more specialized and concentrated over the last 30 years. Additionally, the rapid growth of animal feeding operations (AFOs) in many states and the intensification of these operations has led to significant challenges in waste management (Howarth et al., 2002). Prior to World War II and dramatic increases in commercial fertilizer use, farming communities were more self-sufficient with manure nutrients and could effectively recycle nutrients to meet crop needs. However, after World War II, the increased use of commercial fertilizers in crop production led to the spatial separation of grain and animal production. This evolution of agricultural systems has resulted in a major transfer of nutrients from grain-producing areas to animal-producing areas and, as a result, the accumulation of nitrogen and phosphorus in soils at and near animal-producing areas (Howarth et al., 2002). The potential for nitrogen and phosphorus surplus at the farm scale can be much greater in AFOs than in cropping systems, because nutrient inputs become dominated by feed rather than fertilizer. Many surface and ground water quality issues have resulted from an increase in AFOs because of the imbalance between system inputs (feed) and outputs of nitrogen and phosphorus, where manure production exceeds the total nutrient need for crop production (Howarth et al., 2002). Given the increase of commercial and manure forms of nutrients, concentration of nutrients near AFOs and the decline in total agricultural acreage, the total nitrogen and phosphorus per planted acre has increased dramatically over time. Del Rossi et al. (2023) estimated that nitrogen and phosphorus fertilizer use per acre increased by 15 times and 3 times respectively from 1950 to 2017.

The intensification of agricultural systems and fertilizer use has been shown to affect water quality (Del Rossi et al., 2023; Howarth et al, 2002; Wither et al., 2014). Del Rossi et al. (2023) evaluated the spatial correlation between nutrient use, cropland and nutrients in surface waters and determined that trends in commercial fertilizer and livestock manure usage in U.S. agriculture has a clear correlation with changes in nutrient concentrations in waterways. Cropland acreage was found to be a key indicator of agricultural intensity and nutrient loading into water bodies. Regions with extensive cropland coverage, including the Pacific Northwest, showed higher nutrient concentrations in surface waters compared to areas with less cropland acreage. Furthermore, areas with intensive agricultural activities, characterized by high cropland acreage and fertilizer usage, tended to exhibit higher nutrient contents in nearby waterways. Trends in commercial fertilizer and livestock manure usage also correlated with changes in nutrient concentrations in waterways over time.

Commercial fertilizer use has increased significantly since the 1950s. During this time, agricultural production systems have also become more specialized and concentrated, including the rapid growth of animal feeding operations (AFOs) in many states which has resulted in a major transfer of nutrients from grain-producing areas to animal-producing areas. These increases in fertilizer use and manure production coupled with the specialization and concentration of agricultural production system have resulted in large increases in the amount of fertilizer applied per acre which have been shown to negatively affect water quality, aquatic ecosystems and contaminate drinking water. Given this evolution, proper nutrient management is critically important and is essential to both protect water resources and preserve healthy aquatic ecosystems and support sustainable agricultural.

There are many conservation-based practices that can be used to limit nutrient losses to the environment and nutrient management is the cornerstone of these practices. The following sections will discuss various aspects of nutrient management and seek to identify approaches that can be used to limit nutrient losses to the environment while supporting productive agriculture lands.

Nutrient Management

Nutrient management is an essential component of production agriculture. It involves budgeting and managing the supply of essential nutrients like nitrogen (N) phosphorus (P), and potassium (K), as well as secondary and micronutrient in a way that promotes healthy crop growth, enhances soil fertility, and reduces nutrient losses to the environment. The goal of nutrient management planning is to optimize the use of fertilizers and organic amendments to enhance crop health, yield, and soil fertility while minimizing negative environmental impacts.

Managing agricultural nutrients to achieve water quality goals involves complexities associated with source control and transport processes. Source control is conducted via management decisions and crop nutrient use efficiency, and transport is largely governed by hydrologic controls and nutrient transformation processes (Sharpley et al., 2019). From a water quality perspective, the goal of nutrient management is to prevent nutrient contributions to surface and groundwater through processes such as runoff, erosion, leaching and air deposition; thus, source and transport processes will be considered in addition to management approaches to maximize nutrient use efficiency and crop production.

Primary Components of Nutrient Management

The Natural Resources Conservation Service (NRCS) describes nutrient management as the management of nutrients and soil amendments to maximize their economic benefit while minimizing their environmental impact and emphasizes identifying the appropriate fertilizer type (source), application rate, method of application, application timing and adaptive management. Each of these elements are important to consider when managing nutrients for crop production as they influence whether the goals of nutrient management are met.

The following is a summary of key factors that should be considered when developing a nutrient management plan (U.S. Department of Agriculture, Natural Resources Conservation Service, n.d.).

Source

The type of fertilizer or soil amendment selected can be a complex decision and vary based on many factors such as crop or crop rotation type, tillage practices used, soil type, soil health goals, climate, price, availability, and potential for losses to the environment. When determining a nutrient source, it’s important to choose a nutrient source that can provide the amount nutrients needed at the time they are needed.

Organic sources like compost, manure, and cover crops can release nutrients, especially nitrogen, slowly over time. When using these sources, it’s important to understand the total nutrient content of these sources and when those nutrients are likely to be plant available so they can be matched with crop need. Organic sources also help increase the organic matter content of the soil which provides food for soil organisms, aids in the formation of soil aggregates, provides additional sites for nutrients to bind, and helps maintain soil fertility.

Rate

Different crops have different nutrient requirements. The amount of applied fertilizer must be based on crop specific nutrient needs, current soil tests and credits for soil organic sources to avoid over- or under-application. Technology such as variable rate applications can be used to further refine application rates within a field based on factors such as yield potential and soil nutrient levels. This involves using technology such as GPS, sensors, and data analytics to apply nutrients at a more precise rate, improving efficiency and reducing losses.

Timing

Proper timing of nutrient application is critical to ensure nutrients are efficiently used and to avoid losses to the environment. Application timing will vary depending on the crop, the crop's growth stage and environmental conditions. The goal is to optimize nutrient uptake so there are limited residual nutrients that can be lost to surface water, groundwater or the atmosphere.

Placement or Method

Choosing the right application method can affect how efficiently crops use nutrients and if plants can use them when most they are needed. For example, placing nutrients too deep or too shallow or a manner that increases losses can result in limited rooting development which can create nutrient deficiencies and negative impacts to the environment. Application methods should also be tailored to the nutrient source to ensure nutrients are placed where needed and to limit losses through leaching, runoff or volatilization.

Adaptive Management

Regular soil testing is essential to understand soil nutrient levels and other conditions that affect soil fertility. Soil tests also provide critical information needed to evaluate the effectiveness of nutrient management planning and to understand if practices and nutrient budget assumptions result in application rates and timing that support crop needs while limiting losses and post-harvest soil nutrient concentrations.

Nutrients Used for Agricultural Production

Nutrients are essential for plant growth and for crops to complete their vegetative and reproductive life cycles. As crops grow and are harvested, nutrients are gradually removed from the soil over time which can inhibit the growth and yield of future crops. As a result, most soils will require supplemental nutrients to maintain crop health and yield.

Plants utilize nutrients in different ways and each crop has its own unique set of requirements including the amount and timing of uptake. When and how much nutrients are supplied will affect plant productivity and overall yield and also determine whether nutrients are lost to the environment. For example, when nutrients are added in excess of a plant's ability to utilize them or at times when crop nutrient use is low, there is an increased risk for those nutrients to enter surface water, groundwater or the atmosphere.

Plant nutrients are divided into four categories based on their importance and quantity of use: structural nutrients, primary nutrients, secondary nutrients and micronutrients with each playing important roles in plant development while having differing levels of requirement. Primary, secondary and micronutrients are typically supplemented via commercial products, organic manures, plant residues, and biological nitrogen fixation.

Structural nutrients include carbon (C), hydrogen (H) and oxygen (O) and are the basis for carbohydrate development such as sugars and starch, which provide the strength of cell walls, stems, and leaves, and are sources of energy for the plant. Structural nutrients are obtained from air and water and are the most abundant elements in plants.

Macronutrients are elements used by plants in large quantities and can be further defined as primary or secondary. Primary nutrients include nitrogen (N), phosphorus (P), and potassium (K). These nutrients control processes such as photosynthesis, plant enzyme and biochemical functions, cell wall structure, protein synthesis, nutrient transport, root development, and contribute to plant nutrient content, hardiness and overall health and vigor. Deficiency of these nutrients contributes to reduced plant above and below ground growth, health, and yield. For agricultural production, nitrogen (N), phosphorous (P), and potassium (K) have traditionally been the focus of nutrient management given they are frequently a limiting factor in overall crop productivity.

Secondary nutrients are needed in medium quantities in comparison to primary nutrients and micronutrients and include calcium (Ca), magnesium (Mg), and sulfur (S). Secondary nutrients play critical roles in plant development. Calcium is important in cell division and provides structural support to cell walls, supports the transport and retention of other nutrients, assists in nutrient absorption by the roots, and is essential for nitrogen fixation in legumes. Sulfur is an essential building block in chlorophyll development and plays an important role in the production of lignin. Sufficient sulfur levels also support nitrogen use efficiency and are critical for nitrogen fixation in legumes. Magnesium is a key component of the chlorophyll molecule in all green plants and is essential for photosynthesis making it essential to plant life. It also helps activate many plant enzymes needed for growth. Deficiencies in secondary nutrients prevent plants from fully utilizing primary nutrients which ultimately stunts growth and limits yield. Secondary nutrient deficiencies can also cause additional problems such as deformed or stunted fruit or tubers, weak stalks and yellow leaves among other things.

Micronutrients are needed in very small quantities but are essential for plant survival. These micronutrients include iron (Fe), boron (B), copper (Cu), chlorine (Cl), Manganese (Mn), molybdenum (Mo), zinc (Zn), cobalt (Co), and nickel (Ni). Micronutrients play important roles in photosynthesis, redox reactions, protein synthesis, nitrogen fixation and are part of the enzyme systems of plants and can have significant effects on plant growth especially when levels are too high or too low.

Of the essential plant nutrients, nitrogen, potassium and phosphorus are used in the greatest volume for agricultural production. Nitrogen and phosphorus also have the greatest potential for negative environmental impacts. Hence, the focus of this evaluation will be on the management of nitrogen and phosphorus. While the focus will be on nitrogen and phosphorus, it's recognized that all primary and secondary nutrients are essential for plant development and contribute to the overall health of crops; and most importantly, contribute to a plant's ability to efficiently use nitrogen and phosphorus and limit the amount that is lost to the environment.

Source reviewed:

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Washington State University. (n.d.). *Micronutrient functions in plants*. Washington State University. https://smallgrains.wsu.edu/soil-and-water-resources/essential-nutrients/micronutrients/micronutrient-functions-in-plants/

Nutrient Transport: Hydrologic Controls

The movement and transport of agricultural nutrients in the environment are significantly influenced by hydrological processes including precipitation, surface runoff, infiltration, percolation, and groundwater flow. These processes determine how nutrients, whether in liquid, gas or solid form, are distributed across agricultural fields, and ultimately, how they may reach surface water or groundwater. The goal of nutrient management is to curtail these transport processes while enhancing crop nutrient uptake so applied and residual soil sources stay within the soil-crop system where they can be used and not loss to the environment (Follet, 2008, Singh et al., 2018).

Agricultural production, in both rainfed and irrigated environments, occurs in an inherently leaky system where excess water exits the system through surface runoff or percolation to groundwater. Nutrient transport is controlled by hydrology, whether in arid, irrigated systems, wet environments, or artificially drained landscapes. In more arid environments, hydrology is controlled by seasonal precipitation and irrigation during dry seasons. In wetter areas, precipitation is the primary mechanism for nutrient transport (Sharpley et al., 2019).

Nutrient transport is often more pronounced in areas where connectivity to water is more prevalent (i.e., artificially drained via tile drainage or artificial ditches). However, adverse environmental impacts related to offsite nutrient transport are also common in irrigated and non-irrigated systems in arid and semiarid climates. Significant losses have been found to have seasonal patterns, which often follow wetter periods or snowmelt or during the irrigation season. Losses can be exacerbated when vegetative cover is limited as well (Sharpley et al., 2019).

Understanding the interaction between hydrological processes and fertilizer transport is crucial for managing nutrient runoff, preventing water pollution, and enhancing nutrient use efficiency in agricultural systems. The following is a summary of hydrological processes that affect nutrient transport from agricultural fields to the surrounding environment.

Precipitation and Fertilizer Application

Precipitation is one of the most direct hydrological factors that influences the transport of nutrients. Rainfall can help incorporate fertilizers into the soil but also lead to their loss through surface runoff, erosion and leaching, and the amount, intensity, and timing of rainfall coupled with factors such as vegetation cover, soil properties, slope and other field conditions are often the determining factors.

The timing of fertilizer application relative to rainfall events is crucial for minimizing nutrient loss. Fertilizers applied shortly before or during a rainstorm are susceptible to transport via field by runoff and leaching. On the other hand, applying fertilizers when the soil is dry, and rain is not expected can increase the potential for ammonia volatilization especially when ammonia- and ammonium-based fertilizers, including manure and urea, are surface applied and not incorporated into the soil.

Surface Runoff and Erosion

Surface runoff occurs when rainfall or irrigation exceeds the soil's ability to absorb water and ground cover is limited. Fertilizers that are not immediately incorporated into the soil can be transported via surface runoff. Runoff and the transport of nutrients is influenced by factors such as topography, slope, soil type, compaction and vegetative cover. Fields with steep slopes and/or soils with low infiltration rates are more prone to surface runoff. Vegetative cover can reduce runoff, slow water flow and improve water infiltration. When crop fields lack plant cover, have limited post-harvest residue or are bare, fertilizers are more susceptible to runoff from irrigation and precipitation.

Infiltration, Percolation & Groundwater

Infiltration is a process by which water enters the soil. Infiltration rate is influenced by factors such as crop type, soil texture, soil organic matter, precipitation patterns, irrigation and land management practices. Once water infiltrates the soil, it moves downward through the soil profile via percolation. As water percolates, it can carry soluble nutrients like nitrogen (in the form of nitrate) and phosphorus deeper into the soil. In soils with high permeability (e.g., sandy soils), nutrients are more susceptible to moving deeper into the soil profile, potentially reaching groundwater. In less permeable soils (e.g., clayey soils), nutrients are less susceptible to leaching and more likely to remain within upper soil layers unless there is sufficient precipitation or irrigation for dissolved nutrients (especially nitrogen) to move downward with percolating water. Compacted soils, often caused by heavy machinery use, also affects percolation by impeding water infiltration, increasing surface runoff and the potential for nutrient loss via runoff and erosion.

Groundwater flow also plays an important role in the movement of nutrients that have been leached from the soil. Once nutrients, particularly nitrate, reach groundwater they are transported both vertically and horizontally via groundwater and can contaminate downgradient wells.

Denitrification

Denitrification is a process where nitrite and/or nitrite are converted to gaseous forms of nitrogen including nitrous oxide (N_2O), nitrogen oxides (NO and NO_x) and dinitrogen gas (N_2) which are ultimately lost to the atmosphere. Denitrification primarily occurs in oxygen-poor, waterlogged and low permeable soils. Precipitation patterns and field attributes such as soil type, slope, drainage, and vegetative cover will affect the potential for denitrification.

Nitrogen

Nitrogen is essential for plant development and maintaining crop production, as it plays a critical role in many physiological processes such as photosynthesis, respiration, and protein synthesis. When nitrogen is deficient, plant growth is restricted, and crop yield and crude protein concentrations are reduced. Excessive nitrogen can delay maturity, cause disproportionate vegetative growth at the expense of yield, and increase the likelihood of losses to the atmosphere and surface and groundwater.

Nitrogen used for agriculture has many forms subject to many different transformations processes and loss pathways which can make it difficult to manage. Plants primarily use inorganic nitrogen in the forms of nitrate (NO_3^-) and ammonium (NH_4^+) which can be supplied by inorganic (synthetic) or organic nitrogen sources. Synthetic fertilizers contain inorganic forms of nitrogen that are readily available for plant uptake, while organic fertilizer sources must be converted to inorganic forms before crops can use them. Regardless of whether it's supplied by organic sources such as manure or synthetic fertilizers, nitrogen is subject to many conversions and can be lost to the environment through various pathways such as runoff, leaching and gaseous emissions.

Given the importance of nitrogen inputs for all crop production and the potential for lost nitrogen to negatively affect air and water quality when lost to the environment, it's important to understand how nitrogen cycle processes affect nitrogen transformations, plant availability, transport and the potential for losses to the environment (Follet and Delgado, 2002).

Nitrogen Cycle: Nitrogen Transformations

The nitrogen cycle is a complex process where nitrogen moves through the atmosphere, soil and living organisms and is converted into many chemical forms of nitrogen. Within this process nitrogen constantly cycles among many different forms with nitrate, dissolved ammonia, ammonia gas, ammonium, and nitrogen gas being the major forms. Of these, nitrate and ammonium are the main forms used by plants.

How nitrogen cycle processes affect applied fertilizer will vary depending on the type of fertilizer used. For example, nitrogen fertilizers from organic material sources such as manure, compost, and cover crops release nitrogen more slowly and that release is primarily based on crop biomass composition, soil properties, soil moisture, and soil microorganism processes. However, synthetic fertilizers bypass many of these processes and provide plants with plant-available nitrogen. Despite these major differences, organic and inorganic nitrogen sources are both subject to many chemical and biological transformations and transport processes that affect nitrogen availability and potential for losses to the environment. Therefore, it's important to understand the general nitrogen cycle so practices can be targeted to reduce the rate and duration of nitrogen losses processes (Follet 2008).

Biological Nitrogen Fixation

Nitrogen gas (N_2) is the most abundant gas in the atmosphere (78%) and critical for life. Despite its prevalence, atmospheric nitrogen is stable and chemically inert and not directly usable by most organisms. Biological nitrogen fixation is a process where atmospheric nitrogen (N_2) is converted to ammonia (NH_3) or ammonium (NH_4^+) via specific types of nitrogen-fixing bacteria or by lightning. Organic nitrogen occurs naturally in the soil as organic matter and is also added to the soil via manure, crop residues and through nonsymbiotic and symbiotic biological nitrogen fixation. Symbiotic fixation occurs when rhizobia bacteria form a mutualistic relationship with the root hairs of leguminous plants such as alfalfa, clovers, peas, lentils and beans and these bacteria convert atmospheric nitrogen into ammonia, which the plants can use for growth (Follet 2002). The symbiotic bacteria-legume relationship is quite specific, and each legume species relies on specific types or groups of nitrogen-fixing bacteria for nitrogen fixation.

For agricultural cropping systems, nitrogen fixation via leguminous plants is the most important type of biological fixation. Crop rotations with legumes help restore soil nitrogen and reduce the need for other sources of nitrogen (Follet 2008). While biological nitrogen fixation, especially symbiotic nitrogen fixation, is important and can affect crop production and nutrient management decisions, the fate and transport of applied nitrogen and fixed nitrogen are primarily controlled by nitrogen cycle processes (Follet 2008).

