Standard Operating Procedures for Tracking & Accounting of Agricultural Conservation Practices

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Conservation Crop Rotation	Land that is managed to change crop types cyclically over time with the intention of reducing soil erosion and/or improving long-term soil health and quality, typically between an annual crop (e.g., corn, soybeans) and a perennial crop (e.g., hay). May involve change from continuous cropland to crop rotation or extending duration of perennial crop in existing crop rotation. Strip cropping involves planting different crops in alternate strips to prevent soil erosion on slopes.	Field land use (default Cropland WA) Practice acres HUC12 watershed location Field HSG type (optional) Field average slope (optional)	Practice acres	25%
Conservation Tillage	Any tillage and planting system that leaves a minimum of 30% of the soil surface covered with plant residue after the tillage or planting operation (e.g., reduced till, no-till). For silage corn, this could involve required application of a cover crop or use of strip-till, zone-till or minimum tillage equipment.	Field land use (default Corn WA) Practice acres HUC12 watershed location Field HSG type (optional) Field average slope (optional)	Practice acres	20% used if no slope or HSG data
Cover Crop	Establishing a seasonal cover on annual cropland for soil erosion reduction and conservation purposes. Seasonal cover consists of a crop of winter rye or other herbaceous plants seeded at a minimum rate of 100 lbs/ac or at the highest recommended rate to provide effective soil coverage. When categorized as nurse crop, accounted for as cover crop, but typically used to begin crop rotation and often accounted for as a system with crop rotation.	Field land use (default Corn WA) Practice acres HUC12 watershed location Field HSG type (optional) Field average slope (optional)	Practice acres	28%

Practice Type	Practice Definition & Standards	Data Requirements	Area Treated Definition	TP Load Reduction Efficiency
Crop to Hay	Conversion of cropland to hay. Typical Crop to Hay duration 5 years.	Field land use (default Cropland WA) Practice acres HUC12 watershed location Field HSG type (optional) Field average slope (optional)	Practice acres	70-80% depending on slope No slope data: 80%
Manure Injection	Mechanical application of organic nutrient sources (e.g., manures, composted materials) into the root zone with surface soil closure or minimal soil disturbance at the time of application.	Field land use (Cropland WA or Pasture; default Cropland WA) Practice acres HUC12 watershed location Field HSG type (optional) Field average slope (optional)	Practice acres	40%
Manure Incorporation	Mixing of organic nutrient sources (e.g., manures, composted materials) into the soil profile within 72 hours of manure application.	Field land use (default Cropland WA) Practice acres HUC12 watershed location Field HSG type (optional) Field average slope (optional)	Practice acres	23%
Grazing Management	A range of pasture management and grazing techniques to improve the quality and quantity of the forages grown on pastures and reduce the impact of animal travel lanes, animal concentration areas or other degraded areas. Pastures are required to have a vegetative height of 3 inches or greater.	Field land use (default Pasture; Cropland WA eligible for NRCS only) Practice acres HUC12 watershed location Field HSG type (optional) Field average slope (optional)	Practice acres	24%

Practice Type	Practice Definition & Standards	Data Requirements	Area Treated Definition	TP Load Reduction Efficiency
Grassed Waterways	Stabilizing areas prone to field gully erosion by establishing grass-lined swales.	Field land use (default Cropland WA) Practice acres HUC12 watershed location Field HSG type (optional) Field average slope (optional)	5x buffer acres	20-50% depending on slope and HSG 36% used if no slope/HSG data
Forested Riparian Buffer	Areas of woody vegetation (shrubs and trees) located adjacent to surface waters that filter out pollutants from runoff. Minimum 25-foot width, no manure application, no gully erosion or channelized flow.	Field land use (Cropland WA or Pasture; default Cropland WA) Buffer acres HUC12 watershed location Field HSG type (optional) Field average slope (optional)	5x buffer acres	40% plus loading reduction from converting land to forest
Filter Strip Riparian Buffer	Areas of grasses or hay located adjacent to surface waters that filter out pollutants from runoff. Minimum 25-foot width, no manure application, no gully erosion or channelized flow.	Field land use (Cropland WA or Pasture; default Cropland WA) Buffer acres HUC12 watershed location Field HSG type (optional) Field average slope (optional)	5x buffer acres	40% plus loading reduction from converting land to grass/hay
Livestock Exclusion	Exclusion of livestock from surface waters by installing fence or another barrier, such as a forested riparian buffer.	Acres of pasture excluded HUC12 watershed location Field HSG (optional) Field average slope (optional)	Practice acres If resulting from buffers, 5x buffer acres	55%

Practice Type	Practice Definition & Standards	Data Requirements	Area Treated Definition	TP Load Reduction Efficiency
Production Area Compliance	Exclusion of clean water runoff from the production area and management of the remaining runoff in a way that minimizes its pollution. This involves complete containment and/or control and management of all wastes, including covered barnyards and/or diversion of runoff/silage waste to manure storage facilities. Production area includes barnyards, heavy-use areas, waste storage, feed storage, and access roads. Phosphorus reductions estimated based on compliance status as assessed via AAFM inspections.	Production area acres Water quality/premises ID Size operation of premises Compliance status Date of inspection HUC12 watershed location	Production area acres	80%
Nutrient Management	Management of the rate, source, placement, and timing of plant nutrients and soil amendments to minimize the environmental impacts of agricultural operations. For the purposes of TMDL tracking and accounting, nutrient management is defined as the verified documentation and implementation of a field-by-field nutrient management plan (NMP) consistent with the requirements of the USDA NRCS Nutrient Management Practice Code 590.	Field land use (Cropland WA or Pasture; default Cropland WA) Practice acres HUC12 watershed location Field HSG type (optional) Field average slope (optional)	Practice acres	5%

Introduction

While many of Vermont's surface waters are high quality, several surface waters suffer from non-point source pollution. The State of Vermont is covered by several large scale Total Maximum Daily Load (TMDL) plans that identify pollutant reductions required for an impaired waterbody to meet the State of Vermont's water quality standards. The Lake Champlain and Lake Memphremagog TMDLs target phosphorus pollution to address cyanobacteria blooms, while the five-state Long Island Sound TMDL targets nitrogen pollution causing hypoxia in the Sound.

The US Environmental Protection Agency (EPA) approved the Phosphorus TMDLs for the Vermont Segments of Lake Champlain in 2016 (US EPA 2016). The TMDL Accountability Framework requires the State of Vermont to track investments and progress towards achieving TMDL targets. The Vermont Clean Water Act (Act 64 of 2015) and Clean Water Service Delivery Act (Act 76 of 2019) both establish funding for clean water efforts and require that the state government track and report on all clean water projects across land use sectors. Act 76 of 2019 also requires the state to publish methods for estimating phosphorus reductions for all clean water project types in the Lake Champlain and Lake Memphremagog basins to inform formula grant development for clean water service providers.

The Vermont Agency of Natural Resources Department of Environmental Conservation (DEC) is leading the effort to develop and implement methods for tracking nutrient load reductions relative to TMDL targets. For the agricultural land use sector, DEC collaborates closely with the Vermont Agency of Agriculture, Food and Markets (AAFM), US Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS), and US EPA to develop and implement methods for tracking nutrient reductions from agricultural conservation practices. Together, these agencies form the Vermont Agricultural Tracking and Accounting Workgroup (hereafter, the Workgroup).

The purpose of this document is to outline the current methods used to track and account for total phosphorus load reductions from agricultural practices in the Lake Champlain and Lake Memphremagog watersheds. Total phosphorus load reductions cannot yet be estimated for practices outside of the Lake Champlain and Lake Memphremagog basins. Methods for estimating total nitrogen load reductions in the Connecticut River watershed draining to the Long Island Sound have not yet been developed.

This document is intended to be updated as new information becomes available or if new research is conducted. DEC plans to review methods in this document for accuracy at least every five years but it could be updated more frequently. All methods are subject to change.

TMDL Tracking & Accounting

Practice Tracking

Agricultural conservation practices are implemented through numerous technical, financial, and regulatory programs administered by several agencies and organizations, including:

1. USDA Natural Resources Conservation Service (NRCS)
2. Vermont Agency of Agriculture, Food and Markets
3. Vermont's Natural Resources Conservation Districts (NRCDs)
4. Vermont Housing and Conservation Board (VHCB)
5. University of Vermont (UVM) Extension
6. Lake Champlain Basin Program (LCBP)

The Agricultural Partner Database, managed by AAFM, centralizes practice implementation data resulting from agricultural conservation programs (e.g., state-funded grants and cost-share programs), as well as independently funded conservation practices (i.e., farmer funded practices). Data housed in the Partner Database include practice type, status, location, area, and install date.

NRCS agricultural practice data cannot be included in the Partner Database due to federal data sharing restrictions. As a result, NRCS reports practice data with personal identifiable information removed separately to DEC. To avoid duplicate reporting of practices with cost-share from both state and federal funding programs, a geospatial overlay of these datasets is completed annually to identify duplicates. Duplicate practices are identified based on the following three criteria:

1. NRCS and AAFM practices occur on the same field, as identified via geospatial overlay by NRCS personnel
2. NRCS and AAFM practices occur during a similar timeframe of less than or equal to 90 days based on installed/applied dates, and
3. NRCS and AAFM practices have matching practice codes (a practice crosswalk is done prior to ensure relevant practices will be matched).

All potential duplicates are identified in the Partner Database dataset submitted to DEC. DEC removes the duplicates from the AAFM dataset so that only the NRCS data are included in TMDL reporting.

Agricultural technical assistance providers, such as UVM Extension and Natural Resources Conservation Districts, may collect practice data during technical assistance visits with farmers. Technical assistance providers may gather and enter practice data in the Partner Database where practices are not funded through state or federal programs. Third-party practice data collection by technical assistance providers must be conducted in compliance with AAFM's third-party quality assurance project plan (QAPP) (VT AAFM, 2019).

AAFM and NRCS submit agricultural practice data to DEC annually for legislative and EPA reporting. AAFM also provides DEC with financial data for state-funded grants and cost share programs, as well as regulatory program data to DEC for phosphorus accounting. DEC compiles and manages all clean water project data tracked through state and federal funding and regulatory programs using the Clean Water Reporting Framework (CWRF). CWRF also contains Vermont's Best Management Practice (BMP) Accounting and Tracking Tool (BATT), which is used to estimate total phosphorus load reductions associated with the implementation of various clean water projects.

Limitations

Limitations of practice tracking for TMDL reporting include the following.

1. AAFM and NRCS cannot provide DEC with the specific locations of agricultural practices due to state and federal statutory privacy restraints. As a result, DEC only receives the HUC12 watershed (i.e., sub-watershed hydrologic unit code) location of each agricultural practice. For practices crossing HUC12 boundaries, AAFM assigns the practice to the HUC12 majority area, and NRCS assigns the HUC12 based on field center. This approach provides DEC with sufficient data to estimate pollutant reductions while maintaining privacy of farmers participating in cost-share programs.
2. Production area compliance is the only regulatory agricultural data included in TMDL reporting. The Workgroup plans to expand regulatory tracking mechanisms for TMDL reporting in order to capture the universe of practices installed to comply with Required Agricultural Practices (RAPs) that were not funded by state or federal funding or cost-share programs.
3. NRCS does not currently provide DEC with financial data from federally funded grants and cost-share programs, but there is interest in reporting these data in the future considering federal agricultural practices account for the majority of progress towards achieving the Lake Champlain TMDL.

Phosphorus Accounting

Clean water projects target nutrient and sediment pollution to waterbodies and improve water quality over the long term. While measured water quality parameters are the ultimate indicator of progress, it will take time for Vermont's waters to realize the benefits of clean water projects. To provide incremental measures of accountability, DEC estimates the pollutant reductions associated with clean water projects installed across state and federal funding programs and regulatory programs in Vermont.

Total phosphorus load reduction is estimated based on the clean water project type, as measuring phosphorus load reductions at the project level through water quality monitoring would be cost-prohibitive and very challenging to conduct in a scientifically robust manner at most sites. Most clean water project phosphorus load reduction estimates are based on the following:

1. **Estimated baseline total phosphorus load from land treated**, prior to treatment by a practice. This is based on the area of land draining to the practice, or the practice area, and the average phosphorus loading rate from the land use. Baseline phosphorus loading rates for each land use, soil type, and slope combination are obtained from the TMDL Soil Water Assessment Tool (SWAT) model results (Tetra Tech 2015a).

2. **Estimated annual phosphorus reduction performance** – referred to as an "efficiency" – of the practice type. This is often expressed as a percent of total phosphorus load reduced and is based on research of practice performance relevant to conditions in Vermont.

Phosphorus load reductions are the product of the baseline phosphorus load for the area treated by the practice and the practice phosphorus reduction efficiency (Figure 1). The phosphorus load reduction efficiency is applied starting on the practice implementation date and continues for the expected design life of the practice. Once the lifespan expires, the practice no longer receives credit unless the practice is verified to be extended. Results of accounting methodologies should only be referred to as "total phosphorus load reduction estimates" because phosphorus load reductions were not directly measured.

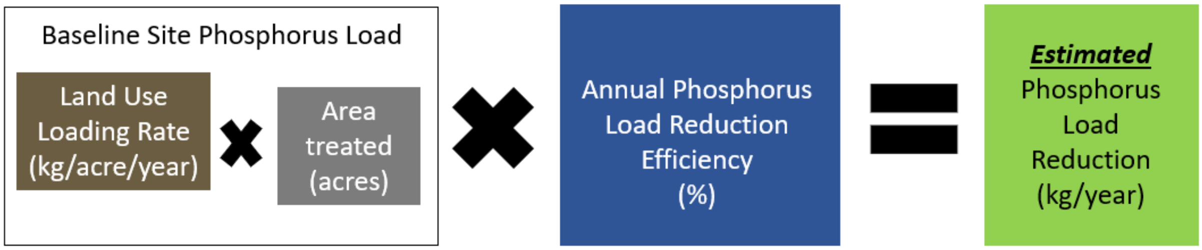

Figure 1. General methodology used to estimate phosphorus reductions from agricultural practices.