Mobilization of Soil Nitrogen

Mineralization of Organic Nitrogen

Ammonium (NH_4^+) and nitrate (NO_3^-) are the primary forms of nitrogen used by plants; however, most organic forms of nitrogen such a manure provide limited plant available nitrogen and must be transformed to inorganic forms (ammonium and nitrite) before they can be used by plants. The process of converting organic soil nitrogen (from decomposed plants and applied organic nitrogen fertilizers like manure) is called mineralization (Follett 2008).

Mineralization is a biologically regulated process whereby organic matter is decomposed and converted to inorganic, plant-available nutrients via soil organisms and their activity. This process is an essential part of the nitrogen cycle, contributing to the availability of nitrogen for plant growth (Sullivan et al., 2020).

The primary steps of nitrogen mineralization include decomposition, ammonification and nitrification, and soil microorganisms and their activities play a critical role in these processes. Organic matter such as crop residue and animal manure contains nitrogen and microorganisms such as bacteria and fungi break down this organic matter through decomposition of plant cell walls. As the organic matter decomposes, nitrogen molecules in the form of amino acids and proteins are converted into ammonium (NH_4^+). This step is known as ammonification. Ammonium can be used by crops, but when oxygen is present, it is readily transformed to nitrate through a two-step, bacterial-controlled oxidation process with nitrite as an intermediate form. Nitrite doesn't typically accrue in the soil because it is rapidly converted to nitrate (Follett, 2008). The process of converting ammonium to nitrate is called nitrification and can be completed within a few days under aerobic conditions. Consequently, nitrate is the most common form of nitrogen available for plant uptake.

Synthetic Fertilizers

Synthetic fertilizers typically provide nitrogen in forms that plants can ready use or are quickly converted to plant available forms. The most common forms of nitrogen found in synthetic fertilizers are nitrate, ammonium and urea. Nitrate is readily available for plant uptake and ammonium is absorbed by plants or quickly converted to nitrate. Urea is not immediately available to plants and is first converted into ammonium (NH_4^+) in the soil by the enzyme urease. This process happens relatively quickly, and the resulting ammonium can be taken up by plants or undergo nitrification to form nitrate. Given the forms of nitrogen in synthetic fertilizers, they generally do not rely on soil microorganism process to become plant available, and when they do, those processes are fairly rapid.

Nitrate (a negatively charged ion) is highly soluble and prone to leaching because it is not easily held by soil particles which are generally negatively charged. Ammonium is also very soluble, but given it positive charge, it can be retained in the soil especially in clayey or organic-rich soils with high cation exchange capacity. However, ammonium can be quickly converted to nitrate. Ammonium is also susceptible to leaching, especially in sandy, low-organic matter soils with limited cation exchange capacity.

Soil Nitrogen Immobilization

Immobilization is a process where soil microorganisms temporarily convert plant available, inorganic nitrogen into organic forms making them unavailable for plant use. When microorganisms such as bacteria and fungi decompose organic matter (e.g., crop residues or manure), nitrogen is used in the process. Immobilization of nitrite and nitrate can also occur through enzymatic activities associated with plant nitrogen utilization processes (Singh et al., 2018).

Nitrogen immobilization is temporary and once microorganisms die the organic nitrogen contained in their cells is converted back to inorganic forms via the mineralization process. Immobilization and subsequent mineralization occur throughout a growing season and the addition of organic sources of nitrogen typically results in the net gain of plant available nitrogen during the growing season (Follet 2008, Singh et al., 2018).

The ration of carbon to nitrogen (C/N ratio) is a critical factor in determining whether nitrogen will be mineralized or immobilized. Materials with more carbon and less nitrogen such as straw and sawdust lead to immobilization because microorganisms require more nitrogen for decomposition than provided by the material itself. Materials like manure or green, leafy material with more balanced carbon-to-nitrogen rations typically lead to nitrogen mineralization.

Like mineralization, immobilization is a biologically regulated process. Factors that influence the process include soil organic matter, pH, type of organic matter added, temperature, moisture and oxygen supply.

Immobilization changes the availability of nitrogen and can lead to nitrogen deficiency in plants if the soil's nitrogen reserves are already low or if immobilization is significant. Also, if immobilization shifts nitrogen availability away from times when most needed by a crop, it can decrease nutrient use efficiency and increase the potential for nitrogen losses to the environment. Therefore, it’s important to understand how soil amendments are likely to influence carbon-to-nitrogen ratios in the soil and use that information to manage nitrogen availability to optimize crop growth and prevent unwanted nutrient losses.

Management Considerations

- The type of organic matter added to the soil and its carbon-to-nitrogen ratios significantly influences the potential for immobilization.
    - Immobilization can occur after the application of organic amendments such as manure, compost, or cover crops if the organic material has a high C/N ratio. As a result, nitrogen may not be immediately accessible to plants which can result in short-term nitrogen deficiency, especially if immobilization occurs when plant need is high.
    - Balancing C/N ratios can help limit excessive nitrogen immobilization. Mixing materials with high carbon-to-nitrogen ratios with material with low carbon-to-nitrogen ratios can help reduce immobilization and promote better nitrogen availability to plants.
- High organic matter soils support organic material decomposition by microorganisms which can increase the potential for immobilization, especially for materials with a high carbon-to-nitrogen ratios.
- Water soil temperature and moisture increase microbial activities which may temporarily immobilize nitrogen.

- Nitrogen immobilization is temporary, and nitrogen will slowly be released back to the soil in plant available form over time. This can effectively work as a slow-release fertilizer; however, availability is not easily predicted.

Ammonia Volatilization

When animal manure and ammonia- and ammonium-based synthetical fertilizers like urea, ammonium nitrate, and ammonium sulfate are applied to the soil, a portion of that nitrogen can be lost to the air as ammonia gas through a process of ammonia volatilization. Ammonia volatilization can lead to inefficiencies in nutrient use, water and air pollution, and reduced crop yields.

Ammonia volatilization is a process where ammonium (NH_4^+) is chemically reduced and converted to ammonia gas (NH_3) which is released to the atmosphere. Nitrogen loss via volatilization reduces the amount of nitrogen available for plants and can also negatively affect water quality as most of the nitrogen volatilized is typically redeposited near its source (Howarth et al., 2002). Deposited nitrogen affects ecosystems by increasing available nitrogen which can lead to nutrient imbalances harming aquatic ecosystems (Withers et al., 2014). Gaseous ammonia also reacts with other atmospheric gases and particles to form solid ammoniated particles, such as ammonium nitrate and ammonium sulfate, that contribute to fine particulate matter pollution which can travel much further than ammonia before settling out of the air (Howarth et al., 2002).

A variety of factors affect ammonia volatilization such as soil type, soil pH, climate, farming practices, and type of fertilizer applied (Howarth et al., 2002). Ammonia volatilization is also more likely when soils are moist, warm, on alkaline soils, and when conditions favor evaporation such as warm weather and windy conditions. (Singh et al., 2018, Sidgel et al., 2024)

Ammonia- and ammonium-based fertilizers, including manure and urea, are easily lost to the atmosphere via ammonia volatilization, and volatilization losses are much higher when fertilizers are surface applied and not incorporated into the soil. Practices or conditions that limit the exposure applied ammonia- and urea-based fertilizers to the atmosphere and facilitate contact with the soil and soil moisture such as incorporation via tillage, irrigation and precipitation reduce volatilization potential. Research suggests surface soil moisture at time of application, irrigation, rainfall and weather conditions significantly affect the volatilization of urea-based synthetic fertilizer and manure (Sidgel et al., 2024).

Soil pH and soil type also affect the potential for ammonia volatilization. Ammonia and ammonium reach an equilibrium in soil solution, and soil-solution ammonia is subject to gaseous losses via volatilization. As soil pH increases above 6.0, ammonia increases thus increasing the potential for loss to the atmosphere. This is especially important on calcareous soils as the pH exceeds 7.0 (Follet 2008). Soil cation exchange capacity also affects ammonia volatilization. Organic-rich, clayey soils with high cation exchange cation capacity have a greater ability to retain ammonium than sandy, low-organic soils with limited cation exchange capacity.

Manure, urea and other ammonium forming fertilizers are commonly used for crop production but are highly susceptible to ammonia volatilization especially when surface applied. Understanding factors and mechanisms that influence volatilization can help agricultural producers manage soil conditions and select application approaches to limit ammonia volatilization thus allowing nutrients to be used for crop production and reducing impacts to the air and water quality.

Factors That Affect Ammonia Volatilization

The following are some common factors that affect ammonia volatilization.

Soil Condition That Affect Ammonia Volatilization

- Soil pH: as pH increases, the potential for ammonia volatilization increases. Alkaline soils (pH>7.0) are generally more prone to volatilization.
- Soil properties: volatilization depends largely on cation exchange capacity and buffer capacity. Soils with high cation exchange capacity and high buffer capacity (high clay, high soil organic matter) have reduced potential for ammonia volatilization.
- Soil temperature: the risk of volatilization increases with soil temperature especially when about 70 degrees Fahrenheit.
- Soil moisture: volatilization will vary depending on the fertilizer type and method. For example, urea is more susceptible to volatilization when surface applied to moisture or wet soils but may benefit from irrigation or precipitation to facilitate incorporation into the soil. Organic sources such as manure slurry may benefit from moist conditions and irrigation or rain to facilitate incorporation in the soil.

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Environmental and Management Factors Affecting Ammonia Volatilization

- Application method: surface applied manure and ammonia- and ammonium-forming fertilizers are more prone to volatilization than when incorporated.
- Environmental conditions: warmer and windy conditions generally increase volatilization. Cool environmental conditions during fertilizer application can reduce the potential for ammonia volatilization. For urea fertilizers that need water for hydrolysis, humidity and weather conditions such as rain will directly affect the potential for volatilization. Surface applied urea is prone to volatilization for these reasons.
- Soil incorporation via irrigation, rainfall or tillage after application decreases volatilization potential.

Source Reviewed:

Dari, B., Rogers, C. W., & Walsh, O. S. (2020). *Understanding factors controlling ammonia volatilization from fertilizer nitrogen applications* (BUL 926). University of Idaho Extension. https://www.uidaho.edu/-/media/UIdaho-Responsive/Files/Extension/publications/bul/bul926.pdf?la=en

Ammonia Volatilization from Manure & Management Strategies

When livestock manure is applied to the soil surface, a significant proportion of the ammonium ($NH4^+$) present in the manure can be volatilized into the atmosphere which reduces the nutrient value of manure, making it less effective as a fertilizer (McGinn and Janzen, 1998). Ammonia volatilization also contributes to air pollution and water pollution. Therefore, it is critical to implement strategies that minimize nitrogen volatilization during manure application.

The amount of ammonia lost through volatilization varies depending on the type of material applied and the management practices. Ammonia volatilization rates following land application of manure are influenced by a variety of factors such as method of application, weather (solar radiation, air temperature, humidity, wind), manure composition and time of day (Gordon et al., 2001, McGinn and Janzen, 1997). The following are strategies that can be used to limit ammonia volatilization.

Incorporation

- Incorporation has been shown to significantly reduce ammonia volatilization. Placing nitrogen sources below the surface using methods like banding, aerators or injection (shallow or deep) minimizes volatilization.
- Incorporation reduces volatilization leading to increased soil nitrate (Bierer et al., 2020, Sigdel et al., 2024).
    - Greater retention may require adjusting nitrogen fertilizer applications to avoid overapplication.
    - It's essential for producers to monitor soil nitrate nitrogen levels consistently to make informed nutrient management decisions (Bierer et al., 2020).

- Incorporation reduces ammonia emissions which may result in greater nitrous oxide emission if unused by crops (Bierer et al., 2020, McGinn and Janzen, 1997, Sigdel et al., 2024).

Broadcast Application

- Broadcast application techniques of manure (liquid, solid and slurry) have the highest rates volatilization because of greater exposure to the atmosphere, solar radiation and less contact with the soil (Bierer et al., 2020, Sigdel et al., 2024).
- For situations when incorporation isn't feasible, broadcast manure at times and during conditions when volatilization potential is lower (see timing).

Timing

- Significant ammonia volatilization from manure spreading can occur within the first 10 hours after application if conducive atmospheric conditions exist. (Gordon et al., 2001)
- Greater rates of ammonia volatilization were positively correlated with solar radiation, wind speed, air temperature and vapor pressure deficit (VPS) (Gordon et al., 2001).
    - VPD is the difference between the amount of moisture in the air and how much moisture the air could potentially hold when it's saturated.
    - A high VPD means that the air can still hold a large amount of water (Gordon et al., 2001).
- Cooler temperatures during the spring are less conducive to volatilization than warmer temperatures in late-spring and summer (Sidgel et al., 2024).
- Volatilization can be substantially reduced by choosing the appropriate timing of manure application (Bierer et al., 2020, Sigdel et al., 2024)
- Nitrogen loss can be minimized by avoiding application on warm, windy days or when weather conditions are forecast to be sunny and dry. (Gordon et al., 2001, Sidgel et al., 2024).
- Scheduling applications on days with low solar radiation and high humidity reduces volatilization (Gordon et al., 2001).
- Performing manure spreading operations later in the day can help minimize ammonia volatilization. However, late-day spreading may increase odor persistence due to lower atmospheric dispersion (Gordon et al., 2001).
- While it's not always feasible to wait for ideal environmental conditions, applying before a light rain, on a cool, cloudy day, or in the evening can help minimize ammonia volatilization.

Apply Manure at Agronomic Rates

- Applying manure at agronomic rates. Higher application rates generally result in greater ammonia emissions.

Limiting Volatilization of Ammonium Forming Fertilizers

Limiting volatilization from ammonia- and ammonium- forming fertilizers is critical to prevent negative impacts to air and water quality and maintain soil fertility and crop production. Implementing effective best management practices (BMPs) can help minimize ammonia volatilization, improve fertilizer efficiency, and protect air and water quality, and methods used will vary depending on the type of fertilizer.

Below is a list of commonly used ammonia- and ammonium-forming inorganic fertilizers and their relative risk for volatilization.

Table 3: List of commonly used ammonia- and ammonium-based inorganic fertilizers and their relative risk of volatilization.

Source	Formula	Nitrogen Content (%)	Form	Volatilization Risk
Urea	$CO(NH_2)_2$	46	Dry Granular	High
Anhydrous ammonia	NH_3	82	Compressed Gas	High
Ammonium nitrate	NH_4NO_3	28	Dry Granular	Low
Ammonium sulfate	$(NH_4)_2SO_4$	21	Dry Granular	Intermediate
Urea ammonium nitrate (UAN)	$CO(NH_2)_2$ + NH_4NO_3	32	Liquid	Intermediate

Practices used to limit volatilization generally apply to all types of ammonia – and ammonium-based fertilizers including manure; however, additional considerations are need when applying anhydrous ammonia and urea they have a high potential for ammonia losses.

The following is a list of strategies that can be used to reduce ammonia volatilization from ammonia- and ammonium-forming fertilizers. The primary management goal of these strategies is to facilitate the movement of nitrogen in the soil profile and avoid conditions that increase ammonia volatilization.

Anhydrous ammonia

- Place anhydrous ammonia shank application equipment 4-8” below the surface to prevent loss.

Urea

- Whenever possible, incorporate soon after it is surface applied using mechanical methods such as surface banding, injection or other tillage and/or irrigation or rainfall. Incorporation minimizes ammonia's contact with the air and increases contact with the soil.
- Use ammonia urease inhibitors (especially to crops where incorporation may not be possible such as perennials, pastures and hayland), to slow down the conversion of urea to ammonia.

- Consider an alternative nitrogen source to urea when conditions are sub-optimal and are difficult to manage.
- Apply when soil and air temperatures are cool or when there is adequate moisture to facilitate incorporation into the soil but not cause runoff.
- Avoid surface broadcasting to moist soil.
- Avoid applying on humid or windy days.

All ammonia- and ammonium-forming nitrogen sources

- Incorporate nitrogen fertilizers whenever possible. Incorporating nitrogen into the soil can significantly reduce or prevent ammonia volatilization.
    - Place nitrogen sources below the surface using methods such as banding, aerators or injection (shallow or deep).
- Delay application under high-risk conditions, including moist soils (urea), high-soil temperature, or when the soil surface is frozen soil.
- Apply when soil and air temperatures are cool or when there is adequate moisture to facilitate incorporation into the soil but not cause runoff.
- Manage soil pH. The potential for ammonia volatilization increases as soil pH increases. Avoid applying urea and liming agents at the same time.
- Avoiding windy conditions.
- Use practices that increase soil organic matter to increase cation exchange capacity.

By combining these strategies, producers can reduce ammonia volatilization and environmental pollution while improving nitrogen use efficiency.

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Rogers, C. W., Dari, B., & Walsh, O. S. (2019). *Best management practices for minimizing ammonia volatilization from fertilizer nitrogen applications in Idaho crops* (BUL 927). University of Idaho Extension. https://www.uidaho.edu/-/media/UIdaho-Responsive/Files/Extension/publications/bul/bul927.pdf?la=enMethods used to limit volatilization will vary depending on the type of fertilizer. Below is a list of commonly used ammonia-, ammonium-forming fertilizers and their relative risk for volatilization.

Denitrification

When mineralization occurs, organic matter is converted to ammonium, then nitrite and finally nitrate through the process of nitrification (Follett 2008). Denitrification is a bacterial process where nitrite and/or nitrate are transformed into gaseous forms of nitrogen including nitrous oxide (N_2O), nitrogen oxides (NO and NO_x) and dinitrogen gas (N_2) which are ultimately lost to the atmosphere (Follett and Delgado, 2002).

Denitrification occurs when the soil is saturated and bacteria use nitrogen as an oxygen source, and therefore, it primarily occurs in oxygen-poor, waterlogged soils where lower oxygen levels lead to increases in microorganisms able to convert nitrate and nitrite. The general conditions for denitrification include: 1) presence of bacteria with metabolic capacity; (2) availability of suitable reductants such as organic carbon; (3) the limited oxygen availability (Follett and Delgado, 2002). In general, heavy texture soils with poor natural drainage are most susceptible to denitrification (Singh et al., 2018).

Denitrification is a natural part of the nitrogen cycle and can reduce the amount of nitrogen available to be lost to the environment through leaching and runoff. Denitrification also decreases the amount of nitrogen available in the soil for crops, and most importantly, is a major source of nitrous oxide emissions. Nitrous oxide is a potent, long-lived greenhouse gas that results from incomplete denitrification to nitrogen gas (N_2) and has 300 times more global warming implications than carbon dioxide. Nitrogen fertilizer application contributes the majority of N_2O emissions in the United States accounting for approximately 68% to 75%. Crop production and fertilization can also negatively impact air quality and the atmosphere via several other air pollutants such as ammonia and nitrogen oxides (Follett and Delgado, 2002, Singh et al., 2018, U.S. Environmental Protection Agency, n.d.)

Nitrogen Loss & Transport Mechanisms

The primary loss pathways of nitrogen in agricultural systems are nitrate (NO_3^-) leaching, surface runoff and erosion of particulate and dissolved nitrogen forms, ammonia (NH_3) volatilization and emissions of nitrous oxide (N_2O), nitrogen oxides (NO and NO_x) and dinitrogen gases (N_2) via denitrification. Nitrogen loss to the environment can lead to many negative impacts to groundwater, surface waters and aquatic ecosystems, and the atmosphere (Singh et al., 2018). These pathways are influenced by nitrogen cycle processes, hydrologic controls, weather and landscape features such as slope, topography, soil type and vegetative cover.

The fate of nitrogen applied as fertilizer to agricultural lands has received extensive study. For the Unites States, it's estimated that 45% to 75% of applied nitrogen is removed in crop harvest. The remainder is stored as organic nitrogen in the soil, volatilized to the atmosphere, leaches to ground and/or runs off to surface waters (Howarth et al., 2002). In North America it is estimated that 20% of the fertilizer nitrogen applied to agricultural fields leaches into ground or runs off to surface waters (Howarth et al. 1996).

Nitrogen losses through mechanisms like leaching, denitrification, ammonia volatilization, and soil erosion have significant implications on both crop production and environmental quality. Leaching leads to nutrient depletion in the root zone, affecting plant health and reducing crop yield. Denitrification results in the loss of nitrogen to the atmosphere, impacting soil fertility and greenhouse gas emissions. Ammonia volatilization leads to inefficient fertilizer use and contributes to air pollution. Soil erosion causes loss of topsoil and essential nutrients, reducing soil quality and productivity. Overall, these nitrogen losses can hinder crop output, increase production costs, degrade soil health, and contribute to environmental pollution and ecosystem disruption. The following is a description of nitrogen loss pathways and strategies that can be used to limit them.

Leaching: Nitrate & Ammonium

Nitrate(NO_3^-) and ammonium (NH_4^+) are both highly soluble in water; however, each has different leaching potential. Ammonium is positively charged and largely retained by soil which has a net negative charge. This is especially true for on organic-rich, clayey soils with high cation exchange cation capacity. However, in the presence of high rainfall or low cation exchange soils, it can still leach or be carried via runoff. Lastly, ammonium is converted to nitrate in the soil relatively quickly under aerobic conditions.

Conversely, soil particles do not retain nitrate well because both are negatively charged. Therefore, nitrate moves easily with water through the soil. Leaching rate varies depending on a variety of factors including rainfall, irrigation, nitrate present and crop uptake. Well-drained soils, high nitrogen inputs, low crop yield, over-irrigation and high rainfall during or after the growing season increase the potential for nitrate leaching (Singh et al., 2018).

Tile Drainage

Subsurface (tile) drainage is an artificial drainage system used on some agricultural lands where perforated drain tubes are placed below the soil surface to drain fields or wet areas within fields to manage excess water in the soil. Tile drainage can serve as a direct conduit for transporting nutrients nitrogen and phosphorus from crop fields to surface waters as most tile drainage outlets directly to streams or artificial waterways such as agricultural ditches or irrigation canals which often outlet to surface waters. Tile discharge is controlled by several site-specific factors including, soil hydraulic conductivity, tile system design (i.e., depth and spacing), precipitation characteristics (e.g., volume, duration, and intensity), antecedent soil moisture and field management (Sharpley et al., 2019).

Tile systems drain soil water which generally increases the water holding capacity of soil between precipitation events, thus decreasing the potential for surface runoff. However, tile drainage serves as a direct conduit for moving nutrient from agricultural field to surface waters especially dissolved nutrients and nutrients adsorbed to fine sediment. Tile drainage has been identified as a significant pathway for both nitrogen and phosphorus transport. Nitrogen losses tend to be in the form of nitrate (NO_3^-) and phosphorus losses are both dissolved, and sediment bound. Because excess soil water is transported through a network of drainage pipes rather than naturally through the soil or conversation practice such as filter strips and riparian buffers, there are limited opportunities for nitrogen denitrification or phosphorus adsorption (Sharpley et al., 2019).

Surface Runoff and Erosion

The transport of dissolved nitrogen (i.e., nitrite, nitrate & ammonium) is largely governed by factors that control runoff including hydrology (time and intensity of rainfall) and soil characteristics. Soils with low runoff potential have high infiltration rates and commonly consist of deep, well drained sands or gravels. Soils with low infiltration rates when wet, high clay content, high water table and shallow clay layer, and shallow soil over a low permeability subsurface layer have high runoff potential. High precipitation events coupled with high runoff conditions are conducive to surface runoff especially on steeper, uninterrupted slopes (Follett and Delgado, 2002).

Nitrogen adsorbed to soil particles can be lost through wind and water induced soil erosion and water erosion (Singh et al., 2018). Nitrogen losses of sediment adsorbed nitrogen are controlled by factors that influence erosion such as rainfall intensity and duration, soil type, topography, slope, vegetative cover, tillage practices, and conservation practices used to mitigate erosion potential. Detachment of sediment and nutrients from the soil is selective for nitrate and fine soil fractions with which nutrients such as ammonium and soil organic nitrogen are associated. As a result, nitrogen contained in runoff and sediment erosion often has higher concentrations than the parent soil (Follett and Delgado, 2002).

Factors That Affect Runoff & Erosion

The volume and rate of runoff is governed by the soil's ability to absorb and retain water which is largely controlled by soil conditions, topography, vegetative cover and precipitation. Soil characteristics and conditions such as compaction, saturation, high clay content, shallow, perched ground, and low organic matter increase the potential for runoff. These soil conditions coupled with steep slopes, lack of vegetation or crop residue, and rainfall intensity and duration all contribute to increased runoff.

Several factors influence erosion including slope, slope length, rainfall intensity, vegetative cover, precipitation and soil texture. Soil texture is determined by the percentage of sand, silt and clay and is an important property contributing to a soil's erodibility. In general, soils with high infiltration rates, high soil organic matter and good soil structure (aggregation) have a greater resistance to erosion. Soils with high silt and fine sand content, low organic matter and disaggregation tend to be most erodible.

Many of the factors that influence the potential for runoff also affect erosion; although, they are not the same. Therefore, when planning the timing of nutrient applications, it's crucial to evaluate the potential for runoff off and erosion independently.

Given that agricultural systems are inherently leaky, and runoff and erosion are affected by other management decisions, it is critical for good nutrient application practices to be coupled with practice that will reduce and/or treat runoff and erosion such as cover crops and edge of field practices such as filter strips and riparian buffers can be used to reduce particulate and dissolved nitrogen.

Factors That Increase the Potential Runoff

- Compacted Soils
- Saturated Soils
- Poor soil drainage & water holding capacity (e.g. low organic matter, high clay content)
- Bare soil or low/sparse vegetative cover
- Steep slopes
- Frequent rain during the wet season
- Intense precipitation and/or extended precipitation
- Rain on snow or rain on frozen soil

Factors That Increase the Potential for Soil Erosion

- Steep, long slopes
- Frequent rain during the wet season
- Intense precipitation and/or extended precipitation
- Water runoff
- Soil texture - soils with high silt and fine sand content, low organic matter and disaggregation are more erodible.
- Poor soil drainage & water holding capacity (e.g. low organic matter, high clay content)
- Bare soil or low/sparse vegetative cover – often more prone on annual cropping soils than biennial or perennial cropping fields.
- Frequent rain during the wet season
- Intense precipitation and/or extended precipitation
- Rain on snow or rain on frozen soil

Gaseous Emissions

Volatilization

Ammonia volatilization is a process where ammonium (NH_4^+) is chemically reduced and converted to ammonia gas (NH_3) which is released to the atmosphere. Nitrogen loss via volatilization reduces the amount of nitrogen available for plants and can also negatively affect water quality as most of the nitrogen volatilized is typically redeposited near its source (Howarth et al., 2002). A variety of factors affect ammonia volatilization such as soil type, soil pH, climate, farming practices, and type of fertilizer applied (Howarth et al., 2002). Ammonia volatilization is also more likely when soils are moist and warm, on alkaline soils, and when conditions favor evaporation such as warm weather and windy conditions. (Singh et al., 2018).

Denitrification

When mineralization occurs, organic matter is converted to ammonium, then nitrite and finally nitrate through the process of nitrification (Follett 2008). Denitrification is a bacterial process where nitrite and/or nitrate are transformed into gaseous forms of nitrogen including nitrous oxide (N_2O), nitrogen oxides (NO and NO_x) and dinitrogen gas (N_2) which are ultimately lost to the atmosphere (Follett and Delgado, 2002). Denitrification occurs when the soil is saturated and bacteria use nitrogen as an oxygen source, and therefore, it primarily occurs in oxygen-poor, waterlogged soils where lower oxygen levels lead to increases in microorganisms able to convert nitrate and nitrite.

Residual Nitrate in the Root Zone

Nitrate is highly mobile and is easily transported to groundwater via percolating water or lost to surface water through runoff or tile drainage. Unless conditions are suitable for denitrification, nitrate transported below a planned crop root zone will be lost to shallow groundwater or be intercepted by tile drainage and transported to surface waters.

Efficient use of nitrogen during the growing season is a critical component of limiting nutrient losses (e.g., nitrogen and phosphorus) to the environment and reduces production costs. Once crops have been terminated or nutrient uptake has ceased or significantly diminished, all nutrients including nitrogen are more susceptible to loss. Further, hydrologic and transport factors that increase the potential for loss such as runoff, erosion, and groundwater recharge are much more prevalent after a typical growing season.

Efficient use of nitrogen during the growing season is the most effective method to reduce the potential for nitrate leaching and losses through other pathways including runoff, erosion, and tile drainage. Many factors affect nutrient use efficiency and approaches to increase that efficiency which will be discussed later, but ultimately, the goal is to apply nutrients at the time, rate and under conditions that optimize plant uptake and limit loss. While limiting residual nutrients is the goal of nutrient management, it should be noted that additional conservation practices can and should be used to help limit the effects of residual nitrogen whenever possible. Many of these practices are outlined in additional chapters of the Clean Water Guidance for Agricultural

Nitrogen Fertilizer Types

There are several forms of nitrogen fertilizers, and each has its unique characteristics, applications, and benefits. The type of nitrogen fertilizer used for a given crop or crop system will vary depending on factors such as fertilizer composition, crop type, tillage and application methods, soil conditions, climate, and economic and environmental considerations. It’s important to note that different types (organic and inorganic) and forms of fertilizers can be used together in complementary ways depending on crop needs and soil health goals.

Therefore, it's useful for agricultural producers to assess their needs and use fertilizers that best suit their operation.

Certain crops may be better suited for nitrate- or ammonium-based fertilizers. Consult Land Grant University extension guides for crop-specific recommendations.

Inorganic Nitrogen Fertilizers

Below is a list of commonly used inorganic nitrogen sources and attributes of each.

Anhydrous Ammonia (NH_3)

Form: A colorless, odorless gas.

Application method: Injected directly into the soil using specialized equipment.

Considerations:

- Highly concentrated, containing 82% nitrogen.
- Readily available to plants - ammonia reacts with soil moisture to form ammonium ions (NH_4+) which is quickly mineralized to nitrite and then nitrate.
- Anhydrous ammonia is easily lost to the atmosphere if not applied properly, especially in warm, dry conditions. This reduces nitrogen availability to crops.
- Special equipment is needed for injection into the soil which can be expensive and complex to operate.
- Anhydrous ammonia is caustic, highly corrosive and requires careful handling and storage.

Ammonium Nitrate (NH_4NO_3)

Form: A white crystalline solid.

Application: Broadcast, injected, or incorporated into the soil.

Considerations:

- Provides both ammonium (NH_4+) and nitrate (NO_3-) forms of nitrogen. This dual form provides both immediate and slow-release nitrogen.
- It is highly soluble in water making is suitable for fertigation applications.
- Ideal for crops that benefit from immediate nitrogen availability.
- Less prone to volatilization.
- It can be broadcast, injected, or incorporated into the soil through various methods.
- Nitrate is soluble in water and prone to leaching, especially under heavy rainfall or irrigation. Careful timing is needed to prevent leaching.

Urea ($CO(NH_2)_2$)

Form: A solid, colorless compound, usually applied as prills or pellets.

Application: Broadcast, injected, dissolved and sprayed, or incorporated into the soil or through fertigation systems.

Considerations:

- Soluble and can be absorbed by plants quickly.
- Urea must be converted into ammonium by soil bacteria, then nitrate, which requires adequate moisture.
- Urea is highly susceptible to ammonia volatilization when applied to the soil surface, particularly under high temperatures, windy conditions and low humidity.
- Incorporation or irrigation is needed to limit volatilization.

Ammonium Sulfate ($(NH_4)_2SO_4$)

Form: Crystalline solid.

Application: Often applied as a granule or in liquid form through fertigation. Other methods including broadcast (with or without incorporation), injection, or dissolved and sprayed, or are also commonly used.

Considerations:

- Contains both nitrogen (21%) and sulfur (24%), which can be beneficial for crops needing sulfur.
- Less concentrated that other nitrogen fertilizers, so larger quantities may be needed.
- Provides a slower-release form of nitrogen, reducing the risk of leaching.
- Less prone to volatilization compared to other fertilizers such urea and ammonium nitrate.
- High levels of ammonium sulfate can increase soil salinity which can be detrimental to crops in certain soil types or climates.
- Known to acidify soils.

Calcium Nitrate ($Ca(NO_3)_2$)

Form: Crystalline solid.

Application: Often used in fertigation or hydroponic systems. Methods such as broadcast, fertigation, dissolved and sprayed, or incorporated into the soil are commonly used.

Considerations:

- Approximately 15.5 to 16% nitrogen.
- Provides readily available nitrogen and calcium important for plant cell structure and overall growth.
- Often used where additional calcium is needed such as with certain fruits and vegetables.

- Easily dissolves in water, making it suitable for fertigation and hydroponic systems.
- Low nitrogen content compared to other forms such as urea or ammonium nitrate.

Urea Ammonium Nitrate (UAN) Solution ($CO(NH_2)_2 + NH_4NO_3$)

Form: A liquid solution containing a mix of urea, ammonium nitrate, and water.

Application: Can be applied through fertigation and spraying via aerial or ground applications.

Considerations:

- Ranges from 28-32% nitrogen.
- Provides both quick-release and slow-release form of nitrogen via nitrate and urea with urea requiring microbial activity in the soil to convert it into nitrate.
- Care must be taken to avoid nitrogen leaching and runoff, particularly in areas with heavy rainfall or irrigation systems.
- UAN contains both nitrate and ammonium forms of nitrogen and can be prone to leaching and runoff if applied in excessive amounts or under improper conditions.
- There is a potential for ammonia volatilization, especially from the urea component, when applied on warm, dry soils.
- UAN is corrosive to metal surfaces and equipment and requires special handling and appropriate storage.
- UAN solutions can be mixed with other fertilizers or pesticides for simultaneous application, making it a convenient option for farmers.

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Organic Nitrogen Fertilizers

Organic forms of nitrogen fertilizers are derived from natural sources such as manure, compost, and cover crops and are beneficial not only for providing essential nutrients but also for improving overall soil quality. Additional soil health benefits provided by organic sources of nitrogen include increased organic matter and microbial activity, better water retention and improved soil structure, all of which improves soil health and its long-term fertility. Organic sources often provide additional other important macro- and micro-nutrients which are released gradually and slower than synthetic fertilizers providing a steadier supply of nutrients. The release rate of nitrogen from organic sources is often influenced by factors such as temperature, moisture, and microbial activity in the soil which can make it difficult to predict.

While organic sources of nitrogen support many positive soil health outcomes, their relatively low nutrient concentrations and slower release rates may not be ideal for all situations and scales. Organic sources of nitrogen are often used where those sources are available, affordable, and where the ancillary benefits of the organic material are valued. Livestock operations of all sizes generate organic nitrogen sources which require careful management.

Organic sources of nitrogen have some disadvantages that affect when and how they are used. The slow-release nature of organic fertilizers can be a disadvantage in situations where crops need more immediately available nutrients but also represent a longer release rate that is valuable in many annual cropping rotations or perennial crops. The nutrient content and nutrient availability of organic sources can also be variable depending on the source which makes it difficult to precisely control nutrient levels, unlike synthetic fertilizers that are formulated for specific nutrient needs. Because organic fertilizers tend to have lower nitrogen concentrations compared to synthetic fertilizers, larger quantities of organic fertilizers may be needed and can be bulky and difficult to handle and apply compared to the more concentrated forms of synthetic fertilizers. The bulkiness or form of organic fertilizer also can make it difficult to apply nutrients evenly or with equipment designed to apply nutrients at planting, especially in large-scale operations. Although organic fertilizers can be cost-effective when locally available, they can be more difficult to transport and more difficult to source than synthetic fertilizers. Despite the many advantages of organic sources of nitrogen, organic fertilizer has limitations which can affect their use especially for large-scale farming.

Incorporating organic nitrogen sources into soil and crop management practices can significantly improve soil health, increase plant growth, and contribute to more sustainable agricultural practices. There are many sources of organic fertilizer, and each has its own unique attributes that must be considered to ensure crop nutrient needs and soil health benefits are met. The following is a list of common types of organic nitrogen fertilizers along with their source, nitrogen content, nitrogen release rate and soil health benefits.

Nutrient Content & Soil Health Benefits

Table 4: Summary of organic sources of nitrogen, nitrogen content of each source, release patterns and benefits.

Type	Source	Nitrogen Content	Release Patterns
Compost	Decomposed plant & animal matter	Low	Slow and gradual as microorganisms break down the organic material.
Animal Manure	Animal waste e.g., cows, horses, chickens, sheep, and other livestock.	Varies	Slow (depends on composting)
Blood Meal	Dried and powdered blood from slaughtered animals (usually cattle or pigs).	High	Quick to medium release, depending on soil conditions.
Fish Meal	Ground fish (byproducts from fish processing)	Moderate	Slow release, but with a high nutrient density.
Fish Emulsion	Emulsified fish remains (byproducts from fish processing)	Moderate	Quick to medium release.
Alfalfa Meal	Ground alfalfa (legume plant)	Moderate	Slow release
Feather Meal	Ground feathers (typically poultry)	High	Quick to medium
Soybean Meal	Ground soybeans (byproduct of oil extraction)	Moderate	Slow release
Worm Castings	Earthworm excrement	Low to moderate	Slow and gradual
Cottonseed Meal	Ground cottonseed (byproduct of cotton oil production)	Moderate	Slow
Seaweed Meal	Processed seaweed	Low to moderate	Slow
Green Manure / Cover Crops	Leguminous plants (e.g., clover, vetch)	Variable	Slow (after incorporation)

Benefits of Organic Sources of Nitrogen

- Slow Release - many organic nitrogen sources release nutrients slowly, providing a steady supply of nitrogen to plants.
  - Reduced application frequency - since nutrients are available over a longer time frame, nutrients can be applied less frequently. This will vary depending on the source of nitrogen and conditions such as temperature, moisture, and microbial activity.
  - Efficiency – nutrients are released slower, so plants have access to nutrients over a longer period, promoting steady growth and increased nutrient use efficiency. Efficiency will vary based on the timing and rate of nitrogen availability.
  - Reduced nutrient loss - slow release and steady plant growth can reduce the potential for leaching including leaching on sandy soils or leaching due to high rainfall or over irrigation. This will vary based on source.
- Organic Matter - organic nitrogen sources contribute to the overall organic matter content in the soil which provides food for soil organisms, aids in the formation of soil aggregates, and helps maintain soil fertility over time while retaining soil moisture longer during dry periods.
- Soil Structure - organic fertilizers add organic matter to the soil, which enhances its structure. The decomposition of organic materials over time increases humus which improved soil properties such as water-holding capacity, porosity and aeration. This can improve drainage for clay soils and increase moisture retention on sandy soils.
- Soil Fertility – organic sources provide additional essential nutrient such as phosphorus, potassium, and micronutrients and increase cation exchange capacity (CEC) enabling the soil to hold and exchange nutrients more efficiently.
- Water Holding Capacity - additional organic matter from organic nitrogen source and the building of humus increases the soil's ability to retain water. This is especially valuable for dryland farming, crops with high water needs, and reducing irrigation needs.
- Microbial Activity and Biodiversity - organic fertilizers support and feed a wide range of soil microorganisms like bacteria, fungi, and earthworms and these microorganisms break down organic matter and convert it into forms that are usable for plants. Healthy and diverse microbial populations support plant health, decompose organic residues and can suppress pathogens.
- Sustainability & Recycling Nutrients – use of organic nitrogen sources can reduce dependence on synthetic fertilizers, recycle nutrients that may otherwise enter other waste streams, replenish depleted soils and contribute to long-term soil health.