Weighted Average Loading Rates

The Lake Champlain TMDL Soil Water Assessment Tool (SWAT) model, which was used to determine baseline and target phosphorus loading to Lake Champlain, contained the following agricultural loading rate categories with individual loading rates for combinations of drainage area, hydrologic soil group, and slope (Tetra Tech, 2015a):

- Generic agricultural land
- Corn-hay rotation on clayey soils
- Corn-hay rotation on non-clayey soils
- Continuous corn on clayey soils

- Continuous corn on non-clayey soils
- Continuous hay
- Pasture
- Farmstead small
- Farmstead medium-large
- Mixed forest
- Evergreen forest
- Deciduous forest

DEC developed two new area weighted and weighted average (WA) loading rate categories for agricultural land uses in the Lake Champlain basin: Cropland WA and Corn WA. These new loading rates were developed for the following reasons.

1. Align land use categories with the data inputs available from AAFM and NRCS. For example, the NRCS database reports "crop" for the land use for many practices rather than specifying the type of crop, such as continuous corn or corn-hay rotation.
2. Smooth out variability in the SWAT model and across a field or farm. The model's generalized assumptions may vary from local conditions, but variation is assumed to average out at the watershed scale.
3. Simplify the data requirements for practice tracking and accounting.

Area-weighted loading rates (kilograms per acre per year) were calculated by dividing the total phosphorus load for all the land use types defined for that weighted average by the total area of that land use for each drainage area (major river basins within each lake segment basin) within the Lake Champlain basin. Weighted averages were computed for both individual HSG and slope combinations, and also for an aggregated HSG and slope value to use when HSG and slope data are unavailable. The following loading rates are used for agricultural TMDL reporting in the Lake Champlain basin. All loading rates vary by drainage area, soil type (if available), and slope (if available).

- Cropland WA: Area-weighted and weighted average for generic agricultural land, corn-hay rotation on clayey soils, corn-hay rotation on non-clayey soils, continuous corn on clayey soils, continuous corn on non-clayey soils.
- Corn WA: Area-weighted and weighted average for continuous corn on clayey soils and continuous corn on non-clayey soils.
- Forest WA: Area-weighted and weighted average for mixed forest, evergreen forest, and deciduous forest.
- Pasture: Unchanged from TMDL model.
- Farmstead small: Unchanged from TMDL model.
- Farmstead medium-large: Unchanged from TMDL model.

The Lake Memphremagog TMDL model included the following agricultural loading rate categories with individual loading rates for each drainage area (VT DEC, 2017). Loading rates in the Lake Memphremagog TMDL were not broken out by slope as they were in the Lake Champlain TMDL, and only corn was broken out by soil group.

- Continuous corn on clayey soils
- Continuous corn on non-clayey soils
- Continuous hay
- Pasture
- Farmstead medium-large

As for the Lake Champlain basin, simplified loading rates were developed for the Lake Memphremagog basin, but there were not enough data available to develop weighted averages. The following loading rates are used for TMDL reporting in the Lake Memphremagog basin. Loading rates only vary by drainage area.

- Cropland WA: Continuous corn on non-clayey soils.[1]
- Corn WA: Continuous corn on non-clayey soils.
- Pasture: Unchanged from TMDL.
- Farmstead medium-large: Unchanged from TMDL.

Stacked Practices

When multiple agricultural practices are in effect on the same agricultural field at the same time, the practices are referred to as "stacked practices". If these practices were accounted for separately rather than as part of a stacked system, phosphorus reductions would be overestimated. To avoid overestimating phosphorus reductions, the combined practice efficiency of stacked practices is calculated by treating the stacked practices as a series (Tetra Tech, 2015b). Stacked practices can currently only be identified within the individual AAFM or NRCS datasets and not across datasets (e.g., cover crop funded by NRCS and conservation tillage funded by AAFM).[2] Field identification is done using the Field ID provided by both agencies, and common time periods are currently identified using common state fiscal years with each practice being prorated if operating for a fractional part of the state fiscal year.

The combined efficiency for multiple practices on the same field is calculated by applying one efficiency first, then applying the second efficiency to the passthrough load from the first practice using the following equation.

$$Efficiency_{Combined} = 1 - \prod_{i=1}^{n} (1 - Efficiency_n)$$

Maximum overlap of all stacked practices is assumed to produce the most conservative phosphorus reduction estimate. For example, if a field has 25 acres of cover crop and 10 acres of

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[1] Note that continuous corn on non-clayey soils is used for both Cropland WA and Corn WA in the Lake Memphremagog basin because the only options to map to Cropland WA are continuous corn or continuous hay, and continuous hay would not be an appropriate assumption for "crop" land uses reported by AAFM and NRCS.

[2] Accounting for stacked practices across AAFM and NRCS datasets is currently a gap and may result in some over estimation of load reductions. This gap will be addressed in the future.

conservation tillage, it is assumed that 10 acres of the 25 cover crop acres are on the same 10 acres as conservation tillage. As a result, phosphorus computations occur for two practice groups, as shown below:

- 15 acres of cover crop = 28% efficiency
- 10 acres of combined cover crop (28%) and conservation tillage (20%) = 42.4%
    - Combined efficiency = 1 - (1 - cover crop efficiency) (1 - conservation tillage efficiency) = 1 - (1- 0.28) (1 - 0.2) = 0.424 = 42.4%

Limitations

Other limitations of total phosphorus load reduction estimates and accounting methods include:

1. Baseline phosphorus loading rates were the result of watershed modeling and not direct loading measurements at study sites. The model's generalized assumptions may vary from local conditions, but variation is assumed to average out at the watershed scale. This supports the use of weighted average loading rates, as described above.
2. Some phosphorus load reduction efficiencies were not derived from experimental studies conducted in Vermont. Many agricultural phosphorus reduction efficiencies were derived from SWAT modeling or studies outside Vermont with different climate and/or agricultural settings. In cases where data were insufficient or conflicting, the best professional judgement of the Workgroup, as documented in this Standard Operating Procedures (SOP) or the Lake Champlain TMDL Scenario Tool report, was used to establish reduction efficiencies. In these instances, the Workgroup incorporated additional conservativeness into reduction efficiencies to avoid overestimating reductions.
3. Realized phosphorus load reductions may differ from estimated phosphorus load reductions due to climate variability (e.g., storm events) and actual practice performance and maintenance over time (e.g., gully erosion through a buffer, cover crops not established fully).
4. Agricultural tracking and accounting methods currently only consider surface total phosphorus reductions, but there may also be sub-surface total phosphorus reductions through tile drains.

Under Act 76 of 2019, DEC is required to review phosphorus accounting methods at least once every five years to confirm the appropriateness of phosphorus load reduction efficiencies and design life. DEC will collaborate closely with the Workgroup when reviewing and updating accounting methods. The methods presented below will be updated as new research or information are made available.

Delivered Load Versus Source Load

Total phosphorus loading rates and targets may be estimated as source load or delivered load. Delivered load is the mass of a pollutant after accounting for estimated pollutant storage or loss enroute to the receiving waterbody. Source load is the pollutant load from the landscape source that does not account for potential storage or loss in the watershed. As water carrying pollutants flows from its landscape source to a receiving water, some pollutants may be attenuated by nutrient uptake in plants, infiltration into soils, or settle out as it flows through inland lakes or ponds before reaching Lake Champlain or Lake Memphremagog. Therefore, the delivered pollutant load is less than at its source (i.e., source load). Delivered load is estimated based on a percent delivery rate that is applied to the source load (summarized in the tables below) and varies and depending on the distance to receiving water and obstacles in its path (e.g., inland lakes). Lake Champlain and Lake Memphremagog phosphorus TMDLs' base load and target load allocations are expressed in delivered load, reflecting total phosphorus load capacity delivered to the lakes. Estimated total phosphorus load reductions are presented as delivered load when reported/presented in the context of TMDLs' base load and target load allocations (e.g., delivered loads are typically reported in the Vermont Clean Water Initiative Annual Performance Report and the Clean Water Interactive Dashboard). However, source loading rates may be used in other applications such as Tactical Basin Planning targets and Water Quality Restoration Formula Grant targets to Clean Water Service Providers (CWSP). Loading rate tables in this document represent source load unless otherwise indicated.

Table 1. The Lake Champlain Phosphorus TMDLs' estimated total phosphorus load delivery percentages by TMDL drainage area

Drainage Area ID	Drainage Area	Champlain Segment	Delivery Percentage
1	Mettawee River	South Lake B	80.4%
2	Poultney River	South Lake B	80.4%
3	South Lake B Direct Drainage	South Lake B	80.4%
4	South Lake A Direct Drainage	South Lake A	98.8%
5	Port Henry Direct Drainage	Port Henry	99.5%
6	Lewis Creek	Otter Creek	63.1%
7	Little Otter Creek	Otter Creek	63.1%
8	Otter Creek	Otter Creek	63.1%
9	Otter Creek Direct Drainage	Otter Creek	63.1%
10	Main Lake Direct Drainage	Main Lake	87.0%
11	Winooski River	Main Lake	87.0%
12	LaPlatte River	Shelburne Bay	79.9%
13	Burlington Bay - CSO	Burlington Bay	96.8%

14	Burlington Bay Direct Drainage	Burlington Bay	96.8%
17	Lamoille River	Malletts Bay	77.6%
18	Malletts Bay Direct Drainage	Malletts Bay	77.6%
19	Northeast Arm Direct Drainage	Northeast Arm	97.4%
20	St. Albans Bay Direct Drainage	St. Albans Bay	90.5%
21	Missisquoi Bay Direct Drainage	Missisquoi Bay	89.9%
22	Missisquoi River	Missisquoi Bay	89.9%
23	Isle La Motte Direct Drainage	Isle La Motte	98.8%

Table 2. The Lake Memphremagog TMDLs' estimated total phosphorus load delivery percentages by HUC 12 watersheds.

HUC 12	Memphremagog Basin HUC 12 name	Delivery Percentage
011100000101	Black River-headwaters to Seaver Branch	91%
011100000102	Black River-Seaver Branch to Lords Creek	100%
011100000103	Lords Creek	98%
011100000104	Black River-Lords Creek to mouth	99%
011100000201	Barton River-headwaters to Roaring Brook	83%
011100000202	Barton River-Roaring Branch to Willoughby River	64%
011100000203	Willoughby River	75%
011100000204	Barton River-Willoughby River to mouth	94%
011100000301	Clyde River-headwaters to Echo Lake stream	34%
011100000302	Seymour and Echo Lakes	11%
011100000303	Clyde River-Echo Lake stream to mouth	60%
011100000501	Direct drainage-south end of Lake Memphremagog	96%

Agricultural Practice Tracking & Accounting Methods

The following section describes the current agricultural practice tracking and accounting methods for each agricultural practice type using the following format.

- Practice definition
- Practice tracking mechanisms

    - Eligible practices, identified by practice name and code
    - Funding program data collection
    - Regulatory program data collection
    - Third-party data collection
- Determination of area treated
- Baseline loading rate
- Practice efficiency
- Practice design life and lifespan

Design life is defined in Act 76 as the period of time that a clean water project is designed to operate according to its intended purpose. Phosphorus reductions are initially assigned to a project based on the project's expected design life. The **lifespan** and associated pollution reduction credit of any single project may be extended beyond the initial design life if an inspection finds the project is still functioning according to its intended purpose. A project's lifespan and associated credit ends when it is no longer functioning, and it cannot or will not be repaired to its original intended purpose.

Conservation Crop Rotation

Conservation crop rotation refers to land that is managed to change crop types cyclically over time, typically between an annual crop (e.g., corn, soybeans) and a perennial crop (e.g., hay). This may involve change from continuous cropland to crop rotation or extending duration of perennial crop in an existing crop rotation. Strip cropping involves planting different crops in alternate strips to prevent soil erosion on slopes.

Practice Tracking Mechanisms

Conservation Crop Rotation (Conservation Practice Standard 328) and Strip Cropping (Conservation Practice Standard 585) are credited under this practice category. It is important to note that Conservation Crop Rotation funded by AAFM during state fiscal years 2016 to 2021 was actually being implemented as Pasture and Hay Planting (Conservation Practice Standard 512) with a two-year lifespan rather than a five-year lifespan and has been credited under the Crop to Hay efficiency below.

The Conservation Crop Rotation standard counts cover crop as a new crop rotation, but there is no double counting with the Cover Crop practice. The efficiency for crop rotation is based on corn to hay rotation change over a longer-term basis, while the cover crop efficiency assumes the practice is seasonal. The Cropland WA loading rate also includes rotations in the aggregated loading rate to address unknowns in the baseline field land use (i.e., if putting continuous corn into a new rotation or extending an existing rotation).

Area Treated

The area treated is defined as the total field acres of conservation crop rotation or strip cropping.

Baseline Loading Rates

The default loading rate for conservation crop rotation is Cropland WA.[3] Acres of conservation crop rotation are multiplied by the TMDL-modeled land use loading rate to determine the baseload for the area treated. The baseline loading rates is based on:

1. HUC12 watershed or TMDL drainage area watershed (required)
2. Hydrologic soil group (HSG) type (if available)
3. Average field slope (if available)

Practice Efficiency

Conservation crop rotation receives a 25% total phosphorus load reduction efficiency for the Cropland WA land use (Tetra Tech 2015a, b). Land use conversions (i.e., conversion of corn to hay) are not accounted for under this practice.

Practice Design Life

The design life and associated credit assigned to conservation crop rotation is one year after the practice is implemented. The reduction credit was scaled to an annual timeframe and would not be extended beyond one year.

Conservation Crop Rotation Tracking & Accounting Summary

Table 3. Summary of data used for estimating phosphorus reductions from conservation crop rotation.