Nitrogen Mineralization: Manure & Other Organic Sources:

Organic sources of nitrogen fertilizers such as manure, compost, legumes, and animal- and plant-based products offer many soil health benefits. However, their use requires careful management given their limited or variable nutrient content (compared to inorganic sources) and reliance of mineralization in the soil to become plant available nitrogen (PAN).

Different organic sources of nitrogen mineralize at different rates, and mineralization is controlled by numerous soil and environment factors. Knowing the mineralization rate of organic nitrogen sources is crucial for effective nutrient management because it allows producers to understand when and how much nitrogen is likely to become available so that fertilizer can be applied to match plant demand which supports better use efficiency.

Considerations

When using organic sources of nitrogen, several important factors must be considered to ensure effectiveness. These considerations involve understanding how organic fertilizers behave, their potential environmental impact, and how they interact with soil and crops.

Below are key factors that should be considered with using organic sources of nitrogen(Cassity-Duffey et al., 2020)

- Initial inorganic nitrogen content: materials with higher initial amounts of inorganic can supply nitrogen more quickly but are also susceptible to losses if not properly applied.
- Total nitrogen concentrations: the total nitrogen concentrations in the materials affects the availability of nitrogen for mineralization, with higher concentrations potentially leading to more nitrogen being mineralized.
- Carbon to Nitrogen (C/N) ratios: the composition and complexity of N-containing compounds, as indicated by the C/N ratios, influenced the optimal rate of mineralization. Lower C/N ratios could lead to faster rates of mineralization while higher C/N ratios could facilitate immobilization.
- Compost maturity: the maturity of compost (including animal manure) affects mineralization rates, with more mature compost typically containing highly stabilized nitrogen compounds that lead to lower mineralization rates or immobilization.
- Release rate: different organic source release nitrogen at different rates, so it’s important to plan fertilizer application according to the crop's nitrogen needs at different growth stages. This may require combining organic sources with inorganic fertilizers or using products that best match crop needs.
- Nutrient ratio: organic fertilizers often contain other nutrients in addition to nitrogen such as phosphorus, potassium and some secondary or micronutrients. However, they may not supply nutrients in ratios needed which can lead to the overapplication of some nutrients if not properly considered.
- Application Timing: organic nitrogen sources often require time to break down in the soil before they become plant available. This slow-release nature means that timing is important to ensure plants have access to nitrogen when they need it most. Plan

applications based on the crop's growth cycle and apply fertilizers during times when soil microbial activity is highest which helps optimize the breakdown of organic matter and the availability of nitrogen.

- Soil Type and environmental conditions: factors such source composition, soil temperature and moisture, soil microbial activity, soil pH, environmental conditions can all affect mineralization making it difficult to predict.

The use of organic sources of nitrogen fertilizers can offer many soil health benefits and while supplying nitrogen needed for crop production. However, careful management is crucial to maximize the benefits and avoid potential drawbacks. There are many factors that should be considered when using organic sources. When using organic sources of nitrogen, it's crucial to understand factors that influence mineralization and know their nutrient content and potential plant availability. Below are resources that can help determine the nitrogen content and predict its availability.

Resources

Oregon State University Organic Fertilizer and Cover Crop Calculators[9] are tools that can assist with preplant nitrogen input decisions and help forecasts the quantity of plant-available nitrogen (PAN) provided by inputs such as fresh organic materials, cover crop residues, and finished compost.

Hart, J. (2007). *Nutrient management for field corn silage and grain in Western Oregon* (EM 8954-E). Oregon State University Extension Service. https://extension.oregonstate.edu/sites/extd8/files/documents/em8954.pdf

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Application Methods

Organic sources of nitrogen can be applied in a variety of ways; but given their composition, different types are more suitable for certain types of application methods. In general, bulky solid or semi-solid materials are best suited for surface and soil incorporation methods. Liquid

[9] https://extension.oregonstate.edu/organic-fertilizer-cover-crop-calculators

sources such as fish and seaweed emulsions or soluble sources are most suitable for fertigation or liquid application.

Sources and Application Methods

- Broadcast - compost, manure, and other granular organic fertilizers like alfalfa meal, blood meal, and fish meal.
- Incorporation - manures, compost, blood meal, and fish meal, particularly when preparing soil before planting.
- Side-Dressing – manure, and other granular organic fertilizers like alfalfa meal, blood meal, and fish meal.
- Top dress - materials like compost, worm castings, and other organic mulches.
- Mulching – compost, manure, or plant-based materials like grass clippings or straw.
- Liquid/foliar - materials like compost, fish emulsion, or seaweed extract.
- Fertigation - liquid fertilizers, such as fish emulsion or seaweed extract, can be diluted and applied through drip irrigation or sprinkler systems.

Controlled-Release Fertilizers

Like organic sources of nitrogen, controlled-release fertilizers provide nutrients gradually over time and are used to provide plants with a steady supply. However, controlled-release fertilizers are made from synthetic materials that control the rate and duration of nutrient release using physical coatings or chemical formulations. Some products may require specific soil or moisture conditions for optimal effectiveness depending on the product selected. Common controlled-release fertilizers include urea formaldehyde, methylene urea and proprietary products such as Osmocote and Nutricote.

The primary benefit of controlled-release fertilizers is their ability to provide nutrients over an extended period. Gradually releasing nutrients reduces the need for frequent applications and can improve nutrient use efficiency and supports steady plant growth which can limit leaching. This is particularly useful on sandy soils or areas with high rainfall. Slow release may not be ideal for crops with high immediate nitrogen needs but is especially useful for crops where maintaining a consistent source of nutrients is important.

Benefits of Controlled – and Slow-Release Fertilizers

- Slow Release – provides a steady supply of nitrogen to plants.
- Reduced application frequency - since nutrients are available over a longer time frame, nutrients can be applied less frequently.
- Efficiency – nutrients are released more slowly, and plants have access to nutrients over a longer period which supports steady growth and increased nutrient use efficiency.
- Reduced nutrient loss - slow release and steady plant growth can reduce the potential for leaching including leach on sandy soils or leaching due to high rainfall or over irrigation.

Nitrogen Management for Cool-Season Grasses: Using T-Sum 200, T-Sum 360, Fall and Winter Nitrogen Applications

Temperature-summation (T-Sum) is a temperature-based system that uses the concept of growing degree days to determine the optimum time to fertilize cool-season grass fields and pastures at the beginning of the growing season to increase earlier forage production. With the T-Sum approach, once a T-Sum value is reached for a given location, plant growth and sufficient nitrogen mineralization is expected. Research shows that cool-season grasses initiate growth at or near this time.

For pastures and hayland, T-Sum timing is founded on the fact that new growth (spring green-up) doesn't occur on a specific date but is dependent on weather conditions of a particular year (temperature). T-Sum avoids using calendar dates or waste storage management needs as a decision for nitrogen applications, and instead, prioritizes nitrogen applications at times according to crop response to improve nutrient efficiency.

It's important to note that T-Sum values mark the beginning of when grass will begin to respond to mineralizing soil nitrogen and applied nitrogen including manure and urea. Ammonium supplied by manure and urea, which are commonly used on pastures and grass crops, are highly susceptible to losses via volatilization and runoff, especially in the spring when soils are damp, colder, often saturated and when significant storm events occur frequently. Therefore, any application of nitrogen made soon after T-Sum 200 or T-Sum 360 is reached must account for field and weather conditions, and fields with elevated potential for losses via runoff, erosion or volatilization must be avoided.

T-sum values used to mark when pastures and hayland may benefit from applied nitrogen are different based on location and are also calculated differently. T-Sum 200 is used to determine when pastures or haylands may begin to respond to applied nitrogen in Western Washington and is calculated in degrees Celsius. T-Sum 360 and T-Sum 720 are used in Eastern Washington using degrees in Fahrenheit.

Western Washington: Using T-Sum 200

For well-managed pastures and hayland containing cool season grass species, the T-Sum method can be used to estimate the appropriate date for the first plant-available nitrogen fertilizer application of a growing year.

Considerations for Using T-Sum 200

- The T-Sum 200 method for early nitrogen application is not appropriate for all pastures or hayland. Pastures and hayland with a poor stand may have growth-limiting factors that would prevent plant growth response to an early nitrogen application.
- The following are characteristics of fields better suited for the use of the T-Sum 200 method:
  - Fields containing grass or a grass/legume forage mix, such as tall fescue, orchard grass, or perennial ryegrass combined with a clover.
    - Bent grass and legume-only pastures are not ideal for early-spring N applications.
  - Fields that are not overgrazed in the fall. For optimal response to T-Sum fertilization, a minimum of 3 inches of forage should remain throughout the winter.
  - Well-drained fields that aren't saturated and are free of standing water. Wet, poorly drained soil does not facilitate forage growth.
  - The field is accessible by equipment for nitrogen application without negatively affecting soil conditions.
  - Soil pH and fertility are properly managed,
  - Soil compaction and other production factors are not significantly limiting crop growth.
  - Nitrogen applications should be limited to those pastures that start growing first in the spring.
- Avoid conditions that are likely to cause nutrients to run off, leach, or be lost via erosion, or conditions conducive to denitrification or volatilization.
- Typical application rates at T-Sum 200 and T-Sum 360 for grass dominated, higher yielding fields range from 40-60 lbs./acre. Lower yielding fields and/or field with a mix of grass and legumes need less nitrogen.
  - Consult Pacific Northwest Land Grant University guidance such as Nutrient Management for Pastures (EM 9224), The Western Oregon and Western Washington Pasture Calendar, and the Inland Pacific Northwest Pasture Calendar for application rate information.
- Ensure field conditions and anticipated precipitation won't cause runoff or erosion prior.
- Use practices to avoid volatilization.
  - See the Ammonia Volatilization section in Part A of the Appendix more information about factors that affect ammonia volatilization and practices that can be used to limit volatilization from ammonia- and ammonium-based fertilizers including manure.

Calculating T-Sum 200

T-Sum 200 is an accumulation of heat units (in degrees Celsius) for consecutive days beginning January 1. Each day, beginning January 1, the daily T-Sum values are added until 200 is reached. Calculate the average daily air temperature by adding the maximum to the minimum, then divide by 2. If the calculated T-Sum value for a day is below 0°C, zero is used.

When T-Sum 200 at reached will vary year-to-year based on location and weather. For Western Washington, the average time T-Sum 200 is reached ranges from February 8 to February 16 depending on location.

Use Pacific Northwest land grant university guidance to ensure T-Sum is accurately calculated. Local weather station data should be used when calculating T-Sum.

Eastern Washington: Using T-Sum 360 & T-Sum 720

For Eastern Washington, T-Sum 360 is used to determining the optimum time to fertilize grass pastures in the spring to increase earlier forage production, and T-Sum 720 is used to determine the best time to apply nitrogen fertilizer to optimize first cutting grass hay production. Earlier and higher forage production can be achieved by applying nitrogen fertilizer based on thermal (growing degree days), and applying nitrogen around T-Sum 360 can stimulate earlier pasture growth and increased yields.

Increase Pasture Forage Production

To increase forage production and reduce feed cost coming out of winter, T-Sum 360 F can be used to time nitrogen applications to increase early pasture forage production. Consider applying nitrogen soon after T-Sum 360 if earlier pasture growth is desired.

First Cutting Grass Hay Response to T-Sum 720 Nitrogen Application

The best time to apply plant-available nitrogen fertilizer to increase first cutting grass yields is near T-Sum 720. Applying higher rates of nitrogen near T-Sum 720 (100 and 150 lbs./ac) has been found to result in a higher yield. For lighter nitrogen rates (near 50 lbs./acre), there isn’t a considerable difference between application timings. Also, high nitrogen application rates can make grasses more susceptible to frost damage.

Calculating T Sum 360 & T Sum 720

T-Sum 360 and T-Sum 720 are accumulations of heat units (in degrees Fahrenheit) for consecutive days beginning January 1. Each day, beginning January 1, daily T Sum values are added until 360 or 720 are reached. When the optimum number of growing degree days is accumulated (reaching 360 or 720), fertilization may occur to increase earlier forage production for pastures or to optimize grass hay yield. Applications at T Sum 720 are best suited for increasing first cutting yields and crop utilization of higher nitrogen application rates. Applications at T-Sum 360 are best to increase pasture forage.

T-Sum 360 F and T-Sum 720 F are calculated by summing the maximum and minimum daily temperatures in degrees Fahrenheit, dividing that sum by 2, and then subtracting the base temperature of 32° F. Only positive values are used, and if a calculated T-Sum value for a day is below 0°F, zero is used.

When T-Sum 360 or T-Sum 720 is reached will vary by location and annual weather. However, T-Sum 320 is likely to be reached between mid-February and mid-March in most years. Use Pacific Northwest land grant university guidance to ensure T-Sum is accurately calculated. Local weather station data should be used when calculating T-Sum.

Key Considerations for Using T-Sum 360

The T-Sum 360 method for early nitrogen application is not appropriate for all pastures or hayland. Pastures and hayland with a poor stand may have growth-limiting factors that would prevent plant growth response to an early nitrogen application.

- The following are characteristics of fields better suited for the use of the T-Sum 360 method:
    - Fields containing grass or a grass/legume forage mix, such as tall fescue, orchard grass, or perennial ryegrass combined with a clover.
        - Bent grass and legume-only pastures are not ideal for early-spring nitrogen applications.
    - Fields that are not overgrazed in the fall. For optimal response to T-Sum fertilization, 3 inches of forage should remain throughout the winter.
    - Well-drained fields that aren't saturated and are free of standing water. Wet, poorly drained soil does not facilitate forage growth.
    - The field is accessible by equipment for nitrogen application without negatively affecting soil conditions.
    - Soil pH and fertility are properly managed,
    - Soil compaction and other production factors are not significantly limiting crop growth.
    - Nitrogen applications should be limited to those pastures that start growing first in the spring.
- Avoid conditions that are likely to cause nutrients to run off, leach, be lost via erosion, or conditions conducive to denitrification or volatilization.
- Typical application rates at T-Sum 200 range from 40-60 lbs./acre. Use land grant university fertilizer guidelines for determining application rates, times and managing soil nutrients. Nutrient Management for Pastures: Western Oregon and Western Washington and The Western Oregon and Washington Pasture Calendar are valuable resources.
- Ensure field conditions and anticipated runoff won't cause runoff or erosion prior to applying.

- Use practices to avoid volatilization.
  - See the [Ammonia Volatilization] section in Part A of the Appendix more information about factors that affect ammonia volatilization and practices that can be used to limit volatilization from ammonia- and ammonium-based fertilizers including manure.

Late Summer/Early Fall Applications

Fall is a time when cool-season grass pastures and hayfields are transitioning from semi-dormancy and/or experiencing steady regrowth due to cooler temperatures and increased precipitation. Cool season grasses may benefit from additional nitrogen during this time if there is insufficient soil nitrogen.

Prior to applying nitrogen (including manure sources) in late summer or early fall, soil tests must be taken to determine if additional nutrients including nitrogen are needed.
Fields should be tested for P, K, buffer pH, and residual nitrate (NO_3^-) to determine if additional nutrients are needed. If additional nitrogen is needed, nitrogen should be applied from approximately mid-August through September based on location and weather conditions and no later than October 1. Nitrogen applications should be coordinated with appropriate temperatures and moisture availability. If organic sources are used to supply nitrogen such as manure, late season nitrogen applications should not result in the over application of phosphorus beyond crop need.

Late Fall & Winter

Nitrogen should not be applied after October 1 until T-Sum 200 or T-Sum 360 is reached (Western vs Eastern Washington). Plants are dormant or slowly growing during this time and ceasing application is necessary to limit excess nitrogen from leaching below the zone into groundwater and/or being intercepted by tile drainage systems and discharged directly to surface water. Ceasing nitrogen application during this time also limits the potential for excess, unused nitrogen and phosphorus form being lost via erosion, runoff and nitrogen denitrification.

Source reviewed:

Fransen, S., Pirelli, G., Chaney, M., Brewer, L., & Robbins, S. (2014). *The Western Oregon and Washington pasture calendar* (PNW 699). Oregon State University Extension Service. https://extension.oregonstate.edu/sites/extd8/files/documents/pnw699.pdf

Moore, A., Pirelli, G., Filley, S., Fransen, S., Sullivan, D., Fery, M., & Thomson, T. (2019). *Nutrient management for pastures: Western Oregon and Western Washington* (EM 9224). Oregon State University Extension Service.
https://extension.oregonstate.edu/sites/extd8/files/documents/em9224.pdf

Phosphorus

Phosphorus is an essential macronutrient that may be added to the soil in relatively large amounts and is the second most limiting macronutrient after nitrogen. Phosphorus is crucial for plant vitality, influencing energy transfer, photosynthesis, root and flower development, and overall stress resilience. Absence or deficiency can lead to stunted growth, poor root development, delayed flowering, reduced yield, and general poor plant health. Therefore, it is crucial for optimal growth.

Phosphorus is somewhat unique in that it is an essential plant nutrient, has low solubility, and is not toxic itself, but can have detrimental effects on water quality even at low concentrations (Howarth et al., 2002). Phosphorus may be transported to surface water either as dissolved phosphorus or as particulate phosphorus bound to eroded soil particles. Dissolved phosphorus is readily available to aquatic plants and animals, and high concentrations of dissolved phosphorus can result in eutrophication. However, particulate phosphorus is not readily available and may be released into an available form slowly over time or remain unavailable. If particulate phosphorus accumulates near streambeds or in lake sediments, the slow release of phosphorus may cause chronic water quality problems for many years. Of all cropland nutrients inputs, phosphorus is arguably the most important nutrient to prevent from reaching freshwater bodies as phosphorus availability usually limits biological productivity in surface waters (Howarth et al., 2002).

Understanding how phosphorus behaves in agricultural soils can help maximize crop productivity and minimize losses of phosphorus to surface waters and its harmful effects. The following section will discuss how phosphorus interacts in the environment in the context of the phosphorus cycle. Common ways phosphorus is lost to surface water will also be discussed in addition to strategies that can be used to limit these losses

Phosphorus Cycle

The phosphorus cycle describes how phosphorus moves and transforms through the environment. The phosphorus cycle is similar to several other mineral nutrient cycles but unlike nitrogen, phosphorus does not have a gaseous phase and mainly cycles through land and water systems.