Data Required	Source
Baseline phosphorus loading rate • HUC12 watershed or TMDL drainage area • HSG type (if available) • Average field slope (if available) • Land use assumed Cropland WA	Lake Champlain TMDL SWAT model (Tetra Tech, 2015a) Lake Memphremagog TMDL model (VT DEC, 2017)

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[3] Note that the Lake Memphremagog basin does not have a corn-hay rotation land use built into Cropland WA. This means that the baseline for crop rotation in the Lake Memphremagog basin does not factor some existing crop rotation being extended and some being newly installed like in the Lake Champlain basin, meaning estimated phosphorus load reductions are less conservative in Memphremagog than Champlain.

Acres of crop rotation or strip cropping	Agricultural Partner Database & NRCS
Practice efficiency	25% (Tetra Tech, 2015a, b)
Practice design life	1 yr.

Conservation Tillage

Conservation tillage is defined as any tillage and planting system that leaves a minimum of 30% of the soil surface covered with plant residue after the tillage or planting operation (e.g., reduced till, no till) to reduce soil erosion and improve production.

Practice Tracking Mechanisms

Residue and Tillage Management – No Till (Conservation Practice Standard 329) and Residue and Tillage Management – Reduced Tillage (Conservation Practice Standard 345) are credited under this practice category.

Area Treated

The area treated is defined as the acres of conservation tillage.

Baseline Loading Rates

The default land use for conservation tillage is Corn WA. Acres of conservation tillage are multiplied by the TMDL-modeled land use loading rate to determine the baseload for the area treated. The baseline loading rate is based on:

1. HUC12 watershed or TMDL drainage area watershed (required)
2. Hydrologic soil group (HSG) type (if available)
3. Average field slope (if available)

Practice Efficiency

Conservation tillage receives a 20% total phosphorus load reduction efficiency when applied to the Corn WA land use (Tetra Tech 2015a, b). There are not separate efficiencies for reduced tillage and no till.

Practice Design Life

The design life and associated credit assigned to conservation tillage is one year after the practice is implemented. The reduction credit was scaled to an annual timeframe and would not be extended beyond one year.

Conservation Tillage Tracking & Accounting Summary

Table 4. Summary of data used for estimating phosphorus reductions from conservation tillage.

Data Required	Source
Baseline phosphorus loading rate • HUC12 watershed or TMDL drainage area • HSG type (if available) • Average field slope (if available) • Land use assumed Corn WA	Lake Champlain TMDL SWAT model (Tetra Tech, 2015a) Lake Memphremagog TMDL model (VT DEC, 2017)
Acres of conservation tillage	Agricultural Partner Database & NRCS
Practice efficiency	20% (Tetra Tech 2015a, b)
Practice design life	1 yr.

Cover Crop

Cover crop establishes a seasonal cover on annual cropland for soil erosion reduction and conservation purposes. Seasonal cover consists of a crop of winter rye seeded at a minimum rate of 75 pounds per acre or other herbaceous plants seeded at the recommended rate to provide effective soil coverage. Cover crops may be planted in the fall after harvest or interseeded with the main crop during the growing season. The cover crop remains on the field through the winter to reduce erosion and nutrient loss, then is harvested or terminated in the spring prior to planting. Nurse crops, which are planted at time of seeding an annual crop field, provide cover on annual cropland for soil erosion reduction and conservation purposes, are also accounted for under this practice type.

Practice Tracking Mechanisms

Cover Crop (Conservation Practice Standard 340) and Nurse Crop (AAFM Practice Code 900VTAg) are credited under this practice category. For NRCS, nurse crop is covered under Practice Code 340.

Area Treated

The area treated is defined as the acres of cover crop or nurse crop.

Baseline Loading Rates

The default land use for cover crop and nurse crop are Corn WA. Acres of cover crop or nurse crop are multiplied by the TMDL-modeled land use loading rate to determine the baseload for the area treated. The baseline loading rates is based on:

1. HUC12 watershed or TMDL drainage area watershed (required)
2. Hydrologic soil group (HSG) type (if available)
3. Average field slope (if available)

Practice Efficiency

Cover crop and nurse crop receive a 28% total phosphorus load reduction efficiency for the Corn WA land use (Tetra Tech 2015a, b).

Practice Design Life

The design life and associated credit assigned to cover crop/nurse crop is one year after the practice is implemented. The reduction credit was scaled to an annual timeframe and would not be extended beyond one year.

Cover Crop/Nurse Crop Tracking & Accounting Summary

Table 5. Summary of data used for estimating phosphorus reductions from cover crops and nurse crops.

Data Required	Source
Baseline phosphorus loading rate • HUC12 watershed or TMDL drainage area • HSG type (if available) • Average field slope (if available) • Land use assumed Corn WA	Lake Champlain TMDL SWAT model (Tetra Tech, 2015a) Lake Memphremagog TMDL model (VT DEC, 2017)
Acres of cover crop or nurse crop	Agricultural Partner Database & NRCS
Practice efficiency	28% (Tetra Tech, 2015a, b)
Practice design life	1 yr.

Crop to Hay Planting

Crop to hay planting converts annual cropland to perennial grass/hay by planting grass or legumes – suitable for pasture, hay, or biomass production – to reduce soil erosion and improve production.

Practice Tracking Mechanisms

Eligible practices

Pasture and Hay Planting (Conservation Practice Standard 512) and Crop to Hay (AAFM Practice Code 917VTAg) are credited under this practice category.

As noted above, Conservation Crop Rotation funded by AAFM during state fiscal years 2016 to 2021 was actually being implemented as Pasture and Hay Planting with a two-year lifespan rather than a five-year lifespan and has been credited under the Crop to Hay efficiency.

Area Treated

The area treated is the acres of crop to hay planting.

Baseline Loading Rates

The default land use for crop to hay is Cropland WA. Acres of crop to hay planting are multiplied by the TMDL-modeled land use loading rate to determine the baseload for the area treated. The baseline loading rates is based on:

1. HUC12 watershed or TMDL drainage area watershed (required)
2. Hydrologic soil group (HSG) type (if available)
3. Average field slope (if available)

Practice Efficiency

Crop to hay planting reduction efficiencies vary based on average field slope (Tetra Tech, 2015a, b). Fields with low slopes (< 5%) receive a 70% efficiency, while fields with medium to high slopes (> 5%) receive an 80% reduction efficiency. When slope data are not available, an 80% reduction efficiency is used.

Practice Design Life

The design life for Pasture and Hay Planting (Conservation Practice Standard 512) is 5 years after the practice is implemented, while Crop to Hay (AAFM Practice Code 917VTAg) is two years after the practice is implemented.

Crop to Hay Planting Tracking & Accounting Summary

Table 6. Summary of data used for estimating phosphorus reductions from forage and biomass planting.

Data Required	Source
Baseline phosphorus loading rate • HUC12 watershed or TMDL drainage area • HSG type (if available) • Average field slope (if available) • Land use assumed Cropland WA	Lake Champlain TMDL SWAT model (Tetra Tech, 2015a) Lake Memphremagog TMDL model (VT DEC, 2017)
Acres of crop to hay planting	Agricultural Partner Database & NRCS
Practice efficiency	70-80% (Tetra Tech 2015a, b)
Practice design life	5 yr. for Conservation Practice Standard 512

	2 yr. for AAFM Practice Code 917VTAg

Manure Injection

Manure injection is the mechanical application of organic nutrient sources (e.g., manures, composted materials) into the root zone with surface soil closure or minimal soil disturbance at the time of application to decrease surface runoff of nutrients and improve production.

Practice Tracking Mechanisms

Manure Injection (AAFM Practice Code 901VTAg) is currently the only practice credited under this practice category. Comprehensive Nutrient Management Plans (NRCS CAP 102) and Nutrient Management Plan Implementation (Conservation Practice Standard 590) can include manure injection, but there is currently not an efficient method for identifying the manure injection acres within nutrient management plans funded by NRCS.

Area Treated

The area treated is the acres of manure injection.

Baseline Loading Rates

Acres of manure injection are multiplied by the TMDL-modeled land use loading rate to determine the baseload for the area treated. The baseline loading rates is based on:

1. HUC12 watershed or TMDL drainage area watershed (required)
2. Agricultural land use (required). Cropland WA and Pasture are both eligible for credit, and the default is Cropland WA if no land use data are provided.
3. Hydrologic soil group (HSG) type (if available)
4. Average field slope (if available)

Practice Efficiency

Manure injection receives a 40% total phosphorus load reduction efficiency. This practice efficiency was developed using the following steps. Additional details can be found in Appendix A: Manure Injection Phosphorus Reduction Efficiency.

1. Tetra Tech conducted an extensive literature review of the effects of manure injection on phosphorus runoff from agricultural fields in 2020. The literature review covered various methods of injection, study scales, study time frames, and types of manure, soil, crops, runoff components, and nutrient components. The literature review was refined to include only studies relevant for determining manure injection phosphorus efficiency in Vermont.
2. The Workgroup believed that results from plot studies and studies without full annual monitoring should be devalued due to their poor representation of actual field

conditions on an annual timescale. Studies were devalued based on precipitation type (i.e., natural vs. simulated rainfall), precipitation proximity (i.e., immediate vs. variable precipitation proximity to manure application), and study time frame (i.e., single event vs. multi event).

3. The final devalued phosphorus reduction efficiency was 40%. This value is conservative compared to the median 84% reduction efficiency from the literature review study and the 55% reduction efficiency from the watershed monitoring study. The 40% efficiency is equal to the median from plot studies using natural rainfall over annual time frames with variable precipitation proximities, which is the best combination of plot study factors available in our phosphorus dataset. Also, in arguably the most well-conducted plot monitoring study from the phosphorus dataset, Jahanazad et al. (2019) found an average surface total phosphorus reduction of 41% across 4 years (annual time frame) of plot monitoring under natural rainfall.

Practice Design Life

The design life and associated credit assigned to manure injection is one year after the practice is implemented. The reduction credit was scaled to an annual timeframe and would not be extended beyond one year.

Manure Injection Tracking & Accounting Summary

Table 7. Summary of data used for estimating phosphorus reductions from manure injection.

Data Required	Source
Baseline phosphorus loading rate • HUC12 watershed or TMDL drainage area • HSG type (if available) • Average field slope (if available) • Land use assumed Cropland WA or Pasture Cropland WA or pasture land use	Lake Champlain TMDL SWAT model (Tetra Tech, 2015a) Lake Memphremagog TMDL model (VT DEC, 2017)
Acres of manure injection	Agricultural Partner Database
Practice efficiency	40% (Appendix A)
Practice design life	1 yr.

Manure Incorporation

Manure incorporation is the mixing of organic nutrient sources (e.g., manures, composted materials) into the soil profile within 72 hours of manure application to reduce surface runoff of nutrients and improve production. There is no accounting distinction between high and low disturbance incorporation methods.

Practice Tracking Mechanism

Manure incorporation is not funded by AAFM but can be tracked by third party partners in the Partner Database. Comprehensive Nutrient Management Plans (NRCS CAP 102) can track manure incorporation, but there is currently not an efficient method for identifying manure injection acres within nutrient management plans funded by NRCS. As a result, this practice is not yet included in TMDL reporting.

Area Treated

The area treated is the acres of manure incorporation.

Baseline Loading Rates

The default loading rate for manure incorporation is Cropland WA. Acres of manure incorporation are multiplied by the TMDL-modeled land use loading rate to determine the baseload for the area treated. The baseline loading rates is based on:

1. HUC12 watershed or TMDL drainage area watershed (required)
2. Hydrologic soil group (HSG) type (if available)
3. Average field slope (if available)

Practice Efficiency

Manure incorporation receives a 23% total phosphorus load reduction efficiency. This practice efficiency was developed using the following steps. Additional details can be found in Appendix B: Manure Incorporation Phosphorus Reduction Efficiency.

1. Tetra Tech conducted an extensive literature review of the effects of manure incorporation on phosphorus runoff from agricultural fields in 2020. The literature review covered various methods of incorporation, study scales, study time frames, and types of manure, soil, crops, runoff components, and nutrient components. The literature review was refined to include only studies relevant for determining manure incorporation phosphorus efficiency in Vermont.
2. The Workgroup believed that results from plot studies and studies without full annual monitoring should be devalued due to their poor representation of actual field conditions on an annual timescale. The same devaluation factors used for manure injection were used for manure incorporation for two reasons: (1) sample sizes for manure injection were more appropriate for developing devaluing comparisons, and (2) consistent devaluation factors for manure injection and manure incorporation allow the bias in study designs to be accounted for equally in both potential manure management practices.
3. The final devalued phosphorus reduction efficiency was 23%. This value is within the range of low (30%) and high (15-30%) disturbance incorporation reduction efficiencies in the Chesapeake Bay watershed.

Practice Design Life

The design life and associated credit assigned to manure incorporation is one year after the practice is implemented. The reduction credit was scaled to an annual timeframe and would not be extended beyond one year.

Manure Incorporation Tracking & Accounting Summary

Table 8. Summary of data used for estimating phosphorus reductions from manure incorporation.

Data Required	Source
Baseline phosphorus loading rate • HUC12 watershed or TMDL drainage area • HSG type (if available) • Average field slope (if available) • Land use assumed Cropland WA	Lake Champlain TMDL SWAT model (Tetra Tech, 2015a) Lake Memphremagog TMDL model (VT DEC, 2017)
Acres of manure incorporation	N/A
Practice efficiency	23% (Appendix B)
Practice design life	1 yr.

Grazing Management

Grazing management includes a range of pasture management and grazing techniques to improve the quality and quantity of the forages grown on pastures and reduce the impact of animal travel lanes, animal concentration areas or other degraded areas. Pastures must have a minimum vegetative residual height of 3 inches after grazing to be credited.

Practice Tracking Mechanism

Rotational Grazing (AAFM Code 911VTAg) and Prescribed Grazing (Conservation Practice Standard 528) are credited under this practice category.

Area Treated

The area treated is the acres of grazing management.

Baseline Loading Rates

Acres of grazing management are multiplied by the TMDL-modeled land use loading rate to determine the baseload for the area treated. The baseline loading rate is based on:

1. HUC12 watershed or TMDL drainage area watershed (required)

2. Agricultural land use (required). For AAFM data, the default land use is always Pasture. For NRCS data, Cropland WA and Pasture are both eligible for credit and the default is Pasture if land use data are not provided.
3. Hydrologic soil group (HSG) type (if available)
4. Average field slope (if available)

Practice Efficiency

Grazing management receives a 24% total phosphorus load reduction efficiency. This practice efficiency was developed using the following steps. Additional details can be found in Appendix C: Grazing Management Phosphorus Reduction Efficiency.

1. Tetra Tech conducted a literature review of the effects of grazing management on phosphorus runoff from agricultural fields in 2020. The literature review covered various methods of study scales, study time frames, and types of soil, runoff components, and nutrient components. The literature review was refined to only include studies relevant to determining a phosphorus reduction efficiency for grazing management in Vermont.
2. As the phosphorus dataset was small for grazing management, the remaining three studies were further analyzed for their applicability to grazing management systems in Vermont. To be conservative with the Vermont grazing management requirements, the Workgroup has adopted the 24% total phosphorus reduction efficiency from the 5 cm rotational grazing treatment practice in Haan et al. (2006). This 24% reduction efficiency aligns with the Chesapeake Bay Program's 24% reduction efficiency for Precision Intensive Rotational/Prescribed Grazing BMP (CBP 2018).

Practice Design Life

The design life and associated credit assigned to grazing management is one year after the practice is implemented. The reduction credit was scaled to an annual timeframe and would not be extended beyond one year.

Grazing Management Tracking & Accounting Summary

Table 9. Summary of data used for estimating phosphorus reductions from grazing management.

Data Required	Source
Baseline phosphorus loading rate • HUC12 watershed or TMDL drainage area • HSG type (if available) • Average field slope (if available) • Agricultural land use (crop or pasture)	Lake Champlain TMDL SWAT model (Tetra Tech, 2015a) Lake Memphremagog TMDL model (VT DEC, 2017)

Acres of grazing management	Agricultural Partner Database & NRCS
Practice efficiency	24% (Appendix C)
Practice design life	1 yr.

Riparian Buffer

Riparian buffers are areas of grasses or shrubs, which may include trees, located adjacent to surface waters that filter out pollutants from runoff. Filter strip riparian buffers are composed of grasses and forbs, while forested riparian buffers are composed of woody vegetation, such as shrubs and trees. To qualify for phosphorus reductions, riparian buffers must be at least 25 ft wide with no manure application, gully erosion, or channelized flow.

Practice Tracking Mechanisms

Filter Strip (Conservation Practice Standard 393) and Riparian Forest Buffer (Conservation Practice Standard 391) are credited under this practice category. Grassed Waterway (Conservation Practice Standard 412) is not considered a riparian buffer and is credited separately. Riparian Herbaceous Cover (Conservation Practice Standard 390) could also be eligible for credit under this practice category, but it has not been contracted in Vermont yet.

Other practices, such as Pasture and Hay Planting (Conservation Practice Standard 512), Field Border (Conservation Practice Standard 328), and Wildlife Habitat Planting (Conservation Practice Standard 420) may also be used by conservation planners to install riparian buffers, but unable to know if they are installed adjacent to surface water in a field. As a result, these additional practices are not credited as riparian buffers.

The State of Vermont's Required Agricultural Practices (RAPs) have established a 25-foot standard for riparian buffers on cropland (VT AAFM 2018; Section 6.07). AAFM inspectors conduct farm visits to ensure RAP compliance for buffers, but this tracking mechanism has not yet been established for TMDL reporting.

Area Treated

Buffers are currently credited with two mechanisms: land use conversion and overland flow treatment. The area treated for the land use conversion credit is defined as the buffer area. The drainage area treated for overland flow credit is defined and estimated as five times the buffer area. A drainage area ratio was developed for two reasons:

1. DEC receives only the HUC12 location of each buffer due to privacy constraints with AAFM and NRCS practice data. Therefore, the area treated cannot be determined by delineating the buffer drainage area using GIS analyses. GIS analyses also have limitations and can overestimate or underestimate buffer treatment areas.
2. Using a standard ratio is consistent with the approach for crediting buffer treatment areas used by the Chesapeake Bay Program (CBP 2014).

The 5:1 drainage area ratio for buffers in Vermont was determined using two agricultural buffer treatment area analyses conducted by AAFM and DEC. To assess the potential treatment area of buffers on pasture in the Lake Champlain basin, DEC conducted an analysis using the following steps.

1. Estimate total pasture acres for each HUC12 in the Lake Champlain basin
2. Estimate the total stream length adjacent to pasture using the National Hydrography Dataset stream layer
3. Estimate the total potential area for buffers by applying a minimum buffer-width (i.e., 35-feet for state or NRCS-funded buffers) to the total stream length adjacent to pasture
4. Calculate the ratio of potential area for buffers to total pasture area. As it was not possible to know if the pasture was bordered on one side by the stream or bisected by the stream, this ratio was calculated assuming both buffers on one side of the stream and buffers on both sides of the streams.
    - Buffer on one side of stream =

$$\frac{Total\ pasture\ acres - Potential\ buffer\ acres}{Potential\ buffer\ acres}$$

    - Buffers on both sides of stream =

$$\frac{Total\ pasture\ acres - 2 * \ Potential\ buffer\ acres}{2 * \ Potential\ buffer\ acres}$$

This analysis found a basin-wide average treatment area ratio of 9.66 assuming buffer on one side of the stream and a basin-wide average of 4.33 assuming buffer on both sides of the stream (Figure 2).

AAFM also conducted analysis of the drainage areas around buffers using Conservation Reserve Enhancement Program (CREP) buffer data. For 9 floodplain buffers, the average treatment area was 4.56 acres for each acre of buffer planted, while the average treatment area for 7 upland buffers was 6.30 acres per acre of buffer planted.

Considering AAFM's analysis found a treatment ratio range of 4.56-6.30 for upland and floodplain buffers and DEC's analysis found a treatment ratio range of 4.33-9.66 for one-sided buffers and two-sided buffers, DEC adopted a conservative 5:1 treatment area ratio for agricultural and non-agricultural forested riparian buffers.

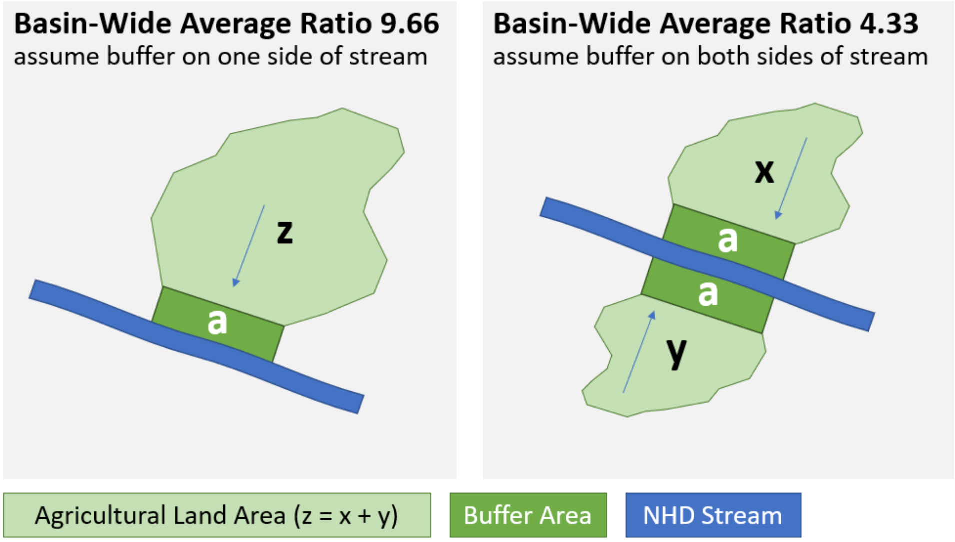

Figure 2. Diagram illustrating the difference in treatment area ratios when assuming buffers are on one side of the stream versus on both sides of the steam.

Baseline Loading Rates

For forested riparian buffers, Cropland WA and Pasture are both eligible land uses, and the default is Cropland WA when no land use data are provided. For filter strip riparian buffers, the land use is assumed Cropland WA since filter strips are installed less often on pasture or hay fields and would be considered a manure spreading setback rather than a riparian buffer. Acres of agricultural land draining to the buffer are multiplied by the TMDL-modeled land use loading rate to determine the baseload for the area treated. The baseline loading rate is based on:

1. HUC12 watershed (to determine TMDL drainage area) or TMDL drainage area watershed (required)
2. Agricultural land use (required)
3. Hydrologic soil group (HSG) type (if available)
4. Average buffer slope (if available)

Practice Efficiency

Forested riparian buffers receive a land use conversion credit from Pasture or Cropland WA (depending on the field land use) to Forest WA. Filter strip riparian buffer receive a land use conversion credit from Cropland WA to Continuous Hay.

The drainage area treated by filter strips and forested riparian buffers greater than or equal to 25 feet in width also receives a 40% total phosphorus load reduction efficiency. Although forested riparian buffers and filter strips may be expected to have a different efficiency due to the differences in vegetation types, forested and filter strip buffers receive the same phosphorus reduction efficiency, but the final phosphorus reduction is greater for forested riparian buffers because the land use conversion to Forest WA results in a greater reduction than the filter strip land use conversion to Continuous Hay.

The 40% efficiency was established by adapting the phosphorus reduction efficiency curve used in SWAT (Figure 3). The Workgroup did not directly use the buffer reduction efficiencies from the Lake Champlain TMDL SWAT model and the Lake Champlain TMDL Scenario Tool, as it was believed that the phosphorus reduction efficiencies for 25 ft forested and filter strip buffers should reflect the average efficiency of 41% of a new buffer (67%) and widened buffer (15%) since the baseline width of the buffer is not tracked. The Chesapeake Bay Program's 40% efficiency aligned closely with this recommendation. The Lake Champlain TMDL SWAT model established a 51% efficiency for the establishment of *new* 10 ft filter strip buffers, as 10 ft buffers would most commonly be applied on ditches and assumed very few ditch buffers were in place during the baseline. However, the Expert Panel did not recommend assigning a higher efficiency for a 10 ft buffer (51%) compared to a 25 ft buffer (40%). Therefore, the Workgroup recommended scaling back the efficiency of the 10 ft buffer based on the phosphorus reduction efficiency curve used in SWAT (Figure 3), shifting the curve so the 25 ft buffer aligns with the 40% efficiency and referenced the 10 ft buffer efficiency at 24%. State and federal funding programs do not fund 10 ft buffers; however, RAPs require a minimum 10 ft ditch buffer and could potentially be tracked and credited through RAP compliance in the future.

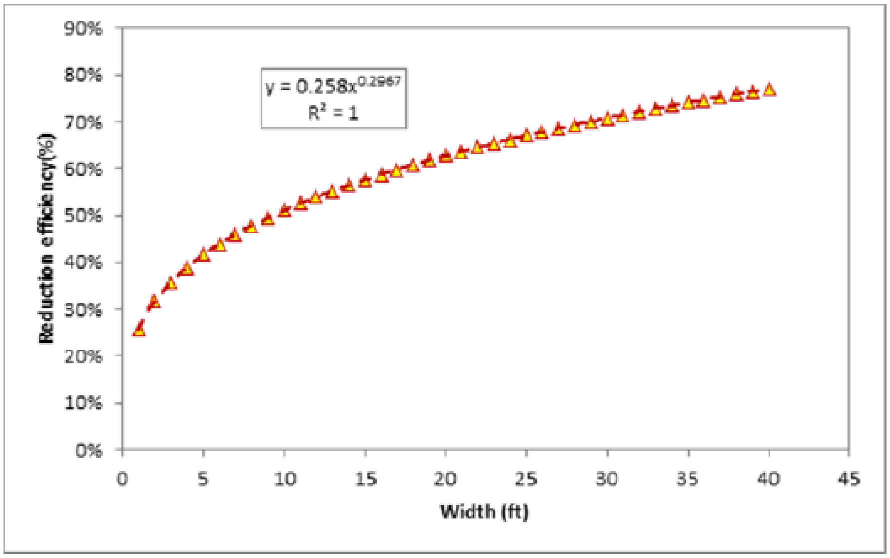

Figure 3. Phosphorus reduction efficiency curve used in SWAT for filter strip BMP.

The 40% value is also similar to the buffer efficiencies used in the Chesapeake Bay watershed, which vary from 13-65% depending on region (Chesapeake Bay Program, 2014). Vermont and the Chesapeake Bay watershed have similar plains, piedmonts, and mountainous regions, as illustrated by the shared biophysical characteristics in Table 10. The Champlain Valley Region is most similar to the poorly drained Outer Coastal Plain subregion considering the relative impermeability of clay and silt soils. Since schist bedrock dominates the Vermont landscape, the Chesapeake Bay Piedmont sub-region comprised of schist and gneiss is likely more similar to

Vermont Piedmont than the sandstone-dominated subregion. Similarly, the Valley and Ridge subregion of sandstone and shale bedrock is more comparable to the mountains of Vermont given the similarity between schist and shale. Given that riparian buffer plantings occur across many physiographic regions in Vermont, averaging the corresponding Chesapeake Bay phosphorus load reduction efficiencies would provide a more robust estimate of riparian buffer effectiveness than adopting any single region's efficiency. The average total phosphorus reduction efficiency of the Chesapeake Bay regions most similar to Vermont's biophysical regions was calculated as 39%.

Table 10. Comparison of the biophysical regions of Vermont and the Chesapeake Bay watershed.