Phosphorus begins its cycle through the weathering and erosion of phosphate mineral found in rocks, releasing phosphate ions (PO_4^{3-}) into the soil and water. Once phosphate is released into the soil, plants can absorb dissolved forms of phosphorus called orthophosphates ($H_2PO_4^-$ or HPO_4^{2-}). Phosphorus moves through the food web as animals consume plants or other animals and excrete phosphorus. When plants and animals die, decomposers such as bacteria, fungi, and other microorganisms decompose their organic matter which releases phosphorus back into the soil and water making it available again. When phosphorus is lost to water bodies, like rivers, lakes, and oceans, it can settle into sediments. Over time, these phosphorus-rich sediments can become part of rock formations through geological processes effectively locking the phosphorus back into rock.

Organic vs. Inorganic Phosphorus:

Phosphorus is present in the soil in two main forms (organic and inorganic). Organic phosphorus comes from the decomposition of plant and animal material, including crop residues, manure, and microbial biomass. As microorganisms break down soil organic matter, they release phosphatase enzymes that break down organic phosphorus into the phosphate form, through a process of mineralization. Phosphate is then dissolved in soil water to form orthophosphates, a form absorbed by plant roots.

While organic phosphorus is abundant in many soils, it is not directly available to plants. The soil serves as a reservoir and the organic phosphorus must first be broken down into simpler compounds before plants can use it. On the other hand, inorganic phosphorus including phosphorus supplied by synthetic fertilizers, supplies readily available forms of phosphate which plants can absorb through their roots. Most phosphate fertilizers are manufactured by treating rock phosphate with acid to make it more soluble. These inorganic forms provide immediate plant nutrition but can quickly become tied up in the soil, forming insoluble compounds with calcium, aluminum, or iron, depending on the soil's pH.

The interaction between organic and inorganic phosphorus is controlled by soil microbes which act as the pathway for converting one form to another. Microbial activity is essential for mineralizing organic phosphorus into inorganic phosphate. However, these microbes can immobilize inorganic phosphorus, incorporating it into their biomass and temporarily making it unavailable to plants. This dynamic process ensures a continuous supply of phosphorus, though its efficiency depends on many factors such as soil temperature, moisture, and microbial diversity.

Soil Phosphorus Reserves

Soil phosphorus chemistry is complex, and phosphorus exists in many different forms within the soil. However, in terms of available and potentially available phosphorus, it helps to consider phosphorus as existing in three pools: solution, active and fixed.

Solution pool - the solution pool is primarily inorganic, plant available and typically is a fairly small amount. It's important because it's the pool from which plants take up phosphorus and is the only pool that has any measurable mobility in water.

Active pool - the active pool is phosphorus in the solid phase that's more readily released to the soil solution. As plants absorb phosphate, the concentration in solution decreases and some phosphate from the active P pool is released. This is the main source of phosphorus available for crops and will contain inorganic phosphate attached to small particles in the soil, phosphate that reacted with elements such as calcium or aluminum to form somewhat soluble solids, and organic phosphorus that's easily mineralized.

Fixed pool – this pool will contain inorganic phosphate compounds that are very insoluble and organic compounds that are resistant to mineralization by soil microorganisms. Phosphate in this pool may remain in the soil for many years without becoming plant available and may have very little positive impact on soil fertility.

Soil pH & Phosphorus Availability

Phosphates from synthetic fertilizers and manure are initially mostly soluble and plant available. However, when fertilizer or manure supplied phosphate contacts soil, various reactions begin occurring that make the phosphate less soluble and less available. The rates and products of these reactions depend on soil conditions such as pH, clay content and type of clay, moisture content, temperature and phosphorus already in the soil.

The amount of phosphorus dissolved in the soil solution at any given time is typically very small, but once it's removed from solution, it is replenished by the residual phosphorus in the soil. When the amount of phosphorus in the soil solution gets too high, phosphorus can be removed from the soil solution. Similarly, when concentrations of phosphorus in the soil solution get too high, some of the dissolved phosphorus will form solid phosphorus minerals by a process called precipitation. Based on soil pH, precipitation can result in the formation of calcium phosphate minerals (high soil pH) or aluminum and iron phosphate minerals (low soil pH). Alternatively, phosphorus can be removed from the soil solution and attach to soil particles like clays or iron (Fe)- or aluminum (Al)-bearing minerals via a process called adsorption.

Soil pH plays an important role in determining how much phosphorus is available to plants. Phosphorus is the most soluble when soil pH is between 6.5 to 7.5. When soil pH is less than 5.5 and greater than 7.5 to 8.5, phosphorus availability is limited due to fixation by aluminum, iron, or calcium, all of which are common in parent soil material. At lower pH levels, phosphorus binds tightly to iron and aluminum, forming compounds that are largely insoluble. Conversely, at higher pH levels, phosphorus becomes bound to calcium. These chemical reactions can lock up large amounts of phosphorus in the soil, reducing its availability even when soil tests show it is present in abundance. Maintaining the right pH range is crucial to avoid these binding processes and to maximize phosphorus efficiency.

Sources reviewed:

University of Minnesota Extension. (n.d.). *Phosphorus and potassium*. https://extension.umn.edu/nutrient-management/phosphorus-and-potassium

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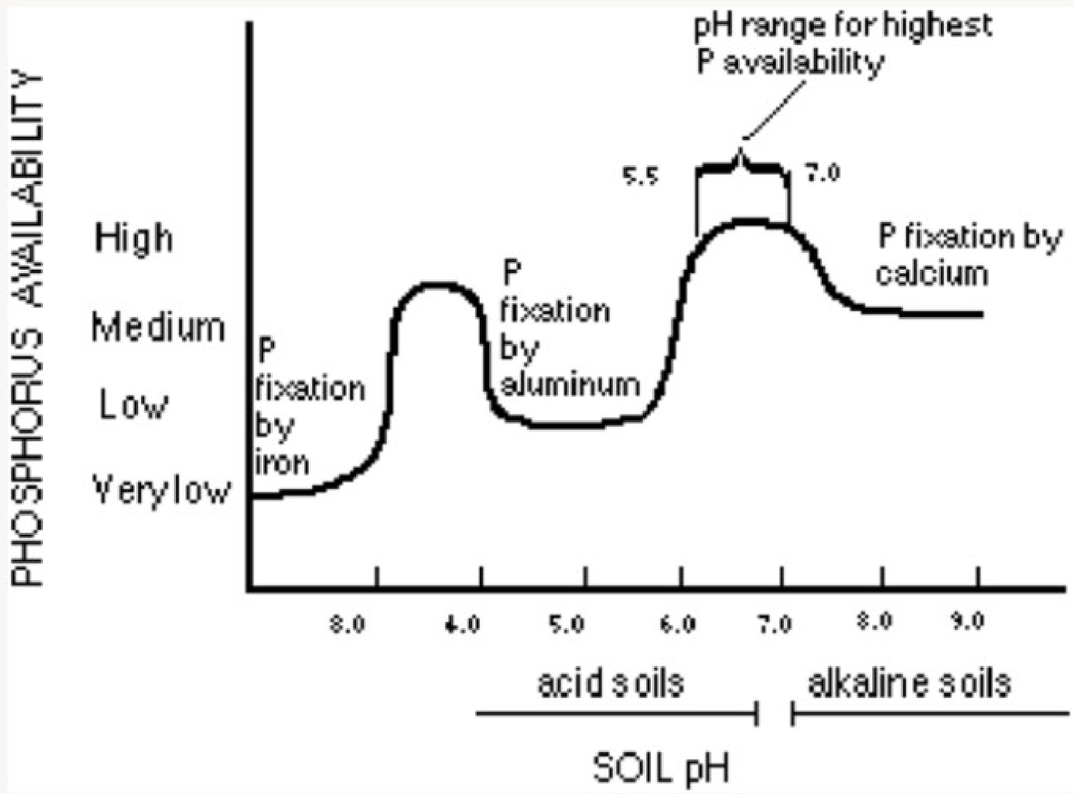

Figure 1: The availability of phosphorus is affected by soil pH.

Figure 1: University of Minnesota Extension. (n.d.). Understanding phosphorus in Minnesota soils. https://extension.umn.edu/phosphorus-and-potassium/understanding-phosphorus-minnesota-soils. The availability of phosphorus is based on soil pH.

Phosphorus Mobility & Phosphorus Transport

Given the high phosphorus fixing capacity of soils, many land managers have incorrectly concluded that dissolved phosphorus transport in runoff and in subsurface flow is absent or unimportant (Sharpley et al., 2013). However, it's now accepted that dissolved phosphorus transport via runoff and the movement of phosphorus through the soil profile can be significant (Hansen et al., 2002, Sharpley et al., 2013). Studies have shown that concentrations of dissolved phosphorus increase with increasing soil test phosphorus, and dissolved phosphorus is mostly likely to leach or run off when soils have a high degree of phosphorus saturation (Hansen et al., 2002).

Dissolved phosphorus moves along pathways of concentrated or preferential flow via features such as rills, gullies, soil macropores, artificial drainage channels and through tile lines and bedrock fractures, and off-site loads are typically associated with phosphorus applications and from accumulation in the soil (Hansen et al., 2002, Sharpley et al., 2013, Kleinman et al., 2011).

The movement of phosphorus through the soil profile can be significant for soils that have very low phosphorus sorption capacity (low in clay, carbonates, and iron- and aluminum- oxides). Although, leaching of phosphorus in fine-texture mineral soils has been reported when soil test phosphorus levels are high which commonly results from frequent applications of organic wastes such as animal manures and food processing waste. Subsurface losses of phosphorus are most likely on soil with elevated soil test phosphorus levels and low phosphorus sorption capacity, and the implications of leaching are greatest for shallow water tables and soils with artificial subsurface (tile) drainage (Hansen et al., 2002, Kleinman et al., 2011). The movement of applied phosphorus via runoff or leaching can be more significant than transport by soil erosion especially when soils are saturated with phosphorus and when runoff follows shortly after the surface application of phosphorus fertilizers and manure (Hansen et al., 2002).

Runoff & Erosion

Runoff and erosion are important mechanisms for phosphorus loss from agricultural lands to waters. When runoff and erosion transports phosphorus from agricultural lands, it typically transports particulate and dissolved phosphorus, with dissolved phosphorus usually coming from the top 1 to 5 centimeters of the soil (0.5 to 2 inches). The concentration of dissolved phosphorus in runoff is directly related to the quantity of and reactivity of phosphorus near the soil surface, and as soil phosphorus concentration increases, so does the concentration of dissolved phosphorus in runoff (Hansen et al., 2002). Further, according to Kleinman et al.(2011), the greatest potential for the acute transport of phosphorus to surface waters is when high rates of phosphorus are applied prior to high rainfall events or shortly before flood irrigation.

While dissolved phosphorus losses are important and are argued to have greater immediate impacts on surface waters because it’s the most plant available (Sharpley et al., 2013), soil erosion presents the greatest concern from a mitigation approach. This is because the concentration of phosphorus attached to soil particles is generally several orders of magnitude greater than that in the soil solution. Additionally, erosional processes preferentially remove the finest particles of soil, resulting in enrichment in sediment phosphorus concentrations that can be up to five times greater than those found in bulk soil from which the sediment eroded (Kleinman et al., 2011). When left unchecked, erosion-related losses of soil phosphorus can match phosphorus removed by crop harvest which can threaten crop production in areas with low soil phosphorus and increase fertilization costs to replenish lost phosphorus (Kleinman et al., 2011).

Transport & Loss

Phosphorus export is influenced by the rate, time, and method of phosphorus application, form of fertilizer or manure applied, amount and time of rainfall after application, and land cover. While phosphorus exports from agricultural systems are typically dominated by surface runoff and erosion, leaching can also occur in low phosphorus sorption capacity soils and soil with elevated phosphorus (Hansen et al., 2002, Howarth et al., 2002). The following table outlines key factors that influence the transport and loss of phosphorus (Howarth et al., 2002).

Table 5: Factors that influence the transport and loss of phosphorus.

Factors	Description
Erosion	Total P loss is strongly related to erosion.
Surface runoff	Water must move off or through the soil for P to move.
Subsurface flow	In sandy, organic, or P-saturated soils, P can leach through the soil.
Soil texture	Influences relative amounts of surface and subsurface flow.
Irrigation runoff	Improper irrigation management can induce surface runoff and erosion of phosphorus.
Connectivity to stream	The closer the field to the stream, the greater the chance of P reaching it.
Proximity of phosphorus -sensitive water	Some watersheds are closer to phosphorus-sensitive waters than others.
Sensitivity P input	Shallow lakes with large surface area tend to be more vulnerable to eutrophication.
Soil P	As soil phosphorus increases, losses in surface runoff and subsurface flow increases.
Applied P	The more phosphorus applied (fertilizer or manure), the greater the risk of phosphorus loss.
Application method	Phosphorus loss increases in this order: subsurface injection, plowed under, and surface broadcast with no incorporation.
Application timing	The sooner it rains after phosphorus is applied, the greater the risk for phosphorus loss.

Legacy Practices & Animal Feeding Operations

Building soil phosphorus reserves has been a long-established practice to maintain soil phosphorus levels for crop growth. However, the application of phosphorus to agricultural soils beyond crop requirements and the related saturation of a soil's phosphorus sorption capacity has increased the potential for chronic releases of phosphorus via leaching, runoff and erosion (Kleinman et al., 2011). In many cases, system level imbalances in phosphorus are the result of national fertilizer policies, regional exports of phosphorus from areas of crop production and the import of phosphorus into areas of intensive livestock production (Kleinman et al., 2011).

Nutrient accumulation is especially challenging for confined animal feeding operations because of the concentration of nutrients imported in feeds and because most of the phosphorus fed to livestock is excreted in manure, which tends to be applied locally (Kleinman et al., 2011). When sufficient acreage is not available for manure application or when hauling and spreading cost limit the distribution of manure, phosphorus accumulations occur and the risk of water quality degradation is elevated (Hansen et al., 2002).

Addressing legacy phosphorus practices and the over-application of phosphorus requires intentional and careful management beginning the reduction of phosphorus applications, seeking options to increase crop uptake of phosphorus, and taking actions to limit losses via runoff, erosion and leaching. Local and farm level phosphorus imbalances can be improved by formulating animal diets to avoid overfeeding phosphorus and by improving phosphorus digestibility. Further, manure treatment, mechanical processing and composting can be used to increase the value of manure and potentially lower the economic cost that may limit hauling distances (Hansen et al., 2002). But even with these efforts, it can take many years to reduce phosphorus concentrations in soil.

Phosphorus Management Strategies

Rate, method and timing of phosphorus applications are important phosphorus management decisions from a water quality and production standpoint. Surface applied fertilizer or manure without incorporation can create a significant risk of direct phosphorus transmission to surface water, especially when runoff occurs shortly after application. Incorporation of applied phosphorus can significantly reduce the concentration of dissolved phosphorus in runoff by limiting the interaction with surface runoff and facilitating contact with the soil to promote sorption (Kleinman et al., 2011). Furthermore, applying phosphorus during periods with dry antecedent conditions and/or low probability for large precipitation events can substantially reduce losses (Howarth et al., 2002).

Soil erosion associated with tillage can increase the risk of particulate phosphorus transport; and therefore, for erosion prone soils, practices that control erosion should be the highest priority. With manures, incorporation has traditionally been by tillage, which involves trade-offs due to greater erosion protentional. However newer, low-disturbance incorporation technologies such as injectors for liquid manures, subsurface applicators for dry manures and aerators that improve infiltration of liquid manure and rainwater are now available. Injection of fertilizers is a means of maintaining residue while placing phosphorus below the soil surface. Specialized equipment can be used to apply fertilizer in band below the soil surface as part of seeding (Hansen et al., 2002).

In situations where incorporation or injections may not be feasible, such as permanent pasture, other management practices should be used to reduce the risk of offsite transport including careful timing to avoid conditions and weather conditions conducive to runoff. This should also include avoiding applications to fields with higher risk of runoff and ensuring edge of field practice such as filter strips and riparian buffers are in place. It should also be noted that broadcast applications of fertilizers including manure can increase phosphorus levels at the surface of the soils (phosphorus stratification) which increases the potential for phosphorus transport via runoff and erosion.

Management practices that reduce erosion and runoff are effective at reducing phosphorus loss from agricultural lands. Specials attention should be given to fields having a high risk of phosphorus movement to surface waters through runoff or erosion. Along with proper timing, application method and rate, practices that reduce erosion and runoff such as conservation tillage, cover crops, filter strips and riparian buffers should be used. It should be noted that conservation tillage practices that reduce sediment loss can cause phosphorus stratification and result in significant concentrations of dissolved phosphorus near the surface because phosphorus from fertilizer and crop residues can accumulate at the soil surface, where it can be transported via runoff. Although, corresponding low runoff volumes can compensate for the accumulation of phosphorus at the soil surface. Additional reductions of phosphorus can also be obtained by routing runoff through vegetative buffer, riparian zones and structures that reduce the concentration of particulate phosphorus (Hansen et al., 2002).

To be most effective, mitigation strategies should also consider critical source areas, which are specific identifiable areas that are most vulnerable to phosphorus. Critical source areas should coincide with transport mechanisms (e.g., surface runoff, erosion, subsurface flow, and channel processes) and source or site management factors (e.g., soil, crop, and management) (Howarth et al., 2002).

Phosphorus Fertilizer Types

Rock phosphate is the raw material used to manufacture most commercial phosphate fertilizers. In the past, ground rock phosphate itself was used as a source of phosphorus; however, very little rock phosphate is currently used in agriculture due to low availability of phosphorus, high transportation costs and small crop responses.

Phosphorus can be supplied by organic sources and by synthetics fertilizers, although selecting a source can be confusing due to the many products available, varying nutrient content and the rate phosphorus may become plant available. Below is a list of common inorganic (synthetic) and organic sources of phosphorus along with their form, nutrient content and common application methods.

For inorganic sources, it’s important to understand how nutrient availability is determined. Available phosphorus is the sum water of water-soluble and citrate-soluble phosphorus and is determined in the following way (Kaiser & Pagliari, 2018).

- Water soluble - fertilizer samples are placed in water and the amount dissolved is measured.
- Citrate soluble - the fertilizer material that isn’t dissolved in water is then placed in an ammonium citrate solution. The amount of P dissolved in this solution is measured and expressed as a percentage of the total in the fertilizer material.
- Available - the sum of the water-soluble and citrate-soluble phosphates is the percentage that’s available to plants and is the amount guaranteed on the fertilizer label. Typically the citrate- soluble component is less than the water-soluble component.

Inorganic Sources

Below is a summary of the types of inorganic phosphorus fertilizers commonly used in commercial agriculture. Except for ammonium polyphosphate (APP), inorganic phosphorus sources are typically found in granular or prill forms which are suitable for pre-planting, side-dressing, broadcasting and banding applications. APP is a liquid and is commonly used for fertigation, foliar application, and side-dressing.

Table 6: University of Minnesota Extension. (n.d.). Percentages of water-soluble and available phosphate in several common fertilizer sources.