Vermont Biophysical Region(s)	Comparable Chesapeake Bay Region	Shared Biophysical Characteristics	CBP TP Reduction Efficiency
Champlain Valley	Outer Coastal Plain (Poorly Drained)	Poorly drained, often saturated soils; low elevations; dominated by wetland ecosystems	39%
Vermont Piedmont	Piedmont (schist and gneiss)	Schist bedrock, seepage wetlands, rolling hills of moderate elevations	36%
Green and Northeastern Mountains	Appalachian Plateau Valley and Ridge (Sandstone and Shale)	Plateau structure; calcium-rich soils; acidic bedrock; relatively high elevations	42% 39%

Practice Design Life

For practices installed through funding programs, the design life of filter strip riparian buffers is 10 years, while forested riparian buffers design life is 15-30 years depending on the landowner contract. There is potential to extend the credit for this practice beyond the design life following a successful verification report that the practice is functioning as intended and has landowner support.

Riparian Buffer Tracking & Accounting Summary

Table 11. Summary of data used for estimating phosphorus reductions from riparian buffers.

Data Required	Value & Source
Baseline phosphorus loading rate • HUC12 watershed or TMDL drainage area	Lake Champlain TMDL SWAT model (Tetra Tech, 2015a)

- HSG type (if available) - Average field slope (if available) - Adjacent land use (Cropland WA or Pasture)	Lake Memphremagog TMDL model (VT DEC, 2017)
Buffer acres	AAFM & NRCS
Practice efficiency	40% (adapted from Tetra Tech 2015b and CBP 2014)
Practice design life	Filter strip riparian buffer = 10 yrs. Forested riparian buffer = 15-30 yrs.

Grassed Waterways

Grassed waterways stabilize areas prone to gully erosion by establishing grass-lined swales. Waterways are constructed to convey runoff from concentrated-flow areas, terraces, or diversions where erosion control is needed. Waterways can be used to control gullies and/or improve the water quality of downstream water bodies by reducing the sediment carried by runoff water.

Practice Tracking Mechanism

Eligible practices

Grassed Waterway (Conservation Practice Standard 412) is the only practice credited under this practice category.

Area Treated

The area treated is defined as five times the acres of grassed waterways installed, which is the same treatment area used for riparian forest buffers and filter strips (see above). The same ratio was adopted for grassed waterways because grassed waterways function similarly to buffers by intercepting runoff and stabilizing erosion. The Chesapeake Bay Program also uses the same treatment area ratio for Riparian Forest Buffers, Filter Strips, and Grassed Waterway (Chesapeake Bay Program 2018).

If site-specific drainage area data are available from the planning process, however, site-specific drainage area data may be used instead of the default 5:1 ratio.

Baseline Loading Rates

The default land use assumed for grassed waterways is Cropland WA. Acres of cropland treated are multiplied by the SWAT-modeled land use loading rate to determine the baseload for the area treated. The Cropland WA baseline loading rate is based on:

1. HUC12 watershed or TMDL drainage area watershed (required)
2. Hydrologic soil group (HSG) type (if available)

3. Average field slope (if available)

Practice Efficiency

Grassed waterways total phosphorus load reduction efficiencies vary from 20-50% depending on average field slope and HSG (Tetra Tech, 2015a, b). When slope and HSG data are not available, a 36% total phosphorus load reduction efficiency is used. Grassed waterways also receive a land use conversion credit from Cropland WA to Continuous Hay.

Practice Design Life

Grassed waterways are assigned a design life of 10 years after the practice is implemented (USDA NRCS Code 412). There is potential to extend the credit for this practice beyond the design life following a successful verification report that the practice is functioning as intended and has landowner support.

Grassed Waterways Tracking & Accounting Summary

Table 12. Summary of data used for estimating phosphorus reductions from grazing management.

Data Required	Source
Baseline phosphorus loading rate • Land use assumed Cropland WA HUC12 watershed or TMDL drainage area • HSG type (if available) • Average field slope (if available)	Lake Champlain TMDL SWAT model (Tetra Tech, 2015a) Lake Memphremagog TMDL model (VT DEC, 2017)
Acres of grassed waterway	Agricultural Partner Database & NRCS
Grassed waterway area treated	5x grassed waterway acres (if site-specific drainage area data are unavailable)
Practice efficiency	20-50% (Tetra Tech, 2015b)
Practice design life	10 years (USDA NRCS Code 412)

Livestock Exclusion

Livestock exclusion involves the exclusion of livestock from surface waters by installing a fence or other barrier. Benefits include reduced soil erosion, nutrient loading, and pathogen contamination.

Practice Tracking Mechanisms

In SFY 2020, AAFM created a new Livestock Exclusion (AAFM Practice Code 918VTAg) practice in the Partner Database to identify areas where livestock exclusion is confirmed by field staff. The following practices and combination of practices may be identified as Livestock Exclusion in the Partner Database.

1. Riparian Forest Buffer (Conservation Practice Standard 391) with or without Fence (Conservation Practice Standard 382) on pasture funded by AAFM Conservation Reserve Enhancement Program (CREP). Livestock exclusion is a CREP program requirement. Fence may already exist and thus may not be tracked through CREP. These practices are accounted for as a BMP system of livestock exclusion and riparian buffer with a combined efficiency 73%.
2. Fence (Conservation Practice Standard 382) on pasture funded by AAFM Conservation Reserve Enhancement Program (CREP). CREP payments for fencing require livestock exclusion from surface waters.
3. Filter Strip (Conservation Practice Standard 393) with Fence (Conservation Practice Standard 382) on pasture. Filter strips are almost exclusively riparian and not installed on ditches. For filter strips with fencing funded by the AAFM Pasture and Surface Water Fencing Program, livestock exclusion is required. Filter strips on pasture are not commonly funded by AAFM but could be used to reseed a denuded area adjacent to surface water.
4. Rotational Grazing (AAFM Practice Code 911VTAg). The state practice standard requires livestock exclusion, but this practice is not always adjacent to surface water. As such, field staff enter the Livestock Exclusion practice from grazing management in the Partner Database *only* when it is field verified and permanent livestock exclusion exists (e.g., not just polywire). Grazing management and livestock exclusion are accounted for as a BMP system if grazing management is verified to be adjacent to surface waters.
5. Other observed livestock exclusion situations confirmed in the field, as appropriate.

The following combination of NRCS practices on pasture are also associated with livestock exclusion from surface waters. Practice combinations must occur on the same field unit ID during the same period of time.

6. Riparian Forest Buffer (Conservation Practice Standard 391) *with* Fence (Conservation Practice Standard 382) on pasture. Forested buffers funded by NRCS must also be installed with a fence in order to restrict livestock access to surface waters. These practices are accounted for as a BMP system of livestock exclusion and riparian buffer.
7. Filter Strip (Conservation Practice Standard 393) with Fence (Conservation Practice Standard 382) on pasture. Filter strips are almost exclusively riparian and not installed on ditches. For filter strips with fencing funded by NRCS funding programs, livestock exclusion can be assumed but not guaranteed. This combination of practices has not been identified within the NRCS dataset as of SFY 2021, as filter strips are usually installed on cropland, not pasture. If this combination of practices is identified in the future, it would be eligible for livestock exclusion credits.

The following practices are not currently credited for livestock exclusion.

1. Filter Strip (Conservation Practice Standard 393) *without* Fence (Conservation Practice Standard 382) on pasture. Filter strips are usually installed on cropland, not pasture. Furthermore, grazing is allowed on filter strips, so filter strips alone are not livestock exclusion.
2. Grassed Waterway (Conservation Practice Standard 412). Grassed waterways are typically applied to cropland rather than pasture, and grassed waterways are not adjacent to surface waters.
3. Fence (Conservation Practice Standard 382) plus Stream Crossing (Conservation Practice Standard 578). The Workgroup agreed that this combination of practices should, in theory, be associated with livestock exclusion because it keeps livestock from wandering up and down the stream. Within the NRCS dataset, however, it is not possible to determine if the fence and stream crossing on the same land unit are installed together in an overlapping area. To be conservative with TMDL phosphorus crediting, this combination of practices is not currently credited for livestock exclusion.
4. Access Control (Conservation Practice Standard 472). This practice may be for livestock or equipment and the practice may be temporary. Livestock exclusion is not required.
5. Prescribed Grazing (Conservation Practice Standard 528) with or without Fence (Conservation Practice Standard 382). Farmers are allowed to flash graze riparian areas and livestock exclusion is only temporary. Livestock are allowed near riparian areas once per year. Fencing may be for paddocks and not necessarily the stream.

Practices resulting in livestock exclusion are mainly tracked through state and federal funding programs. The State of Vermont's Required Agricultural Practices (RAPs) have established management standards for pastures where livestock may have access to surface waters (VT AAFM 2018; Section 7). AAFM inspectors conducting farm visits to ensure RAP compliance can identify and record livestock exclusion practices that meet various RAP standards, but this tracking mechanism has not yet been established for TMDL reporting.

Area Treated

The area treated is the acres of pasture with livestock excluded from surface waters. For the Livestock Exclusion practice (AAFM Practice Code 918VTAg), the area treated is the acres of Livestock Exclusion. If livestock exclusion is resulting from an NRCS buffer installation, and if pasture field area is unknown, the area treated is assumed to be the same as the estimated buffer area treated (i.e., ratio of 5 acres of livestock exclusion: 1 acre of buffer). If pasture field area is known in a buffer-livestock exclusion BMP system, maximum overlap of area treated is assumed to avoid over estimating pollutant reductions.

Baseline Loading Rates

Acres of pasture with livestock excluded are multiplied by the TMDL-modeled pasture loading rate to determine the baseload for the area treated. Pasture loading rates in the Lake Champlain

TMDL model were based on livestock population by county, phosphorus excretion rates, and animal grazing assumptions (Tetra Tech, 2015a). The pasture baseline loading rate for a given practice is based on:

1. HUC12 watershed or TMDL drainage area watershed (required)
2. Hydrologic soil group (HSG) type (if available)
3. Average field slope (if available)

Practice Efficiency

The livestock exclusion practice efficiency was derived from the Lake Champlain TMDL SWAT model, which compared a livestock exclusion model scenario to baseline pasture loading rates without livestock exclusion (Tetra Tech, 2015a, b). In the livestock exclusion scenario, the model assumed that the 5% of manure previously deposited directly into surface waters was now deposited on pasture. Across the entire Lake Champlain basin, the livestock exclusion model produced an average 55% annual total phosphorus load reduction from pastures (Tetra Tech, 2015b). The 55% reduction efficiency is similar to the findings of experimental livestock exclusion studies in the Lake Champlain basin (Meals, 2000: 49% TP reduction) and elsewhere (Jones and Knowlton 1999: 52% TP reduction; Line et al., 2016: 47% TP reduction), although TP reductions from livestock exclusion can vary widely from 27% (Sunohara et al. 2012) to 76% (Line et al., 2000).[4]

Practice Design Life

The design life for livestock exclusion begins on the practice installation date. If the record of date practice applied/installed is unavailable, design life is estimated from date the practice was verified through inspection or other field-based assessment.

Livestock Exclusion (AAFM Practice Code 918VTAg) has a design life of 10 years. If livestock exclusion is associated with NRCS filter strip riparian buffer and forested riparian buffer contracts, the design life of the buffer is applied to livestock exclusion. Therefore, phosphorus reduction credits for livestock exclusion applied for 10 years for filter strips and 15-30 years for forested buffers depending on the landowner contract (USDA NRCS). There is potential to extend the credit for this practice beyond the design life following a successful verification report that the practice is functioning as intended and has landowner support.

Livestock Exclusion Tracking & Accounting Summary

Table 13. Summary of data required for estimating phosphorus reductions from livestock exclusion.

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[4] Note that the livestock exclusion efficiency does not factor in stream bank erosion benefits. Livestock exclusion may be eligible for stream stability credits through the Functioning Floodplains Initiative (FFI) phosphorus accounting methods. FFI methods are described in the separate Natural Resources Tracking & Accounting SOP.

Data Required	Source
Baseline phosphorus loading rate • HUC12 watershed or TMDL drainage area • HSG type (if available) • Average field slope (if available) • Land use assumed Pasture	Lake Champlain TMDL SWAT model (Tetra Tech, 2015a) Lake Memphremagog TMDL model (VT DEC, 2017)
Acres of pasture with livestock excluded	Agricultural Partner Database & NRCS
Practice efficiency	55% (Tetra Tech 2015a, b)
Practice design life	Standalone practice for AAFM Livestock Exclusion = 10 yrs. Co-practice lifespans for NRCS practice combinations • Filter strip = 10 yrs. • Forested buffer = 15-30 yrs.

Production Area Compliance

Production area compliance is defined as the exclusion of clean water runoff from the production area and management of the remaining runoff in a way that minimizes its pollution. Production areas include animal housing (barns and barnyards), heavy use areas, waste storage, and feed storage. Production areas must divert clean water runoff and then manage remaining runoff in a way that minimizes pollution. Production area compliance involves complete containment and/or control and management of all wastes, including diversion of contaminated runoff and silage waste to waste storage facilities.

Practice Tracking Mechanisms

AAFM and NRCS funding programs track individual production area practices, such as waste storage facilities or heavy use areas, but production area management is credited solely through AAFM inspection of production areas.

The State of Vermont's RAPs require that production areas, barnyards, animal holding or feedlot areas, manure storage areas, and feed storage areas utilize runoff and leachate collection systems, diversion, or other management strategies in order to prevent the discharge of agricultural wastes to surface water or groundwater (VT AAFM 2018, Section 6.01). During inspections, AAFM inspectors check all production area management units (waste storage structures, silage bunkers, milk-house waste management, barnyard and heavy use areas, and animal mortality facilities) to assess compliance. Inspection data are stored in the AAFM Regulatory/Inspection Database and compliance results are submitted annually to DEC for each site inspected.

Area Treated

AAFM quantifies production area acres during inspection process. AAFM inspectors map each structure within the production area using the outer-most vertices of each structure. The total production area includes an additional 100 feet around the outer-most vertices of the structures to provide a buffer.