P_2O_5 source	Nitrogen	Total	Available P2O5	Water soluble* P2O5
Superphosphate (OSP)	0%	21%	20%	85%
Rock Phosphate	0%	34%	3%	0%
Monoammonium Phosphate (MAP)	11%	49%	48%	82%
Diammonium Phosphate (DAP)	18%	47%	46%	90%
Concentrated Superphosphate (CSP)	0%	45%	45%	85%
Ammonium Polyphosphate (APP)	10%	34%	34%	100%
*Water-soluble data are a percent of the total P2O5.				

Application Methods

Diammonium Phosphate (DAP): pre-planting, side-dressing, broadcasting, banding

Monoammonium Phosphate (MAP): pre-planting, side-dressing, broadcasting, banding

Triple Superphosphate (TSP):

- Phosphorus Content: 44-48% P_2O_5
- Form: Granular solid
- Application Methods: Pre-planting, side-dressing, broadcasting, banding

Single Superphosphate (SSP)

- Phosphorus Content: 16-20% P_2O_5
- Form: Granular solid
- Application Methods: Pre-planting, side-dressing, broadcasting, banding

Ammonium Polyphosphate (APP)

- Phosphorus Content: 10-34% P_2O_5 (varies by formulation)
- Nitrogen Content: Varies (typically 4-10% N)
- Form: Liquid
- Application Methods: Fertigation, foliar application, side-dressing

Rock Phosphate

- Phosphorus Content: 30-40% P_2O_5

- Form: Solid (powder or granules)
- Common Crops: Organic farming, legumes, and cereal crops.
- Application Methods: Pre-planting, broadcasting, incorporation, soil amendment
- Phosphorus from rock phosphate is largely unavailable to plant roots and takes years for release.

Organic Phosphorus Fertilizers

Organic forms of phosphorus come from natural sources such as manure and fish meal, and like organic sources of nitrogen, can also provide additional essential nutrients and improve soil quality.

When using organic sources, it's important to know the nutrient content and understand that organic sources contain much less plant-available phosphorus than inorganic sources which have been manufactured to increase solubility. Therefore, organic sources rely on mineralization more heavily when initially applied. That said, most organic phosphorus sources readily decompose, but factors such as temperature, soil moisture and soil pH all influence phosphorus mineralization rates.

Table 7: Summary of organic sources of phosphorus, phosphorus content of each source, release patterns.

Source	Phosphorus Content (P_2O_5)	Rate	Release Pattern
Bone Meal	15-25%	Slow	Provides phosphorus over several months to years as it breaks down.
Fish Meal	4-7%	Slow to medium	Phosphorus is released gradually over time.
Manure (Chicken, Cow, etc.)	1-3%	Medium	Phosphorus is mostly plant-available. Chicken manure has a higher phosphorus content than cow manure.
Composted Manure	2-5%	Slow	Phosphorus is released as it breaks down over time (often over a year or more).
Bone Char (Bone Ash)	18-28%	Slow	Phosphorus is available slowly over months to years.
Guano (Bat and Seabird)	10-15%	Medium	Releases phosphorus more quickly than bone meal but slower than synthetic fertilizers.

Secondary & Micronutrients

Plant nutrients are categorized into three main groups including macronutrients, secondary nutrients, and micronutrients and this distinction is largely based on the amounts that are needed for growth and development. Macronutrients are required in large quantities, while secondary nutrients are only needed in moderate amounts; however, availability and proper balance of each will directly influence plant performance.

While macronutrients and secondary nutrients are needed in greater amounts, micronutrients can play equally critical roles in crop development and are indispensable for various biochemical and physiological processes that are crucial for plant health, growth, and productivity and soil microbial health. Their availability and balance in the soil can significantly influence crop yield, quality, and resistance to diseases. All secondary and most micronutrients are managed via fertilizer and other soil amendments.

Secondary Nutrients

Secondary nutrients include sulfur, calcium, and magnesium. Below is a brief description of the key plant functions they support.

Sulfur (S) plays an important role in the plant's production of lignin and chlorophyll. Proper sulfur levels in soil help to increase nitrogen use efficiency, is essential for nitrogen fixing nodules in legumes, helps the plant's resistance to disease, and aids in seed formation. Plants that produce a high amount of dry matter, such as corn and alfalfa, require the most sulfur and respond the greatest to sulfur applications. In general, crops remove about as much sulfur as they do phosphorus.

Adding organic materials and maintaining adequate organic matter content is the best way to ensure crops have a good supply of sulfur. Plants can't use sulfur until bacteria convert it to sulfate, which is very soluble and mobile in the soil. Sandy soils and saturated soils tend to have lower levels of plant available sulfur because of this mobility.

Calcium (Ca) helps to improve nutrient absorption by the roots, is important in cell division and cell wall development, and is essential for nitrogen fixation in legumes. When calcium containing liming agents are regularly applied to manage soil pH, calcium is usually supplied in sufficient amounts.

Magnesium (Mg) is critical for photosynthesis, is a phosphorus carrier in plants, and is a key component in nitrogen metabolism. Most magnesium deficiencies are related to imbalanced fertility levels within the soil.

Micronutrients

Micronutrients are needed by plants in small amounts but are crucial for the proper plant growth and development. These nutrients support various physiological processes, enzyme functions, and structural components. Below is a list of micronutrients and their roles in crop development. Zinc (Zn), iron (Fe), manganese (Mn), boron (B), chlorine (Cl), copper (Cu), and molybdenum (Mo) are micronutrients that are typically managed, with zinc being the most likely to be in short supply.

Boron (B): Boron is important for cell wall formation, cell membrane integrity, and regulating plant metabolism of carbohydrates. sugar transport within the plant.

Chlorine (Cl): Chlorine plays an important role in osmoregulation (the balance of water and solutes) and contributes to photosynthesis. Chlorine deficiency is rare.

Copper (Cu): Copper is an activator of several enzyme systems in plants and supports electron transport and energy capture by oxidative proteins and enzymes. Copper is crucial for photosynthesis, respiration, and production of lignin which strengthens plants. A deficiency in copper can cause wilting, stunted growth, and leaf discoloration.

Iron (Fe): : Iron is critical in the formation of chlorophyll in plant cells. It serves as an activator for biochemical processes such as respiration, photosynthesis and symbiotic nitrogen fixation. Iron deficiency can lead to chlorosis (yellowing of leaves) and poor growth.

Manganese (Mn): Manganese serves as an activator for enzymes in growth processes, assists chlorophyll formation and plays a role in nitrogen assimilation. Deficiency can lead to poor root development and reduced resistance to disease.

Molybdenum (Mo): Molybdenum serves as cofactor for the enzyme nitrate reductase and is necessary for the proper function of nitrogenase (an enzyme that facilitates nitrogen fixation in legumes). Molybdenum deficiency can lead to poor nitrogen utilization and stunted growth.

Nickel (Ni): Nickel is important for activating urease (an enzyme that converts urea to ammonium). Deficiency is rare but can lead to poor nitrogen utilization and chlorosis.

Zinc (Zn): Zinc is essential for protein synthesis, production of growth hormones, and the synthesis of enzymes involved in metabolism. Zinc deficiency often results in stunted growth, reduced fruit bud development and chlorosis.

Management

Secondary and micronutrients are vital for healthy crop growth and development, and though needed in smaller amounts than macronutrients, are critical for achieving optimal crop performance and nutrient use efficiency. All secondary and most micronutrients can be managed via fertilizer and soil amendments

Regular soil testing is an important element in nutrient management, and it’s important to test for these nutrients and adjust their levels or soil conditions affecting their availability to promote crop health and support nutrient use efficiency of macronutrients nitrogen, phosphorus and potassium. The Oregon State University Soil Test Interpretation Guide provides information that can be used to determine if soil levels are in proper ranges and identify options for adjusting them. Land Grant University extension publications can be an additional guide to understand crop-specific nutrient needs.

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Application Timing & Rate

Timing

According to NRCS, the timing and amount (rate) of applied crop nutrient must correspond as closely as practical with plant nutrient uptake (utilization by crops) and consider nutrient source, cropping system limitations, soil properties, weather conditions, drainage system, soil biology, and nutrient risk assessment results (U.S. Department of Agriculture, Natural Resources Conservation Service, n.d.)

Proper nutrient application timing ensures that plants have the necessary nutrients available at the right stages of their growth which leads to greater productivity, improved nutrient use efficiency and reduced the potential for residual nutrients to be left in the soil after a growing season. Timing also influences the potential for applied nutrient to be lost to the environment during the growing season.

Different crops have varying and distinct nutrient demands in terms of types of nutrients needed, amount and when they are needed, and these needs vary based on crop type, management factors and site-specific factors such a soil type, application method, irrigation availability, soil quality, water availability and associated yield potential of a given field. Timing fertilization with peak nutrient uptake demand is essential for optimizing both yield and limiting potential negative impacts to water quality and air quality. Many factors influence nutrient application timing including crop type, growth stage, soil nutrient levels, type and efficiency of fertilizer used, tillage management practices, nutrient application equipment used, weather and field conditions, irrigation availability and irrigation timing.

Understanding and evaluating field and weather conditions is critical for limiting nutrient losses. When nutrients are applied under poor field and climatic conditions, they can be easily lost through pathways including runoff, erosion, and leaching. Nutrients lost the environment often results in many negative environmental consequences but can also reduce the amount of nutrients available to support crop production.

Ultimately, the goal of nutrient timing is to apply crop nutrients at times when they are most efficiently used by crops and avoid times when they are most likely to be lost to the environment. Therefore, nutrients should be applied as close to crop uptake as possible but must also be applied under field conditions with the least potential to cause losses.

Rates

Many factors affect the amount of nutrients that can and will be used by a crop in a given year. Similar to application timing, the goals of applying nutrients at proper rates are to ensure optimal crop yield while simultaneously ensuring that excess nutrients are not left in the soil which can be lost to surface and groundwater or the atmosphere.

The Natural Resource Conservation Service's Field Office Technical Guide outlines criteria for determining application rates which recommends that nitrogen, phosphorus and potassium rate be based on crop and/or cropping sequence, current soil test results, and realistic yield goals and associated plant uptake rates. (U.S. Department of Agriculture, Natural Resources Conservation Service, n.d.).

Realistic yield goals are crucial for proper nutrient management and are an anticipated amount of crop production (e.g. weigh or volume) that is achievable and based on the specific field conditions and farm operations. It's recognized that yields for the same crop are variable from field-to-field and can vary considerably based on climate, crop variety and genetics, water availability crop management and soil fertility. Given that application rates are typically based on yield goals, it's critical to ensure yield goals are achievable and not aspirational especially since residual nutrients in the soil after a growing season are most susceptible to losses via runoff, leaching, erosion and gaseous emissions. Therefore, realistic yield goals must be established based on historical yield data, soil productivity information, climatic conditions, nutrient test results, level of management, and local information that considers comparable production conditions and estimated yield response. Further, yield goals must also consider factors that may limit yield such as poor soil quality, drainage, pH, salinity, etc., prior to establishing nutrient application rates.

Applying nutrients in amounts needed (rate) based on realistic yield goals and at times when they are most needed and least likely to be lost supports crop production and nutrient use efficiency which can reduce the potential for applied nutrients to negatively affect water and air quality. Application rate and timing decision are influenced by many interrelated factors, and these factors must be accounted for to ensure that fertilizers are applied to avoid under- or over-application.

Nutrient Budgets

A nutrient budget is a detailed plan that is used to establish how much plant nutrients are applied to a specific crop in a given year. Crop budgets account for nutrients currently available in the soil, nutrients that will become available and additional sources including starter fertilizer, fixed nitrogen from legumes, and nitrate from irrigation all of which are often referred to as credits. Budgets also include yield goals, calculated amount of nutrients needed to meet the yield goal (minus credits), the type of fertilizer(s) to be used and the rate they will be applied.

Information needed to create a nutrient budget includes:

- Realistic annual yield goals and corresponding N, P and K requirements based on crop nutrient removal rates,
- Current soil nutrient analysis,
- Sources of nutrients that will be used and their nutrient content,
    - Estimation of plant-available nitrogen and phosphorus from organic nutrient sources and predicted timing of availability,
- Estimation of nitrogen and phosphorus supplied by soil organic matter mineralization,
- Estimation of nitrogen loss from the source and application method (primarily surface applied manure or urea via volatilization),
- Calculation of the net nutrient balance (surplus or deficit) for N, P and K,
- Calculation of the amount of additional nutrients needed to meet the yield goal,

The Natural Resource Conservation Service has templates that can be used to develop a nutrient budget which also includes tools to estimate nitrogen credits from legumes and crop removal rates for nitrate, phosphorus and potassium. Crop advisors can also credit similar products.

Nutrient Application Method & Placement

In nutrient management, placement is the positioning of nutrients in the soil to ensure accessibility for plants and maximize plant uptake while minimizing the potential for losses. In general, it involves determining the optimal depth, location, and method of nutrient application relative to the crop's root zone. Nutrient placement is done through a variety of mechanical methods, therefore it’s important to ensure application equipment is in good working order and well maintained.

Nutrient application method is an important factor for maximizing crop utilization and minimizing environmental impacts. Each application method has its own unique challenges and benefits, and the technique chosen often depends on the type of fertilizer used, crops grown, growth stage of the crop, equipment used for planting and fertilization, and other specific soil and growing conditions. Tailoring application techniques to crops and crops rotations can help ensure the most efficient use of applied nutrients by crops.

Methods used for nutrient placement should be most compatible with the tillage system used and work to limit losses via runoff, erosion, leaching and volatilization. In most cases, practices that incorporate nutrients or place them below the soil surface are preferred.

The following is a brief description of common application practices including some advantages and disadvantages of each.

Table 8: Summary of common nutrient application types, associated methods, and advantages and disadvantages.

Application Type	Description	Methods	Advantages	Disadvantages
Band Application	Fertilizer is placed in narrow bands near the plant root zone.	Subsurface banding: fertilizer is injected below the soil surface. Surface banding: fertilizer is applied directly on the soil surface in bands, typically between rows.	Subsurface banding helps reduce nitrogen volatilization and improves nutrient uptake by placing fertilizer closer to plant roots.	Equipment cost may be higher.
Broadcast Application	Fertilizer is spread evenly over the soil surface.	Dry Broadcast: solid granules are applied using a spreader. Liquid Broadcast: liquid fertilizers are sprayed fields.	Easy to apply over large areas and on crops that where incorporation may not be feasible e.g., pastures or perennial crops.	May result in nutrient losses through volatilization, leaching, or runoff if not properly incorporated into the soil.
Fertigation	Fertilizer is dissolved in irrigation water and applied through the irrigation system.	Dissolved fertilizer is delivered via irrigation systems such as drip and sprinkler systems.	Reduces runoff, supports precision application and increased use efficiency, and reduces labor.	Initial costs can be high, risk of emitters clogging, risk of leaching.

Application Type	Description	Methods	Advantages	Disadvantages
Foliar Application	Liquid fertilizer is applied directly to plant leaves.	Liquid fertilizer is applied using sprayers.	Allows rapid nutrient uptake by plants and can address deficiencies quickly.	Not commonly used as a primary method for macronutrient applications but can be used for other nutrients.
Incorporation	Fertilizer is worked into the soil after application.	Fertilizer is worked into the soil after application by plowing, tilling, or using specialized equipment.	Reduces volatilization and improves nitrogen efficiency.	Labor and equipment costs can increase; can disrupt soil structure and organic matter.
Injection	Fertilizer is placed several inches below the surface near the plant roots, often using specialized equipment.	Fertilizer is place into the soil using nozzles, shanks, or tines attached to tractors or implements.	Supports precise nutrient delivery and nutrient use efficiency, and improved crop response.	Requires specialized equipment and careful calibration, may require larger tractors and may not be suitable for all soil types.
Mulching	Using organic material as a mulch material which naturally breaks down and adds nitrogen and other nutrients to the soil.	Organic materials are placed on the soil surface around plants. Mulching materials may also be enriched with nutrients.	Support moisture retention, weed suppression and improved soil health, and can supply slow-release fertilizer.	Slow release may not meet crop nutrient demand, can cause temporary nitrogen immobilization, can be labor intensive, can harbor pest and cause soils become waterlogged.
Side Dress	Fertilizer is applied to the side of the	Fertilizer is placed on one or both sides of the row.	It is used for supplemental fertilization when	Requires careful timing to avoid root

Application Type	Description	Methods	Advantages	Disadvantages
	growing plants, typically after planting but before the plants are fully grown.		crops most need it. Can improve nutrient use efficiency.	damage or losses.
Top Dress	Spreading fertilizer on the surface of the soil around plants.	Fertilizer is applied manually or mechanically via broadcasting or spot applications.	Ease of application, flexibility, supports precision timing and application rates, and can be used to correct deficiencies.	Nutrients are more prone to be lost, can be ineffective without watering or incorporation, labor intensive.

Soil pH

Soil pH is a measure of how acidic or alkaline the soil is and directly affects nutrient availability, microbial activity, and overall plant health (McFarland, Huggins, & Koenig, 2015). Each crop has an optimal pH range where it can best absorb nutrients and grow efficiently. For most agricultural crops, the ideal pH range is between 6.0 and 7.5. Within this range, essential nutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium are readily available.

Soil acidification, a process by which the soil becomes more acidic over time, can be a significant issue in modern agriculture, particularly in regions with intensive cropping or high rainfall. While climate and a soil's parent material and history of formation affects the likelihood of acidification, soil acidification in agricultural areas is primarily associated with crop production and the removal of base cations such as calcium (Ca^{2+}) and magnesium (Mg^{2+}) from the root zone and the use of ammonia- and ammonium-forming fertilizers. When ammonium is converted to nitrate by soil microbes, hydrogen ions (H^+) are released. Continued use of ammonia- or ammonium-based fertilizers can eventually lead to soil acidification.

Managing soil pH requires a proactive approach and there are a variety of products that can be used adjust pH. In acidic soils, applying calcitic lime (calcium carbonate) or dolomitic lime (calcium and magnesium carbonates) can help raise pH. For alkaline soils, adding organic matter such as compost or manure can help buffer pH, and sulfur or sulfur-based amendments such as aluminum- or iron-sulfates can be used to lower soil pH.

Regular soil testing is important to monitor pH levels and guide amendments. Keeping soil pH at crop-specific optimal levels can help ensure nutrients are accessible to crops, improve nutrient uptake and reduce the need for additional fertilizer inputs.

Soil Monitoring & Organic Source Testing

Soil and organic source testing are the cornerstone for any nutrient management strategy and is used as both a diagnostic tool and to identify trends. Knowing soil nutrient levels and the nutrient content of organic sources is essential to identify deficiencies that may negatively affect productivity, to identify when nutrients have been under- or over-applied or inefficiently used, and to ensure nutrients are applied consistently with nutrient budget and realistic yield goals.

The following sections outline general criteria for soil and organic and nutrient source sampling. Adaptive management strategies using end-of-season, post-harvest soil sampling are also outlined.

Routine Sample for Nutrient Budgets and Assessment of Budgets

Routine soil and organic source testing are required to ensure nutrients are applied at the proper rate, and to assess nutrient budget effectiveness. The following are minimum expectations for soil sampling to support nutrient budget development and to assess nutrient budgets including post-sampling.