Baseline Loading Rates

Acres of production area are multiplied by the TMDL-modeled farmstead loading rate to determine the baseload for the area treated. The farmstead loading rate for a given production area is based on:

1. HUC12 watershed or TMDL drainage area watershed (required)
2. Farmstead size based on animal numbers to determine TMDL loading rate (required). Farmstead – Medium/Large refers to farms with greater than 200 cattle (i.e., Medium Farm Operation (MFO) and Large Farm Operation (LFO) facilities), while Farmstead – Small refers to farms with less than 200 cattle (e.g., Certified Small Farm Operations (CFSOs)).
3. Hydrologic soil group (HSG) type (if available)
4. Average field slope (if available)

Practice Efficiency

The Vermont NRCS office estimated that production area RAP compliance is associated with an 80% phosphorus reduction efficiency (Tetra Tech, 2015b; Potter, 2013). This estimated production area management efficiency is consistent with clean water diversion studies conducted in Wisconsin (85-87%) and New York (80%). Phosphorus reduction credit is only given when all management units are considered fully compliant by AAFM.

As only 10% of farmsteads were assumed to be production area management compliant during the baseline TMDL modeling period, based on the status of regulatory requirements during the TMDL baseline period, production area RAP compliance currently found in place were likely implemented since the TMDL baseload period and, therefore, count as a reduction from the TMDL baseload.

Practice Design Life

The design life assigned to a production area is related to the inspection schedule of the farm. Large farm operations (LFOs) are inspected at least annually, medium farm operations (MFOs) are inspected at least once every three years, and certified small farm operations (CSFOs) are inspected once every seven years and these timeframes align with their assigned design life. Inspections for LFOs, MFOs, and CSFOs may occur more frequently if driven by complaints. RAP-compliant production areas are credited with phosphorus reductions until their next AAFM inspection. If new inspections find non-compliant structures or practices, phosphorus credits will cease until the production area is brought back into compliance. If the production area is found to be compliant, the credit will be extended beyond the initial design life.

Production Area Management Tracking & Accounting Summary

Table 14. Summary of data used for estimating phosphorus reductions from production area management.

Data Required	Source
Baseline phosphorus loading rate • HUC12 watershed or TMDL drainage area • Farmstead size (small or medium/large) • HSG type (if available) • Average field slope (if available)	Lake Champlain TMDL SWAT model (Tetra Tech, 2015a) Lake Memphremagog TMDL model (VT DEC, 2017)
Production area acres	AAFM Regulatory/Inspection Database
Production area RAP compliance status	AAFM Regulatory/Inspection Database
Practice efficiency	80% (Potter, 2013)
Practice design life	AAFM inspection schedules • LFO: 1 yr. • MFO: 3 yrs. • CSFO: 7 yrs.

Nutrient Management

Nutrient management is the management of the rate, source, placement, and timing of plant nutrients and soil amendments to improve plant health and productivity and to reduce the risk of nutrients reaching surface and groundwater. For the purposes of TMDL tracking and accounting, nutrient management is defined as the verified documentation and implementation of a field-by-field nutrient management plan (NMP) consistent with the requirements of the USDA NRCS Nutrient Management Practice Code 590. Nutrient management plans are required to include up-to-date field maps, soil samples, manure samples, and recommended nutrient application rates. NMPs are required to follow nutrient application guidelines, minimize leaching to groundwater or surface water and to provide effective management for soil health. Recordkeeping is a required component of NMPs.

Practice Tracking Mechanisms

Nutrient Management (Practice Code 590) funded by NRCS funding programs is the only practice credited under this practice category. NMP Implementation Assistance (Practice Code 916VTAg) does not receive nutrient management phosphorus credit, as assistance is provided on an existing nutrient management plan that would already be captured in the funding and regulatory program data collection below.

The State of Vermont's Required Agricultural Practices (RAPs) require that all certified small farm operations (CSFOs), medium farm operations (MFOs), and large farm operations (LFOs) implement a field-by-field nutrient management plan consistent with the requirements of the USDA NRCS Nutrient Management Practice Code 590 (VT AAFM 2018; Section 6.03). If a farm is not compliant with the NMP requirements, the farm will not receive a phosphorus reduction credit for nutrient management until an inspection verifies compliance.

AAFM's nutrient management inspection process varies depending on farm size.

- **LFO**s
    - **Annual information requirements**: LFOs submit an Annual Compliance Report that identifies the number of animals, total acreage of annual and perennial cropland, a farm level nutrient balance and if the farm has 180 days of storage. LFOs also submit the NMP, as well as GIS files of fields being managed.
    - **Plan review**: AAFM reviews LFO NMPs for deficiencies in the NRCS 590 standard while in the office in preparation for the field visit. Basic items evaluated include field and production area maps included and have appropriate labels and sensitive areas, soil tests and manure tests up-to-date, N-leaching identified, P-Index submitted and filled out correctly, nutrient recommendations calculated correctly and per standard, crop yield records incorporated correctly, records and reconciliation submitted.
    - **Field inspections**: Three fields are selected to compare actual field practices to the NMP recommendations. Fields are selected based on priority criteria, including previously identified fields that did not have buffers or setbacks, corn fields close to surface water and/or ditches, corn or grass fields that have been recently spread on near surface water and/or ditches, fields that show gully erosion in LiDAR (accurate, detailed land surface information), pastures next to surface water or where animals have access to surface water.
- **MFO**s
    - **Annual information requirements**: MFOs submit an Annual Compliance Report that identifies the number of animals, total acreage of annual and perennial cropland, a farm-level nutrient balance and if the farm has adequate 180 days of storage. MFOs do not submit the NMP, but instead submit a reconciled P-Index and/or manure samples depending on the year, as well as GIS files of the fields being managed.
    - **Plan review**: AAFM reviews MFO NMPs on-site. Basic items evaluated include field and production area maps have appropriate labels and sensitive areas, soil tests and manure tests up-to-date, N-leaching identified, P-Index submitted and

    filled out correctly, nutrient recommendations calculated correctly and per standard, crop yield records incorporated correctly, records and reconciliation submitted.

  - **Field inspections**: Three fields are selected to compare actual field practices to the NMP recommendations. Fields are selected based on priority criteria, including previously identified fields that did not have buffers or setbacks, corn fields close to surface water and/or ditches, corn or grass fields that have been recently spread on near surface water and/or ditches, fields that show gully erosion in LiDAR, pastures next to surface water or where animals have access to surface water.

- **CSFO**s
  - **Annual information requirements**: Annual Certification Form that identifies number of animals and total acreage of a variety of cropland types as well as NMP status.
  - **Plan review**: AAFM reviews CSFO NMPs on-site. Basic items evaluated include fieldmaps included and have appropriate labels and sensitive areas, soil tests and manure tests up-to-date, N-leaching identified, P-Index complete and filled out correctly, nutrient recommendations calculated correctly and per standard, crop yield recommendations calculated correctly, records and reconciliation submitted.
  - **Field inspections**: Three fields are selected to compare actual field practices to the NMP recommendations. There is less preparation in the selection of fields to inspect for CSFOs, and fields are often selected at the time of inspection.

DEC and AAFM have not yet established a mechanism for obtaining this data for TMDL tracking and accounting. Once this tracking mechanism is established, a quality review process will be developed to avoid double counting NMP acres with NRCS funding program data.

Area Treated

The area treated is defined as total farm acres under nutrient management. Acres are tracked and reported at the farm level rather than the field level as for other agricultural practices.

Baseline Loading Rates

Acres of nutrient management are multiplied by the TMDL-modeled land use loading rate to determine the baseload for the area treated. The baseline loading rate is based on:

1. HUC12 watershed or TMDL drainage area watershed (required)
2. Agricultural land use (required). Cropland WA or Pasture are eligible for this practice, and the default is Cropland WA if land use data are unavailable.

Practice Efficiency

Nutrient management acres receive a 5% total phosphorus reduction efficiency. Since preliminary exploration of the available scientific literature indicated that scant data exist on edge-of-field nutrient losses from nutrient management, the Workgroup reviewed the Chesapeake Bay Program's approaches for nutrient management crediting and established a modified efficiency for Vermont.

The Chesapeake Bay Program's (CBP) Phase 6 Nutrient Management BMP report summarizes their current approach for crediting nutrient management, defined as the implementation of a site-specific combination of nutrient source, rate, timing, and placement into a strategy that seeks to optimize agronomic and environmentally efficient utilization of N and P (Chesapeake Bay Program, 2018b). The Phase 6 model credits nutrient management using first a Core Nutrient Management BMP, then Supplemental Nutrient Management BMPs for rate, placement, and timing. While this approach is sophisticated in how it breaks nutrient management into multiple components, this level of tracking would be onerous for Vermont's agencies, and it was challenging for the Workgroup to understand how the application rate and loss multipliers could be adapted to Vermont's BMP Tracking and Accounting Tool. In order to better understand the methods, the Workgroup reviewed the prior CBP nutrient management approach.

The CBP's Phase 5.3.2 Nutrient Management BMP report utilizes an efficiency approach rather than a multiplier approach, which is consistent with the crediting methods in Vermont's BMP Tracking and Accounting Tool (Chesapeake Bay Program, 2015). The Phase 5.3.2 BMP provides credits across the following three tiers:

1. **Tier 1** - Documentation exists for manure and/or fertilizer application management activities in accordance with basic land grant university (LGU) recommendations. Receives 10% total phosphorus (TP) reduction efficiency for high-till with manure and low-till with manure and 8% TP reduction efficiency for high-till without manure, pasture, hay with nutrients, alfalfa, and nursery. Tier 1 efficiencies were modeled based on changes in LGU nutrient recommendations over time due to the lack of scientific literature documenting efficiencies on nutrient management.
2. **Tier 2** - Implementation of formal nutrient management planning is documented and supported with records demonstrating efficient use of nutrients for both crop production and environmental management. Receives 6.6% TP reduction efficiency for high-till manure, low-till manure, hay with nutrients, alfalfa land uses (15.94% when combined with Tier 1). Tier 2 efficiency considered the effects of manure incorporation, implementation of the phosphorus site index, and manure setbacks.
3. **Tier 3** - Implementation of Tier 2 nutrient application management, plus adaptive multi-year monitoring of nutrient use efficiency with the results of this monitoring being integrated into future NM planning. Includes precision application technologies. The Phase 5.3.2 report did not adopt a Tier 3 efficiency due to time constraints.

The Workgroup appreciated the multi-tiered approach presented in the Phase 5.3.2 report. The Workgroup noted that nutrient management under Code 590 in Vermont is a combination of the CBP's Tier 1 and Tier 2 definitions requiring both the development (Tier 1) and implementation (Tier 2) of a nutrient management plan. The Workgroup also noted that Tier 3 is similar to Precision Agriculture (Practice Code 913VTAg) funded by AAFM. As such, the Workgroup began to consider two possible tiers for crediting nutrient management in Vermont: Tier 1 - Nutrient Management and Tier 2 - Precision Agriculture (Precision Agriculture discussed in the following section).

When beginning discussions on an efficiency for VT Tier 1, the Workgroup first considered the combined 15.94% efficiency for CBP's Tiers 1 and 2. The Workgroup ultimately chose to use the more conservative 10% CBP Tier 1 efficiency as a starting point for VT Tier 1 since it is impossible to fully verify the implementation (CBP Tier 2) of nutrient management. In order to determine whether 10% would be appropriate for Vermont nutrient management, the Workgroup needed to determine whether the assumptions behind CBP's Tier 1 efficiency would be applicable for Vermont. The CBP Tier 1 TN and TP efficiencies were based on a sensitivity analysis that simulated a 20% change in N application rates on corn, which yielded a percent change in TN and TP load where a reduction in manure application on corn with a reduction in N in manure yields a companion reduction of P.

To determine whether a 20% reduction in nutrient application rates was an appropriate assumption, the Workgroup consulted with UVM Extension to understand how nitrogen and phosphorus recommendations have changed over time. In general, N recommendations have become more granular and, in some cases, increased and other decreased depending on yields and drainage class. There have been no changes in soil test P recommendations, but more farmers use crop removal for P recommendations and crop removal for corn silage has changed. The crop removal of phosphorus (i.e., uptake by the plant) for corn silage was previously at 5 lbs per ton and was changed to 4 lbs per ton of crop produced in 2020, which is quite substantial for many farms. Furthermore, farmers using the new P-Index have increased restrictions on the amount of P allowed in medium risk situations, which results in a reduction in nutrients applied. Overall, although the workgroup was unable to put an exact value to the percent decrease in nutrient application rates over time, this evidence underscores a downward trend in nutrient applications from the baseline consistent with the CBP approach, which provides confidence for adopting a nutrient management efficiency.

After these investigations with UVM Extension, the Workgroup believed that it was appropriate to start efficiency discussions for VT's Tier 1 at the CBP's Tier 1 10% efficiency. However, the Workgroup wanted to build in additional conservativeness to Vermont's Tier 1 efficiency because NRCS only verifies 10% of 590 fields for the implementation of nutrient management and AAFM inspectors only verify implementation on three fields during farm inspections. As a result, the nutrient management efficiency is extrapolated to all farm acres based on the verification of only a sub-set of acres. Since extrapolation may not always be accurate, the Workgroup decided to reduce the efficiency to 5% to be more conservative in light of this tracking implication.

Practice Design Life

For nutrient management verified through AAFM inspections, the design life is the same as frequency of inspections: 1 year for LFOs, 3 years for MFOs, and 7 years of CSFOs. For Code 590 reported by NRCS, the practice contract is for three years but the design life is one year because there may be updates to the nutrient management plan due to annual manure tests, changes in animal numbers or land, new soil tests, etc. The credit for this practice may be extended beyond the design life following a successful inspection report that the practice(s) still function as intended.

Nutrient Management Tracking & Accounting Summary

Table 15. Summary of data used for estimating phosphorus reductions from nutrient management.

Data Required	Source
Baseline phosphorus loading rate • HUC12 watershed or TMDL drainage area • Agricultural land use (Cropland WA or Pasture) • HSG type (if available) • Average field slope (if available)	Lake Champlain TMDL SWAT model (Tetra Tech, 2015a) Lake Memphremagog TMDL model (VT DEC, 2017)
Nutrient management acres	NRCS Database & AAFM Inspection Database
Nutrient management RAP compliance status	AAFM Inspection Database
Practice efficiency	5%
Practice design life	NRCS: 1 yr. AAFM inspection schedules • LFO: 1 yr. • MFO: 3 yrs. • CSFO: 7 yrs.