- Routinely test soils for primary, secondary, and micronutrients to evaluate soil nutrient levels and develop nutrient budgets to ensure nutrients aren't over- or under-applied.
    - At a minimum, soil tests should include pH, sodicity and electrical conductivity (EC) where salts are a concern, soil organic matter, nitrogen (nitrate plus ammonia), phosphorus, potassium, and other nutrients recommended by appropriate Pacific Northwest land grant university crop production guidelines.
- Test for soil nitrogen (ammonium-N plus nitrate-N) each spring to finalize nutrient budgets ahead of the growing season. Soil testing in the spring should occur as close to fertilizer application as possible.
    - West of the Cascades, soil nitrate is evaluated within the first foot.
    - In arid regions east of the Cascades, soil nitrate is evaluated by measuring nitrate nitrogen (NO_3^-) in one-foot depth increments to a depth of 2 to 5 feet as necessary for the planned crop or crop rotation.
    - Consult nutrient management guidelines for individual crops to determine sampling depth and method for crediting soil nitrogen.
- For phosphorus:
    - Use the Bray P1 method for acidic soils and the Olsen sodium bicarbonate ($NaHCO_3$) method for alkaline soils. Phosphorus fertilizer recommendations are typically based on results from these methods.
    - Sample fields at least once every 3 years.

        - Increase the frequency to every 1-2 years on soils with low cation exchange capacity, regular manure or compost applications, intensive cropping systems or when there is a history of deficiencies.
        - When sampling soil for phosphorus, it's important to be aware of previous phosphorus management.
        - Avoid fertilizer bands when collecting soil samples.
    - Conduct a post-harvest soil test at least once every three years and use results to adaptively manage soil phosphorus.
        - Increase the frequency to every 1-2 years for soils with low cation exchange capacity, regular manure or compost applications, intensive cropping systems or when there is a history of deficiencies.
        - See the adaptive management section below for additional information.
- For secondary nutrients (calcium, magnesium and sulfur):
    - Test for secondary nutrients every 1-3 years.
    - Sulfur can leach, especially in low cation exchange soils. Increase the frequency to every 1-2 years if leaching is an issue.
    - Calcium and magnesium are commonly evaluated every 2-3 years.
- For micronutrients,
    - Soil micronutrients are typically evaluated every 2-4 years or as needed.
    - Micronutrients to be test for will likely vary based on based on crop or crop rotation, history of management and soil properties.
    - Certified crop advisors can help identify which micronutrient to test for.
- Plant tissue or stem testing may also be used to support nutrient management planning.
- Follow Pacific Northwest Land Grant University sampling, handling and testing procedures that are regional and crop appropriate. Below are examples of available resources.
- Consult the Natural Resource Conservation Service (NRCS) Field Office Technical Guidance (FOTG) for Nutrient Management (590) for additional information and to identify additional resources when needed.

Sources reviewed:

- Monitoring Soil Nutrient Using a Management Unit Approach, Staben, M. L., Ellsworth, J. W., Sullivan, D. M., Horneck, D. A., Brown, B. D., & Stevens, R. G. (2003).
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- Oregon State University Extension Service. (n.d.). *Fertilizing with manure* (EM 8832). https://extension.oregonstate.edu/sites/extd8/files/documents/em8832.pdf
- NRCS FOTG for Nutrient Management – Practice code 590.

Manure & Other Organic Sources

- Nutrient values of manure, organic by-products and biosolids must be determined prior to land application.
- Analyses of manure or other organic nutrient sources should include total nitrogen (N), ammonium (N), total phosphorus (P) or phosphate (P_2O_5), total potassium (K) or potassium oxide (K_2O), and percent solids.
- Manure, organic by-products, and biosolids samples must be collected and analyzed at least annually, or more frequently if needed to account for operational changes (feed management, animal type, manure handling strategy, etc.) that impact manure nutrient concentrations.
    - If no operational changes occur, less frequent manure testing is allowable where operations can document a stable level of nutrient concentrations for the preceding three consecutive years, unless federal, State (Washington State Department of Ecology, and Washington State Department of Agriculture), or local regulations require more frequent testing.
    - For livestock feeding operations such as dairies where nutrient concentrations often change through a growing season, testing before each manure application is recommended.
- Samples must be collected, prepared, stored, and shipped according to land-grant university guidance or industry standards.
- Biosolids application must follow Washington State Department of Ecology guidelines.
- Use land grant university guidance for nutrient source sampling and estimating the nutrient content and nutrient availability from organic sources.

Sources reviewed:

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Adaptive Management for Nitrogen & Phosphorus

Of all plant nutrients, nitrogen and phosphorus are used in the greatest amounts and have to greatest effect on water quality. Therefore, it's critically important that post-harvest soil levels remain low because residual soil nitrogen and phosphorus are highly susceptible to losses to surface water groundwater and the atmosphere and result in many negative effects.

Adaptive Management for Nitrogen Using Post-Harvest Soil Monitoring

Residual (post-harvest) soil nitrate-nitrogen is a useful measurement to evaluate nutrient (nitrogen) management. Excess soil nitrate in the fall can result from the over-application of nitrogen, mistimed nitrogen application, soil nutrient imbalances or poor growing conditions such as drought, pests or lack of irrigation.

When post-harvest nitrate levels are elevated, management decisions including nutrient budgets (and yield goals), application timing and method, nutrient sources used and soil nutrient imbalances should be evaluated and adjusted to prevent excessive post-harvest, soil nitrate-nitrogen in subsequent years.

Post-harvest nitrogen testing is conducted in the fall to evaluate nutrient budget effectiveness. The following is a description of soil nitrate levels along with actions that should be taken based on soil nitrogen concentrations.

Table 9: Adaptive management actions for nitrogen using post-harvest soil monitoring.

Soil Nitrate-N (ppm)	Description	Actions Need
<10	Low	• Continue to follow nutrient budgets and yield goals. • Continue to test soils for primary, secondary and micronutrients (as needed) and manage nutrients to appropriate levels. • Maintain soil pH near neutral (7.0) and/or adjust pH as necessary based on crop or crop rotation needs. • Continue to use spring soil sample results to establish application rates. • Continue to use post-harvest soil sampling to evaluate nutrient management.
10-20	Medium	• Reduce application rates for fall-planted crops. • Consider planting cover crops. • Revaluate nutrient budget assumptions including yield goals, soil mineralization, nitrogen volatilization, and other sources of nutrients e.g., legumes, irrigation water or atmospheric/precipitation deposition. • Verify application rates and recalibrate land application equipment when necessary. • Ensure nitrogen applications occur prior to peak crop uptake. • Reduce nutrient applications to the field when other factors affecting soil nitrate levels aren't determined. • Continue to test soils for primary, secondary and micronutrients (as needed) and manage nutrients to appropriate levels. • Continue to use spring soil sample results to establish application rates. • Continue to use post-harvest soil sampling to evaluate nutrient management. • Maintain soil pH near neutral (7.0) and/or adjust pH as necessary based on crop or crop rotation needs. • Maintain nutrient balances between macronutrients, secondary and micronutrients.

Soil Nitrate-N (ppm)	Description	Actions Need
		• Consider hiring a professional/consultant to evaluate nutrient budget assumptions, application methods and timing to develop revised annual nutrient budgets and application rates.
20-30	High	• Reduce application rates for fall-planted crops. • Plant cover crops. • Consult a professional crop advisor to evaluate nutrient budget assumptions, application methods and timing to develop revised annual nutrient budgets and application rates. • Reestablish nutrient budget assumptions including yield goals, soil mineralization, nitrogen volatilization, and other sources of nutrients e.g., legumes, irrigation water or atmospheric/precipitation deposition. • Reduce future nitrogen application rates. • Verify application rates and recalibrate land application equipment when necessary. • Adjust land application timing so nutrient availability aligns with peak crop uptake. • Enhance nutrient removal via crop management. • Ensure nitrogen is applied as close as possible to peak crop uptake. • Continue to test soils for primary, secondary and micronutrients (as needed) and manage nutrients to appropriate levels. • Continue to use spring soil tests for nitrogen to adjust application rates. • Continue to use post-harvest soil sampling to evaluate nutrient management. • Maintain nutrient balances between macronutrients, secondary and micronutrients. • Maintain soil pH near neutral (7.0) and/or adjust pH as necessary based on crop or crop rotation needs.
>30	Very High	• Significantly reduce application rates for fall-planted crops.

Soil Nitrate-N (ppm)	Description	Actions Need
		• Plant cover crops. • Consult a professional crop advisor to evaluate nutrient budget assumptions, application methods and timing to develop revised annual nutrient budgets and application rates. • Reestablish nutrient budget assumptions including yield goals, soil mineralization, nitrogen volatilization, and other sources of nutrients e.g., legumes, irrigation water or atmospheric/precipitation deposition. • Significantly reduce future nitrogen application rates. • Verify application rates and recalibrate land application equipment when necessary. • Enhance nutrient removal via crop management. • Ensure nitrogen is applied as close as possible to peak crop uptake. • Continue to test soils for primary, secondary and micronutrients (as needed) and manage nutrients to appropriate levels. • Continue to use spring soil tests for nitrogen to adjust application rates. • Continue to use post-harvest soil sampling to evaluate nutrient management. • Maintain nutrient balances between macronutrients, secondary and micronutrients. • Maintain soil pH near neutral (7.0) and/or adjust pH as necessary based on crop or crop rotation needs.

Adaptive Management for Phosphorus Using Post-Harvest Soil Monitoring

Phosphorus soil test results are an index of phosphorus availability but can’t be used to predict plant phosphate availability (lbs./acre) given the many site-specific soil factors that affect phosphorus availability such as pH and soil concentrations of minerals such as calcium, aluminum and iron. Nevertheless, soil phosphorus test results do provide an indication of the amount of plant available, soluble phosphorus likely to be available given the relationship between the forms of phosphorus (organic, adsorbed, and labile phosphorus) and soluble phosphorus.

In general, as soil test phosphorus increases, so does the amount of soluble phosphorus that can be used crops or transported to surface water or leached. So, as soil phosphorus concentrations increase, so does the potential for losses of soluble phosphorus. Further, phosphorus is strongly bonded to soil particles, so fields with elevated soil phosphorus that are prone to erosion pose a higher risk of contributing larger amounts of phosphorus if eroded soils reach surface water.

Whether eroded, leached or transported via runoff, phosphorus can significantly impact water quality. Therefore, crop fields must be properly managed to prevent the buildup of soil phosphorus; and if buildup occurs, steps must be taken to reduce levels and the subsequent risk to water quality.

The following is a description of soil phosphorus levels along with actions that should be taken should they become elevated.

Table 10: Adaptive management actions for phosphorus using post-harvest soil monitoring.

(Bray P1 test) (ppm P)	(Olsen test) (ppm P)	Description	Actions Need
<20	<10	Low	• Continue to follow nutrient budgets and yield goals and apply phosphorus at crop removal rates. • Continue to test soils for primary, secondary and micronutrients (as needed) and manage nutrients to appropriate levels. • Maintain soil pH at crop-specific optimal levels for the planned crop or crop rotation. • Continue to use post-harvest soil sampling to evaluate nutrient management practices. • Monitor crops for signs of phosphorus deficiencies.
20-40	10-25	Medium	• Consider reducing application rates and apply only at crop removal rates. • Use band applications when possible. • Revaluate nutrient budget assumptions including yield.

(Bray P1 test) (ppm P)	(Olsen test) (ppm P)	Description	Actions Need
			• Verify application rates and recalibrate application equipment when necessary • Consider adjusting application timing so nutrient availability aligns with peak crop uptake. • Continue to test soils for primary, secondary and micronutrients (as needed) and manage nutrients to appropriate levels. • Maintain soil pH at crop-specific optimal levels for the planned crop or crop rotation. • Continue to use post-harvest soil sampling to evaluate nutrient management practices. • For fields routinely used for manure application, consider additional approaches such increasing acres available for spreading and/or selling manure or identifying other marketable uses. • Evaluate fields for their potential to erode and for eroded soils to reach surface waters. • Consider using NRCS' Phosphorus Index to evaluate fields that may require additional practices to prevent phosphorus transport to surface water via runoff, erosion, leaching and through subsurface tile drainage. • Consider planting cover crops especially on field with tile drainage and/or higher potential for erosion and excessive runoff.
40-100	20-50	High	• Stop applying phosphorus until medium or low phosphorus levels are reached. • Plant crops with high phosphorus uptake. • Continue to test soils for primary, secondary and micronutrients (as needed)

(Bray P1 test) (ppm P)	(Olsen test) (ppm P)	Description	Actions Need
			and manage nutrients to appropriate levels. • Maintain soil pH at crop-specific optimal levels for the planned crop or crop rotation. • Continue to use post-harvest soil sampling to evaluate nutrient management practices. • For fields regularly used for manure applications, consider additional approaches such increasing acres available for spreading and/or selling manure or identifying other marketable uses. • Evaluate fields for their potential to erode and for eroded soils to reach surface waters. • Plant cover crops especially on fields with tile drainage and/or higher potential for erosion and excessive runoff. • Consider using NRCS' Phosphorus Index to evaluate fields that may require additional practices to prevent phosphorus transport to surface water via runoff, erosion, leaching and through subsurface tile drainage.
>100	>50	Very High	• Stop applying phosphorus until a medium or low phosphorus levels are reached. • Plant crops with high phosphorus uptake. • Continue to test soils for primary, secondary and micronutrients (as needed) and manage nutrients to appropriate levels. • Maintain soil pH at crop-specific optimal levels for the planned crop or crop rotation.

(Bray P1 test) (ppm P)	(Olsen test) (ppm P)	Description	Actions Need
			• Continue to use post-harvest soil sampling to evaluate nutrient management practices. • For fields regularly used for manure applications, consider additional approaches such increasing acres available for spreading and/or selling manure or identifying other marketable uses. • Evaluate fields for their potential to erode and for eroded soils to reach surface waters. • Plant cover crops especially on fields with tile drainage and/or higher potential for erosion and excessive runoff. • Consider using NRCS' Phosphorus Index to evaluate fields that may require additional practices to prevent phosphorus transport to surface water via runoff, erosion, leaching and through subsurface tile drainage.

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Chapter 3 Appendix Part B: Implementation Considerations (Nutrient Management)

Introduction

Nutrient management is a source control practice, and its effectiveness primarily relies on applying nutrients in amounts that can be used by crops during a growing season and at times they are most efficiently utilized. Effective nutrient management also requires applied nutrients to be in a form that can be used by plants or will become plant available when needed and for those nutrients to be placed in a manner that promotes efficient use while limiting losses to the environment.

Nutrient Management in Washington State

Nutrient management (NRCS CPS 590) is key in Washington state for maintaining water quality and ecosystem health and is also widely applied to save costs for on-farm operations. In some cases, such as licensed cow dairies, Nutrient Management Planning is required as a condition of licensing (NMP Fact Sheet: Washington[10]). Nutrient Management Plans are highly site-specific and dependent on the type of agricultural or livestock operation. As such, there is no one-size-fits all approach for the state of Washington. However, there are commonly used components and processes of Nutrient Management Planning that are highlighted and described throughout this chapter, including nutrient budgeting, planning for precision nutrient application, and application of manure. The following topics are described in this implementation section:

Table 11: Topics and sub-topics described in the implementation section of this chapter.

Overarching Topic	Sub-Topics in this chapter
Nutrient Management Planning	Soil testing and manure/organic solid sampling for nutrient budgeting
Precision Nutrient Application	Soil grid sampling and yield mapping for precision nutrient application; Variable Rate Application
Manure Application	Injection and broadcasting for manure application

[10] https://nationaldairyfarm.com/wp-content/uploads/2021/09/NMP-Fact-Sheet-Washington.pdf

Costs and Benefits Associated with Nutrient Management

There are monetary and time costs associated with Nutrient Management on farming systems. Costs may include equipment for nutrient application, laboratory fees, equipment costs for nutrient mapping, and ongoing costs of software, among others. However, Nutrient Management Planning has many benefits to farming operations, in addition to environmental benefits.

- **Cost savings from reduced use of nutrients:** By managing and applying the most optimal amount of nutrients via fertilizer and other sources to reduce loss, producers ultimately buy, pay, and use less thereby resulting in cost savings.
- **Potential increases in livestock sizes or crop returns:** Improved nutrient management can lead to improved forage production, quality, and storage, all of which can lead to increased crop returns and livestock health. A case study in Homer, New York found that farms saw an increase in animal numbers, milk per cow, total milk sold and decreases in purchased feed costs as a result of improved nutrient management (Tylutki et al. 2004).
- **Enhanced monitoring of plant health:** For tree fruit producers, leaf tissue sampling as part of nutrient management planning is one of the most validated indicators of nutrient status and is also cost effective (Sallato 2021).
- **Reduced nutrient runoff and erosion:** In some cases, improved nutrient management has been found to reduce erosion and the associated nutrient runoff through improved plant health (Darby et al. 2015).
- **Environmental benefits:** Including reduced risk of pathogen transfer to surface and ground water, emissions of objectionable odors, emissions of greenhouse gases, and emissions particulate matter, and particulate matter precursors (NRCS 2019).

Ultimately, nutrient management planning can be right-sized and specific for producer’s needs, making it an adaptable and effective practice that is well-tailored to providing a range of benefits.

Barriers to Implementation

There are a few barriers to effectively implementing nutrient management. Weather considerations may inhibit sample collection at required times. Second, nutrient management plans often require frequent updates to remain effective and relevant. Third, it may be an initial high cost for laboratory analysis of samples and/or equipment and software.

Even though nutrient management has been shown to reduce fertilizer costs, the cost of fertilizer fluctuates quite frequently and dramatically. As a result, there may not be an initial savings because the total cost may be the same for required fertilizer and nutrients. However, the total amount of nutrients applied is generally reduced and does ultimately save money (Darby et al. 2015).

Nutrient Management Planning for Clean Water

The amount, timing, source and placement of nutrients is highly crop specific; however, information needed to make crop specific nutrient management decisions are common among most cropping systems. Below is a list of the key components of nutrient management that should be included in the implementation section of Chapter 3 along with additional application methods that support high-level management of nutrients and prevent excessive losses to the environment.

Nutrient Budgets

Nutrient budgets are planned rates (amounts) of nutrients that will be applied to meet crop need, and typically include nitrogen, phosphorus, and potassium, among others as needed. A nutrient budget balances nutrients applied from products such as organic manures and inorganic fertilizers with crop requirements and are based on realistic yield goals. Realistic yield goals and anticipated crop harvest are based on historical yield data, soil productivity information, climatic conditions, nutrient test results, level of management, and local research results considering comparable production conditions. Crop nutrient use estimates are typically based on land-grant university guidance or other industry-based information.

Nutrient budgets designed for precision nutrient management include each nutrient being variably applied. The budget considers all nutrient sources to be applied such as animal manures, organic by-products, wastewater, and irrigation water. The budget is then the nutrient application prescription (recommendation) used by the applicator to apply the nutrients. Budget documentation includes application prescription maps for each nutrient variably applied detailing the target rates to be applied.

Nutrient budgets should be assessed annually, and typically include conduction of soil sampling, manure/organic material nutrient sampling, and plant tissue sampling. There can be a range of methods utilized to establish a nutrient budget. Here, we highlight two sampling methods which can inform nutrient budgeting, including soil sampling and plant tissue sampling. Using both methods together can improve the predictability of phosphorus and potassium available to plants (Silveria et al. 2011). While soil testing can be done any time of the year, it is recommended to be done at the same time year-to-year. The timing of plant tissue sampling is crop specific. Plant maturity stage and timing can greatly affect plant nutrients, and samples should be taken when the plant is actively growing.

Table 12: Implementation information for key components of nutrient budgeting, including soil analysis, manure/organic material nutrient sampling, and plant tissue sampling.

<table>
<tr><th>Considerations</th><th>Details</th></tr>
<tr><td>Soil and Tissue Sampling</td><td>

Soil test must include an analysis of pertinent soil conditions and nutrient content for developing or amending the annual nutrient budgets.
The number of soil samples required per acre depends on the diversity of soil types and topography and on the history of previous nutrient applications (NRCS 2003).Manure/Organic Material Nutrient Sampling
Seasonal variation and management can affect the nutrient composition of manure. Manure stored in barns as bedded pack or litter or stored in covered stacks is typically not affected by weather, but there is often variation in nutrient content throughout the manure based on the uneven mixing of bedding, hay, and/or spilled feed. (Beegle and Martin 2014)
Recommended to sample during loading of manure application equipment or in the field as manure is being spread (Beegle and Martin 2014).
Single liquid manure source can have a large variation in nutrient content if not agitated and mixed before spreading (Beegle and Martin 2014).
Most labs have a basic manure test package with options to add other tests for an additional fee. The following should be included as a minimum for nutrient management planning: Percent moisture or percent solids; total N, P, and K; and ammonium-nitrogen.
Other analyses that may be useful include: pH, carbon-to-nitrogen ratio, water-extractable P, calcium carbonate equivalent, secondary nutrients, and micronutrients (Beegle and Martin 2014).

Plant Tissue Sampling

Protocols for plant tissue sampling can vary between crops.
Most fruit tree species: Use Land Grant University guidance to determine the appropriate timing for plant tissue sampling.
In general, avoid being too early or too late in the growing season and sample appropriately for the plant species and growth stage.

</td></tr>
</table>

Considerations	Details
	○ Aim to diversify your sampling – multiple areas within a given field. • There are multiple laboratories that can do plant tissue analyses in Washington and Oregon. The list of accredited laboratories is kept by the Soil Science Society of America and can be accessed here. • A complete analysis would include: Total N, P, K, S, B, Ca, Mg, Zn, Mn, Cu, and Na. Depending on soil type and limiting conditions, some analyses might be more important to monitor than others. (Sallato 2021). • May be valuable to do in conjunction with a soil sample analysis to understand what's going on in a field or plot.
Capital Cost	Soil Sampling • Costs will vary based on the type of testing conducted. Basic soil test (e.g. pH, N, P, K) can range from$20 - $40. Tests that include pH, N, P, K and key secondary and micronutrients and soil organic matter can range from $90 - $130 per sample (Colorado State University, 2024; HomeGuide, 2024). Manure/Organic Material Nutrient Sampling • Cost includes laboratory analysis costs and transfer costs. A NRCS document from 2003 assumed a price of $50 per sample though this is likely out of date (NRCS 2003). Plant Tissue Sampling • $20 - $50 per sample, depending on the laboratory Other added costs from nutrient management planning • On farm transport costs including those associated with additional acres required manure application • Land application costs • *Total estimated cost (NRCS 2024):* $2,898 annually for an HU planning livestock with less than 300 AU to $10,619 for planning for a dairy greater than 700 AU with land
Operational and maintenance requirements and costs	Ongoing costs and activities to update budgets
Technical Requirements	Soil analysis

Considerations	Details
	• Step 1: Find or select a soil testing lab via your local NRCS office or Extension office • Step 2: Acquire clean materials to collect samples, including pail, soil sampling tube, auger or spade, large paper or plastic bag to hold 15 – 20 soil cores or sub-samples, and sample bag/box from the soil test lab. • Step 3: Collect sample • Avoid farm lanes and field borders, fertilizer bands in crop rows, any area that is very different from the rest of the field (NRCS 2022) • Follow Pacific Northwest Land Grant University sampling, handling and testing procedures that are regional and crop appropriate. Manure/Organic Material Nutrient Sampling • Follow individual lab requirements for sampling. • Manure samples should be taken with clean steel or plastic shovels, scoops, or cups and placed in a clean five-gallon plastic bucket to make composite samples. • Use nonreactive materials, such as stainless steel and plastic and thoroughly clean between samples to prevent contamination. Do not use galvanized containers. • Composite samples should be sent to the lab in plastic bottles (liquid and solids) or one-gallon heavy-duty zip lock bags for dry material like broiler litter. Do not use glass containers as they are more likely to break during transportation. • Other required equipment (depending on methods): Tarps, piece of plywood, or solid manure sampling probe. Ice chests should be used in warm weather to keep samples cool during the process (Beegle and Martin 2014). Plant Tissue Sampling • For fruit trees, it is recommended to collect 50 leaves maximum over 10 acres if the block is fairly homogenous. Do not mix species, cultivars, young and old blocks. • Do not sample from too old or too young leaves, too vigorous or weak shoots, or dirty tissue that show things like insect or bird droppings. • Samples should be collected at least 15 days after a foliar nutrient spray or at least take the spray into account when reviewing results.

Considerations	Details
	• Samples should be collected in paper bags to avoid condensation and kept cool. Label each sample according to laboratory requirements and submit within 24 hours of sampling (Sallato 2021).
Lifespan	• Nutrient budgets should be assessed annually. • Manure/Organic Material Nutrient Sampling: The need for manure/organic material testing is determined by the timing of manure application to the land, which is in turn influenced by manure storage capacity. Frequency of sampling varies according to types of manure handling systems. For example, farms handling manure as a solid, manure application is assumed to occur twice a year (180 days of storage)
Other Implementation Factors	• Plant tissue analysis can account for the plant-available nutrient pools present at multiple soil depths.

Precision Nutrient Application for Clean Water

There are many forms of crop nutrients, and these nutrients can be applied in a variety of ways depending on factors such as fertilizer type, tillage and planting techniques used, and when nutrient are applied, and these factors are often crop specific. Precision nutrient application expands on common methods of nutrient applications and allows producers to fine tune nutrient applications within a field to best match realistic yield expectations with the amount of nutrients applied.

To conduct precision nutrient application, information needs to be collected to determine how much nutrients to apply and where. Yield mapping and soil grid sampling are two common inputs to determine nutrient application methods and implementation info is expanded upon below. In both cases, NRCS (2010) states that “the most important aspect to precision agricultural technology is evaluation and assessment of results after implementing each year.” (NRCS 2010[11])

Yield Mapping

Yield mapping is a process of collecting georeferenced crop yield data within fields. Yield maps can identify low and high yield areas, and this information can be used to make management changes, so nutrients are applied where most needed and most likely to be utilized. For example, during harvest producers can accurately view, map, and record crop yield and

[11] https://www.nrcs.usda.gov/sites/default/files/2022-10/AG_TechNote_3_Precision_Nutrient_Management_Planning_2010.pdf

moisture data in real-time to instantly understand how well crops performed. Assessing crop yield information can help producers improve nutrient management and supports other types of precision agriculture such as variable rate nutrient application.

Soil Grid Sampling

Traditionally, soil sampling is conducted in a way that determines the average nutrient status of a field as a whole and provides limited information about nutrient variability within a field. Grid sampling has similar objectives to traditional sampling but at a finer scale. Instead of understanding the nutrient status of a field, grid sampling provides information about areas with fields which gives producers the ability to relate trends in soil fertilizer levels to other field properties including yield and is necessary for precision agriculture approaches such as variable rate application technology. Cell Sampling and Point Sampling are closely related and fall under the collective title of Grid Sampling (Clemson[12])

Table 13: Implementation information for key components of precision nutrient application.

Considerations	Details
Soil Mapping and Grid Sampling	Yield Mapping • Yield data should be collected on a field basis or on a management zone basis. When a GPS-guided yield monitor is being use, the yield data are mor precise – it collects and tracks data that detail field variations (Casady et al. 1998). • Yield data is collected at each harvest and incorporated as another layer for a precision management plan. • Data collected is downloaded and imported into an appropriate software package. • Yield data post processing will be developed into maps with color-coded displays of the classes, ranges, or counts of yield values within the fields. • Results from soil tests can be displayed on yield maps to aid interpretation. • Yield maps provide a permanent visible record of harvest yields but variability from a single year does not provide enough info to determine long-term trends in productivity. Variables such as soil fertility, rainfall and weed pressure need to be considered (Casady et al. 1998).

[12] https://lgpress.clemson.edu/publication/precision-agriculture-based-soil-sampling-strategies/

Considerations	Details
	• Yield monitors consist of: Mass flow sensors, moisture centers, and a DGPS (USDA 2023). Yield monitoring can be used to identify where chemical inputs are most efficient. Soil Grid Sampling • Consider soil sampling (versus management zone sampling) if previous management significantly altered soil nutrient levels through confined livestock, heavy manure application, aggressive leveling for irrigation or other means; Small fields with different cropping histories have been merged into one; or an accurate base map of soil organic matter is desired. • Optimum grid density depends on the site and on the nutrient(s) of interest (Ferguson and Hergert 2009). • Any VRT applications of fertilizer or lime can potentially change patterns of nutrient levels or soil pH over time. Lime applications should amend soil pH for 8-10 years, so it is not necessary to grid-sample for pH for 8-10 years (Ferguson and Hergert 2009) • Grid sampling for nitrate is not recommended due to annual fluctuations in nitrate levels. Nitrate sampling can instead be done on a directed sampling basis (Ferguson and Hergert 2009). Digital Soil Mapping • Digital soil mapping is a relatively new tool - it involves creating geographically referenced soil databases and enabled by soil maps maintained by the USDA NRCS. However, these maps are not as dynamic and localized as other mapping and sampling options (USDA 2023).

Capital Cost	Yield Mapping
	• Yield monitoring equipment costs can range between $5,000 and $15,000 depending on the brand, complexity, and features.
	  ○ USDA (2023) found that equipment replacement for yield monitors ranged from approximately $8000 (for soybean operations) and $13,775 (for cotton operations).
	• Yield monitoring system software to develop maps can range from $500 to $1,000 for packages.
	  ○ USDA (2023) found that annual fees (i.e., subscriptions for software and effective use of technologies) were approximately $1,000 (for soybean operations) and on average $1,772 (for cotton operations)

Considerations	Details
	• Many yield monitoring equipment manufacturers include a free year or more of the software needed to develop mapping Soil Grid Sampling • $8 - $16 per sample depending on the size of grids and laboratory/service provider.
Operational and maintenance requirements and costs	Yield Mapping • Maintenance of yield monitors according to manufacturer recommendations • Data management and elimination of outlier data as needed (Franzen et al. 2018) Soil Grid Sampling • Regular updates and maintenance as required to keep up to date maps for precision agriculture.
Technical Requirements	Yield Mapping • Accurate yield mapping requires a yield flow sensor, a moisture sensor, header position sensor, Differential GNSS receiver, ground speed sensor, and computer display or field console. • To produce yield maps, yield data is needed through a yield monitoring system tied to a GPS (Franzen et al. 2018). Soil Grid Sampling • Regardless of which Soil Grid Sampling method is selected, samples should be taken after harvest and as close to the next planting as possible (Farmaha et al. 2020). Point Sampling • Samples are collected from the center of each grid square and mixed in a 5-gallon bucket as a subsample for analysis. Alternatively, samples can be taken at the intersection of the grid line. For the second method to be effective, samples should be collected between 100 – 200 ft apart. (Farmaha et al. 2020) Cell Sampling • Density: One sample per 1-2.5 acres is recommended. The number of samples needed is typically based on in-field variability rather than historical management (Ferguson and Hergert 2009). Sampling density less than 2.5 samples per acre will limit confidence of nutrient maps. • Sampling Pattern and Depth: Offset grid pattern are recommended to provide more information at a lower cost.

Considerations	Details
	Collect 4-5 cores in a radius of 8' – 10' of the grid point to a depth of 8". Grid point should represent the central position of the composited sample. Sampling in a tight radius about grid points is preferred to more dispersed.
	Yield Mapping • Yield mapping can be used year by year, but building multi-year maps is often considered more meaningful. Meaning, data should be collected every year (Franzen et al. 2018) Soil Grid Sampling • If collecting one sample per acre, the data should be sufficient to maintain a map of soil organic matter and cation exchange capacity for 10-20 years; pH for 5-10 years; and phosphorous, potassium, and zinc for 4-5 years.
Land Area Requirements	Both yield mapping and soil grid sampling use the whole field, either in grids to take core samples or during harvest.

Variable-rate nutrient application (VRA)

VRA is a precision agriculture technique that enables farmers to apply different rates of fertilizer, seed, and other inputs at different rates in locations across a field. Utilizing data such as soil grid sampling and yield monitoring results, farmers can adjust the amount of fertilizer they apply in different areas of a field to increase nutrient use efficiency and avoid over-fertilization. VRA technology can help improve crop yields, reduce fertilizer costs, and minimize environmental impact (NRCS 2020).

Table 14: Implementation information for variable-rate nutrient application.

Considerations	Details
Applicability	For VRA, yield monitoring systems are not realistic in pastures – producers should use soil data and soil test results to develop nutrient prescriptions (NRCS 2020)
Capital Cost	• Costs associated include soil sampling, development of site-specific maps and soil analyses. The total cost will vary based on the number of cells in a grid and soil analysis costs. Basic soil tests analyses range from \$20-\$40 per sample. • Custom variable rate application of fertilizer: \$6 - \$10 per acre (Paxton and Morris 2006; Ward et al., 2024) • Yield monitor: \$3 - \$4 per acre (Paxton and Morris 2006) A 2020 survey in the Great Plains found that VRA costs a premium of \$1.52 to \$1.91 per acre for application of dry and liquid fertilizer compared to solid uniform rate application. Rental rate of VRT

Considerations	Details
	equipment for liquid application was $1.17 over the average rental fate for uniform rate technology (USDA 2023).
Operational and maintenance requirements and costs	Application from VRA will have an electronic or “as-applied” maps for maintenance and record keeping – all recordkeeping information for nutrient sources need to meet the CPS Code 590 (NRCS 2010).
Technical Requirements	• VRA technology can be map-based, sensor-based, or manual. VRA requires site-specific production maps using soil data, soil test results, or yield mapping to determine management zones (NRCS 2020). • Yield goals developed through nutrient management depend on the ability of VRA equipment (NRCS 2010).
Lifespan	• N that is applied using VRA should be tested each year when an annually planted crop is produced (NRCS 2010) • P and K may be completed once every 3 years after a baseline or consistent data based is established (NRCS 2010).
Land Area Requirements	Not applicable
Other Implementation Factors	Though the cost of VRA may come at a small premium, reports show cost savings related to reduced use of fertilizer costs of up to 4% (Griffin and Traywick 2020).

Manure Application for Clean Water

Solid and liquid manures are typically applied to cropland via broadcasting, broadcasting with incorporation and injection. Broadcasting manure onto the surface of a field is a simple and inexpensive method but leads to significant nitrogen losses to the atmosphere via ammonia volatilization. Incorporation of broadcast nutrients reduces gaseous losses of nitrogen and increases the amount of crop available nitrogen in the year it is applied. However, it requires tillage and may not fit with all agricultural systems. Manure injection is used to apply liquid manure below the soil surface which reduces ammonia volatilization losses and increases the amount of available nitrogen in the year it is applied.

Broadcasting as a manure application method is most common but is most likely to lead to nitrogen volatilization after just a short time. While not the most recommended practice, it does allow for irrigation at the same time as nutrient application and may not disturb perennial crops. An alternative to traditional broadcasting for use with perennial crops is aeration and injection at the same time.

Injection and broadcast with incorporation are the most effective manure application methods for limiting ammonia volatilization and ensuring applied nutrients are available in the planned crop year.

Table 15: Implementation information for manure injection.

Considerations	Details
Applicability and Considerations	• Injection can be used by all livestock operations that produce liquid manure or compost and poultry operations that produce dry litter with a moisture content less than 25% (Leytem et al. 2012). • Manure should not be applied if a storm event is forecasted within 24 hours (NRCS 2019)
Cost	Drag Hose Method • \$140,000 for equipment (Leytem et al. 2012) • \$0.01 - \$0.015 per gallon for application up to one mile from wastewater pond or lagoon (Leytem et al. 2012) Slurry tank wagon • Cost of additional fuel and labor
Operational and maintenance requirements	• Any maintenance needed on the tractor and manure applicator, and tillage implement being used (Leytem et al. 2012) • Maintenance on drag hose system, including the pumps and hoses (Leytem et al. 2012)
Technical Requirements	• Soil-engaging components include chisel or sweep injectors, dis-type applicators, coulter-type applicators, among others. • When applying manure, it is important to consider precipitation and to apply at a time when rain or other precipitation is not forecasted. • If applying in row-crop systems, tire spacing of equipment should be adjusted to conform to plant row spacing wherein the tires are centered in the rows (Shelton 2012). • Liquid and solid manures should be deposited 3" – 6" below the soil surface – for liquid manures, this can be accomplished via shank injection or with a system combining tillage to incorporate manures. Solid manure can be deposited with a device developed by the Agricultural Research Service called a "subsurfer" (Leytem et al. 2012) • A solid trench is created in the soil, manure is placed in the trench, and then the soil is replaced to close over the manure (Leytem et al. 2012).

Considerations	Details
	• Plug or spike aerators, seed bed conditioners, and vertical till may be used from incorporation (NRCS 2016) • Manure should be applied on the contour as opposed to the uphill and downhill to reduce potential soil erosion and runoff of manure (Shelton 2012)
Lifespan	Not applicable
Land Area Requirements	Not applicable

Table 16: Implementation information for broad application of manure.

Considerations	Details
Considerations	• Placement of broadcast manure is essential, and less nutrient loss occurs when incorporated. • If broadcasting is the method used for manure spreading, it should be incorporated within 12 - 24 hours to retain nitrogen and reduce volatilization. Most inorganic nitrogen will volatize as manure dries within 5 days (NRCS 2023) • For broadcast recommendations based on soil testing results, see NRCS 2023.
Capital Cost	• Equipment: Rental for a manure spreader at Pierce Conservation District costs \$60 -\$70 • Dragline application: 1,000 gallons at \$10- \$15 • Costs depend on farm characteristics, such as the travel path to the field, and the amount of distance for hauling
Operational and maintenance requirements and costs	• Ongoing sampling as needed to determine nutrient needs and regular maintenance of broadcasting and incorporation equipment.
Technical Requirements	• Most solid manure (20% or more solids) is broadcasted using equipment. • Following broadcasting, tillage is utilized to incorporate the material into the soil. • Broadcasting can technically be done during any season, however, there can be limitations based on local weather patterns. Spring application is considered best for conserving nutrients and reducing likelihood of runoff (Fulhage 2018).
Lifespan	Not applicable
Land Area Requirements	Not applicable

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