Anticipated Future Improvements

The practices at the end of this document (Precision Agriculture and Soil Aeration) were reviewed by the Workgroup, but it was determined that there was not enough information at the time to warrant assigning a phosphorous credit. These practices may be reconsidered if new studies become available.

Precision Agriculture

Precision agriculture is an advanced nutrient management system that considers in-field variability during the planning process to reduce nutrient loading and improve production. Manure application rates are varied on a sub-field spatial scale based on crop nutrient needs assessed by contemporary testing of soil, plant tissue, or other soil/crop parameters. This management requires the use of technologies, information management tools, and measurements to determine field conditions, assess management information, and understand variable management requirements.

Practice Efficiency

An extensive literature review was used to try to determine a total phosphorus load reduction efficiency for precision agriculture, but there was not enough conclusive evidence to adopt a reduction efficiency at the time of the literature review. The following section summarizes the findings of the literature review and the workgroup's decision making. The full precision agriculture literature review can be found in **Appendix D**.

Since precision agriculture is a broad concept, Tetra Tech focused the literature review on the variable rate application of manure phosphorus to cropland. Preliminary exploration of the available scientific literature, however, indicated that scant data exist on edge-of-field nutrient losses from variable rate nutrient management. While some decreases in nutrient losses have been reported under variable rate management, other work has reported no significant effect. As a result, the literature review also considered indirect metrics that potentially indicate water quality effects of variable rate nutrient management, including changes in net nutrient application rates, changes in soil test phosphorus, changes in crop yields, and the economics on variable rate nutrient management.

Changes in net nutrient application rates. Because variable rate nutrient management would reduce or eliminate phosphorus (P) application to field zones with greater than optimum soil test phosphorus (STP) levels, the practice could potentially reduce the total amount of P applied to a field. This could subsequently reduce potential P losses from the field, particularly losses of dissolved P in surface runoff or tile drainage either directly through transport of residual manure nutrients or by decreasing STP. While substantial net decreases in nutrient application under variable rate (VR) nutrient management compared to uniform rate (UR) applications have been reported, results are inconsistent; some research has documented either very small changes in net P or N application rates or even higher rates under variable rate nutrient management, compared to uniform rate nutrient management. From discussions in the literature, it is clear that changes in actual nutrient applications with variable rate nutrient management are highly dependent on initial conditions in a field (e.g., the distribution of initial STP values). If a field contains a high proportion of excessive STP compared to moderate STP areas, less P might be applied under VR than UR because no P will be added to the areas of excess STP. In contrast, a field with a high proportion of low STP zones and a few over optimum STP areas may receive a lower uniform application because the average STP will be elevated by the high STP areas, while a variable rate application will apply large amounts of P to the low STP soils. Therefore, it cannot be assumed that variable rate nutrient management would always result in lower net nutrient application.

Changes in soil test P. Research has confirmed the fundamental outcome that variable rate nutrient application will tend to increase soil nutrients in deficient or low concentration areas and decrease soil nutrients in high-testing soils where less P or N is applied. In general, studies have shown that this process can reduce variability in STP across a field under variable rate application management and that this effect may occur fairly quickly. Based on our understanding of the influence of STP on P loss in runoff or tile drainage, it seems likely that reductions of STP, especially in high STP field areas, can lead to decreases in P loss from the field. As a field moves toward a more homogeneous STP, overall P application may be able to be done at a basic crop removal rate, potentially reducing the total P application rate to the field and facilitating optimum nutrient management. However, it is clear that these effects are variable and highly dependent on initial conditions. Thus, it is difficult to generalize the effect of VR nutrient management on soil nutrients.

Changes in crop yields. Changes in crop yields may influence nutrient losses from a field by reducing surplus nutrients left in the soil after harvest (increased uptake with increased yields) or by leaving excess nutrients in the soil (decreased uptake with decreased yields). Thus, changes in crop yields in response to variable rate nutrient management may provide another indirect measure of the impacts of variable rate nutrient management on P losses. However, variable rate nutrient management appears to generally maintain or slightly increase crop yields; reports of decreased yields are few. Effects on yield appear to depend on soil characteristics and initial soil nutrient levels, as well as on nutrient application strategy. To the extent that maintenance or increase in crop yield may be coupled with decreased nutrient application rate, yield may be an indirect indicator of potential water quality effects of variable rate nutrient management. However, the metric is unlikely to be quantitatively large.

Economics of variable rate nutrient management. Several reviewed studies included data and analysis of the economics of precision agriculture and variable rate nutrient management. While economic aspects are not directly relevant to estimating P loss reductions, the financial impacts of new nutrient management practices will undoubtedly influence adoption by producers and thereby the extent of any potential effects on water quality. Based on the limited review of economic effects, it appears that variable rate nutrient management does not consistently offer improved economic return to the farmer, despite any environmental or nutrient use efficiency benefits. Increased costs for soil testing and advanced equipment, coupled with inconsistent yield increases suggest that on-farm net benefits are likely to be small or non-existent. Several authors have noted that changes in profitability with variable rate nutrient management are highly dependent on initial conditions of STP and nutrient management.

Conclusions. Because of the lack of convincing evidence of a measurable water quality benefit for variable rate nutrient application, the Workgroup agreed that no P reduction credit can be given to precision agriculture/variable rate nutrient management at this time. While it is still a potentially valuable practice in improving manure P use efficiency and managing soil test P in the long term, there is no scientific basis at this time to recommend an immediate P loss reduction credit. This practice will be reconsidered if/when new research is available.

Soil Aeration

Soil aeration is the punching of holes, pits, or slots into the soil to reduce soil compaction and promote soil infiltration/adsorption of manure. Soil aeration may be associated with reduced nutrient runoff and water quality benefits, but there is insufficient evidence for adopting a reduction efficiency at this time.

Practice Efficiency

Tetra Tech conducted an extensive literature review of the effects of soil aeration on phosphorus runoff from agricultural fields. The literature review included various methods of aeration, study scales, study time frames, and types of manure, soil, crops, runoff components, and nutrient components. The literature review was refined to only include studies relevant to determining a phosphorus reduction efficiency for soil aeration in Vermont.

The research on soil aeration was more variable and contradictory than for other agricultural practices. Many references reported no significant effect of soil aeration on nutrient loss or reported increases in nutrient losses. There was also a generally low number of studies available to identify under what conditions aeration is consistently beneficial or detrimental for total phosphorus runoff. Additional details about the literature review can be found in **Appendix E**.

UVM Extension published manuscript on the effects of soil aeration on nutrient loss from hay fields in Vermont (Twombly et al., 2021.). This paired watershed study with a calibration period and year-round edge-of-field monitoring was conducted in Chittenden County, Vermont from 2012 to 2018. Overall, soil aeration reduced TP concentrations by 32% but increased surface runoff volume by 16%, which resulted in no significant reductions in TP loads. These findings may be due to multiple factors, such as increased compaction from aeration on poorly drained soils. The literature review conducted for the introduction and discussion of the paper also found no significant TP load reductions associated with soil aeration.

Altogether, there was not enough evidence to establish a phosphorus reduction efficiency based on Tetra Tech’s literature review and recent UVM research. This practice will be reconsidered when if/new research is available.

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Appendix A: Manure Injection Phosphorus Reduction Efficiency

This appendix outlines the methods used to determine a phosphorus reduction efficiency for the Manure Injection BMP. The Manure Injection BMP is defined as: the mechanical application of organic nutrient sources (e.g., manures, composted materials) into the root zone with surface soil closure or minimal soil disturbance at the time of application.

Literature Review

Tetra Tech conducted an extensive literature review of the effects of manure injection on nitrogen and phosphorus runoff from agricultural fields. Tetra Tech identified 45 relevant studies, covering various methods of injection, study scales, study time frames, and types of manure, soil, crops, runoff components, and nutrient components. Don extracted data from these studies to produce 158 individual records of phosphorus reductions/increases and 86 individual records of nitrogen reductions/increases. These individual records represented single measurement events within a study, where possible.

Don provided a summary of the literature review to the Vermont Agricultural BMP Tracking and Accounting Workgroup (hereafter Workgroup) in spreadsheet format. Don also presented an overview of his literature review to the workgroup, where he provided the following recommendations:

1) Focus on median efficiency values or select the results most relevant to Vermont or the Lake Champlain basin.
2) Devalue nutrient reduction efficiencies from plot studies and studies without full annual or seasonal monitoring, as these are not representative of natural field conditions.
3) Consider stratifying reduction efficiencies by soil characteristics.
4) Condition efficiency values only on the surface runoff component of phosphorus loss.

The Workgroup agreed with many of Don's recommendations and adopted a statistically driven approach to develop a manure injection phosphorus reduction efficiency value. A nitrogen reduction efficiency will be assessed separately after all phosphorus reduction methods have been established.

Phosphorus Dataset Development

The original literature review dataset was narrowed down to include only studies relevant for determining manure injection phosphorus efficiency in Vermont. The following conditions and methods were applied to the original literature review dataset.

1. Only surface runoff and total phosphorus (TP) data. The Lake Champlain TMDL model is limited to the surface component of total phosphorus runoff, so subsurface flow and leaching data were removed from the dataset. The model also only applies to total phosphorus, so particulate phosphorus and soluble phosphorus data entries

were removed. If data were classified as surface runoff and subsurface flow ("Both" in dataset), the data were excluded since the surface component could not be quantified.

2. All significant and non-significant findings. The literature on manure injection varies greatly in statistical significance, with some studies not reporting on the significance of findings. To avoid narrowing down the dataset too much, all results were included regardless of statistical significance. All studies were peer-reviewed and published in scientific journals; while reporting of statistical significance is helpful, it is not an automatic (or standard) component of all rigorously conducted studies of this type.
3. All manure types, soil types, and equipment types. Including all these data captures the wide range of possible manure injection practices in Vermont.
4. For studies with multiple measurement events, one phosphorus reduction value was calculated as the difference between the summed control loads and summed treatment loads. Calculating summed differences minimizes the variability that arises from multiple measurement events across various time scales when comparing to other articles that only reported averaged multiple events.
5. Phosphorus load increases were considered on a case-by-case basis. Don reviewed all of the studies with phosphorus load increases and provided recommendations on how to handle the data. Phosphorus load increases were included if there was no apparent methodological reason to exclude. On one occasion, the phosphorus load increase was recoded to 0% reduction because the mathematical differences between the control and treatment phosphorus runoff values were small and inflated the percent difference (e.g., 0.013 vs 0.016 = 23% increase changed to 0% reduction).

The final dataset included 20 individual studies and 34 individual records of phosphorus load reductions or increases. This dataset included 18 plot monitoring studies, one annual watershed monitoring study, and one literature review study. Of the 18 plot monitoring studies, the dataset included 6 single event studies, 8 multi-event studies, and 4 annual studies. Based on this original phosphorus dataset, the median total phosphorus reduction efficiency was 61%.

Study Devaluation

In general, the Workgroup believed that results from plot studies and studies without full annual monitoring should be devalued due to their poor representation of actual field conditions on an annual timescale. To establish an objective percentage for devaluing studies, the medians for different classifications of manure injection records were calculated and compared (Table 1).

To devalue studies based on study scale, our initial intent was to compare the median phosphorus reduction efficiency for plot monitoring studies with the median reduction for field, farm, or watershed monitoring studies. Literature review studies were not included, as literature reviews summarize various study types. Of the 35 phosphorus records, there were 30 plot records, but only one watershed monitoring study record for comparison (Table 1). The median values were similar for the plot and watershed monitoring studies (61% vs 55%, respectively). Even if there were significant differences between watershed and plot monitoring studies, it would be inappropriate to devalue by study scale based on the low sample size of field, farm, or watershed total phosphorus monitoring studies in our phosphorus dataset.

To address the statistically low sample size arising from study scale comparisons, manure injection studies were instead devalued based on precipitation type (i.e., natural vs. simulated rainfall), precipitation proximity (i.e., immediate vs. variable precipitation proximity to manure application), and study time frame (i.e., single-event vs. multi-event). Most plot studies are conducted with simulated rainfall, often immediately after manure application and only for a single event, all of which is effective for comparing treatment scenarios, but the runoff generated by these study parameters is not reflective of natural field conditions. In the Chesapeake Bay's manure injection report, the Expert Panel recommended that studies addressing annual timescales under natural rainfall must be considered when establishing efficiencies, which provides support for the devaluing methodology used here (CBP 2016, Section 4.10).

Overall, the median phosphorus reduction efficiency of natural rainfall plot studies was 52% lower than the median from simulated rainfall plot studies. However, as seen in Table 1, simulated rainfall plot study results are primarily higher due to the single-event, immediate proximity factors. Specifically, the median phosphorus reduction efficiency of annual timeframe studies was 15% and 57% lower than multi-event and single event studies, respectively. As a result, an 85% devaluation factor was applied to multi-event studies and a 43% devaluation factor was applied to single-event studies to equate to annual studies with natural precipitation and variable time frame. In doing so, the median reduction efficiencies from simulated rainfall plot studies were also equated to natural rainfall studies (Table 2). These devaluation efforts attempt to adjust inflated simulated rainfall, single-event, immediate proximity results to more realistic results of natural rainfall occurring at variable proximities across an annual time frame.

Table 1. Comparisons of median values from manure injection record classifications before devaluation. "Immediate" proximity is defined as less than three days after manure application, while "variable" proximity captures all other measurement time frames.

All	**Study Scale**	Median (n)	**Precip. Type**	Median (n)	**Time Frame**	Median (n)	**Precip. Proximity**	Median (n)
61% (34)	Literature review	84% (3)	N/A	N/A	N/A	N/A	N/A	N/A
	Watershed monitoring	55% (1)	Natural	55% (1)	Annual	55% (1)	Variable	55% (1)
	Plot monitoring	61% (30)	Natural	40% (8)	Annual	40% (8)	Variable	40% (8)
			Simulated	83% (22)	Multi-event	47% (11)	Variable	47% (11)

					Single event	92% (11)	Immediate	92% (11)

Table 2. Comparisons of median values from manure injection record classifications after devaluation. Plot study results with simulated rainfall, either single or multi-events, and immediate temporal proximity have been devalued to reflect more natural conditions (natural rainfall with variable measurements over an annual time frame).

All	**Study Scale**	Median (n)	**Precip. Type**	Median (n)	**Time Frame**	Median (n)	**Precip. Proximity**	Median (n)
40% (34)	Literature review	84% (3)	N/A	N/A	N/A	N/A	N/A	N/A
	Watershed monitoring	55% (1)	Natural	55% (1)	Annual	55% (1)	Variable	55% (1)
	Plot monitoring	40% (30)	Natural	40% (8)	Annual	40% (8)	Variable	40% (8)
			Simulated	40% (22)	Multi-event	40% (11)	Variable	40% (11)
					Single event	40% (11)	Immediate	40% (11)

Phosphorus Reduction Efficiency Recommendation

Using a statistically driven approach to devalue and evaluate phosphorus reduction efficiencies, a 40% manure injection reduction efficiency was determined (Table 2 and Figure 1).

The 40% reduction efficiency from plot studies is conservative compared to the median 84% reduction efficiency from the literature review study and the 55% reduction efficiency from the watershed monitoring study (Table 1). The 40% efficiency is equal to the median from plot studies using natural rainfall over annual time frames with variable precipitation proximities, which is the best combination of plot study factors available in our phosphorus dataset. Also, in arguably the most well-conducted plot monitoring study from the phosphorus dataset, Jahanazad et al. (2019) found an average surface total phosphorus reduction of 41% across 4 years (annual time frame) of plot monitoring under natural rainfall.

The 40% efficiency value is similar to the 45% efficiency value developed by the Chesapeake Bay Program, though the Chesapeake Bay value was derived somewhat differently. The Chesapeake Bay Manure Injection Expert Panel adopted an overall 45% total phosphorus reduction efficiency for manure injection (CBP 2016, Section 4.6), but the final report provides no specific justification for this value, other than that phosphorus reductions in the literature were typically 70-90% and that the Expert Panel believed the reduction efficiencies should be more conservative due to the limitations of plot studies. We hypothesize that the Expert Panel devalued the upper 70-90% range by approximately 50% using best professional judgement to result in the 45% reduction efficiency.

Altogether, the 40% reduction efficiency determined here appears to be conservative or in agreement with other studies on manure injection. The devalued dataset has less variation than the original phosphorus dataset, which provides added confidence in the median value of 40% (Figure 1).

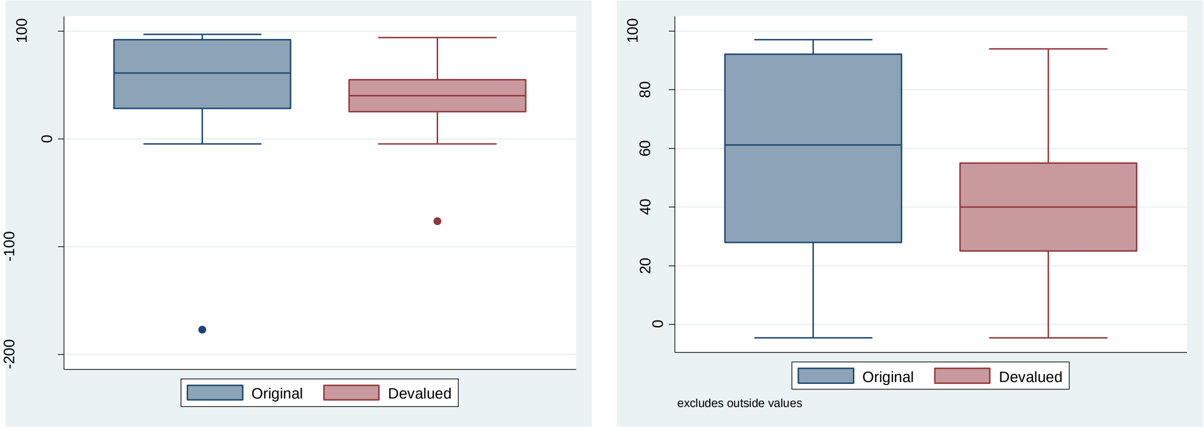


Figure 1. Comparison of phosphorus load reduction data spreads form the original phosphorus dataset (blue) and devalued dataset (red). The plot on the right removes outliers. The devalued dataset is characterized by a lower median phosphorus reduction efficiency and lower overall variability.

Table 3. Comparison of phosphorus load reduction data spreads between original and devalued phosphorus datasets graphed above in Figure 1.

	Median	**Mean**	**Number**	**Min**	**Max**	**SD**
Original	61%	52%	34	-177%	97%	52%
Devalued	40%	39%	34	-76%	94%	31%

Limitations

As with any nutrient reduction efficiency, there are limitations associated with the 40% phosphorus reduction efficiency determined here. To begin, this analysis was limited by the manure injection studies identified in the original literature review. There may be other reputable manure injection studies that could be relevant to conditions in Vermont, but this analysis assumes that the studies identified in this literature review are a good representation of manure injection research. In addition, although a statistical approach was used to determine an efficiency, quantitative evaluations were also complemented with best professional judgement to evaluate the appropriateness of the result.

Lastly, it should again be noted that subsurface flow and leaching were not assessed or assigned a load reduction efficiency from manure injection in Vermont. The Lake Champlain TMDL only applies to the surface component of total runoff, so all BMP efficiencies in the Lake Champlain basin must only apply to the surface runoff component. The Workgroup expressed some concern in not considering tile drainage when determining a reduction efficiency from manure injection in Vermont. While it is possible that there are some subsurface load reductions associated with manure injection in Vermont, BMP reduction efficiencies must be consistent with the assumptions in the original Lake Champlain TMDL model. Altogether, the 40% phosphorus reduction efficiency for manure injection in Vermont was based on the best available literature at the time, a statistical methodology, and the knowledge of the Workgroup.

References

Chesapeake Bay Program. 2016. Manure incorporation and injection practices for use in Phase 6.0 of the Chesapeake Bay Program Watershed Model.

Appendix B: Manure Incorporation Phosphorus Reduction Efficiency

This appendix outlines the methods used to determine a phosphorus reduction efficiency for the Manure Incorporation BMP. The Manure Incorporation BMP is defined as: The mixing of organic nutrient sources (e.g., manures, composted materials) into the soil profile within 72 hours of manure application. There is no accounting distinction between high and low disturbance incorporation methods in Vermont due to the anticipated difficulties in tracking and verifying specific incorporation types. A 72-hour window for incorporation after manure application was adopted from the Chesapeake Bay Program's Manure Incorporation BMP definition but tracking the time frame may not always be possible in Vermont.

Literature Review

Tetra Tech conducted an extensive literature review of the effects of manure incorporation on nitrogen and phosphorus runoff from agricultural fields. Tetra Tech identified 38 relevant studies, covering various methods of incorporation, study scales, study time frames, and types of manure, soil, crops, runoff components, and nutrient components. Don extracted data from these studies to produce 177 individual records of phosphorus reductions/increases and 68 individual records of nitrogen reductions/increases. These individual records represented single measurement events within a study, where possible.

Don provided a summary of the literature review to the Vermont Agricultural BMP Tracking and Accounting Workgroup (hereafter Workgroup) in spreadsheet format. Don also presented an overview of his literature review to the Workgroup, where he provided the following recommendations:

5) Focus on median efficiency values or select the results most relevant to Vermont or the Lake Champlain basin.
6) Devalue nutrient reduction efficiencies from plot studies and studies without full annual or seasonal monitoring, as these are not representative of natural field conditions.
7) Condition efficiency values only on the surface runoff component of phosphorus loss.

The Workgroup agreed with many of Don's recommendations and adopted a statistically driven approach to develop a manure injection phosphorus reduction efficiency value. A nitrogen reduction efficiency will be assessed separately after all phosphorus reduction methods have been established.

Phosphorus Dataset Development

The original literature review dataset developed by Don was narrowed down to include only studies relevant for determining manure incorporation phosphorus efficiency in Vermont. The following conditions and methods were applied to the original literature review dataset.

6. Only surface runoff and total phosphorus (TP) data. The Lake Champlain TMDL model is limited to the surface component of total phosphorus runoff, so subsurface flow and leaching data were removed from the dataset. The model also only applies to total phosphorus, so particulate phosphorus and soluble phosphorus data entries were removed. If data were classified as surface runoff and subsurface flow (“Both” in dataset), the data were excluded since the surface component could not be classified.
7. All significant and non-significant findings. The literature on manure incorporation varies greatly in statistical significance, with some studies not even reporting the significance of findings. To avoid narrowing down the dataset too much, all results were included regardless of statistical significance.
8. All manure types, soil types, and equipment types. Including all these data captures the wide range of possible manure incorporation practices in Vermont.
9. For studies with multiple measurement events, one phosphorus reduction value was calculated as the difference between the summed control loads and summed treatment loads. Calculating summed differences minimizes the variability that arises from multiple measurement events across various time scales when comparing to other articles that only reported averaged multiple events.
10. Phosphorus load increases were considered on a case-by-case basis. Don reviewed all of the studies with phosphorus load increases and provided recommendations on how to handle the data. All phosphorus load increases for incorporation were included because there was no apparent methodological reason to exclude.

The final dataset included 12 studies and 43 individual records of phosphorus load reductions or increases. This dataset included two annual farm modeling records and 41 plot monitoring records. Of the 41 plot monitoring records, the dataset included 27 single event records, 13 multi-event records, and 2 annual records. Fifty percent of our literature review studies were based on immediate or less 24-hour incorporation, but 50% did not have a time frame for incorporation specified. Immediate incorporation, same day incorporation, not reported incorporation categories had phosphorus reduction efficiencies of 20%, 21%, 28%, respectively. Based on this original phosphorus dataset, the median total phosphorus reduction efficiency was 42%.

Study Devaluation

In general, the Workgroup believed that results from plot studies and studies without full annual monitoring should be devalued due to their poor representation of actual field conditions on an annual timescale. To establish an objective percentage for devaluing studies, the medians for different classifications of manure incorporation records were calculated and compared (Table 1).

To devalue studies based on study scale, our intent was to compare the median phosphorus reduction efficiency for plot monitoring studies with the median reduction efficiency for field, farm, or watershed monitoring studies. Of the 42 manure incorporation phosphorus records, however, there were no field, farm, or watershed monitoring records that could be compared to the 41 plot monitoring studies for devaluing (Table 1). As with manure injection devaluation, we did not have sufficient data to devalue based on study scale.

Since we could not devalue manure incorporation studies based on study size, we considered devaluing based on precipitation type (i.e., natural vs. simulated rainfall) similar to the manure injection method. For manure incorporation, however, there were 40 simulated rainfall records but only two natural rainfall records for comparison, and we believed it would be inappropriate to devalue using the low sample size for natural rainfall. As a result, we decided to adopt the same devaluation factors used for manure injection for two reasons: (1) sample sizes for manure injection were more appropriate for developing devaluing comparisons, and (2) consistent devaluation factors for manure injection and manure incorporation allow the bias in study designs to be accounted for equally in both potential manure management practices. As such, an 85% devaluation factor (meaning we reduced the value to 85% of the full value) was applied to multi-event studies and a 43% devaluation factor was applied to single-event studies. See the *Manure Injection Phosphorus Reduction Efficiency Recommendation* for more information.

Table 1. Comparisons of median values from manure incorporation record classifications before devaluation. Manure injection devaluation factors were used for incorporation, as there were no comparison data for devaluing based on study scale and there was a low sample size for devaluing based on precipitation type.

All	**Study Scale**	Median (n)	**Precip. Type**	Median (n)	**Time Frame**	Median (n)	**Precipitation Proximity**	Median (n)
42% (43)	Farm modeling	-41% (1)	Simulated	-41% (1)	Annual	-41% (1)	< 5 days	-41% (1)
	Plot monitoring	42% (42)	Natural	32% (2)	Annual	32% (2)	Variable	32% (2)
			Simulated	43% (40)	Multi-event	44% (13)	Variable	44% (13)
					Single event	43% (27)	≤ 10 days	43% (27)

Table 2. Comparisons of median values from manure incorporation record classifications after devaluation with manure injection devaluation factors.

All	**Study Scale**	Median (n)	**Precip. Type**	Median (n)	**Time Frame**	Median (n)	**Precipitation Proximity**	Median (n)
23% (42)	Farm modeling	-41% (1)	Simulated	-41% (1)	Annual	-41% (1)	< 5 days	-41% (1)
	Plot monitoring	23% (42)	Natural	32% (2)	Annual	32% (2)	Variable	32% (2)
			Simulated	21% (40)	Multi-event	38% (13)	Variable	38% (13)

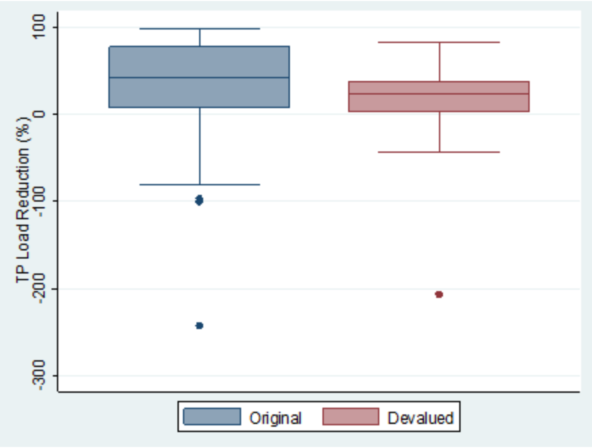
					Single event 19% (27)	≤ 10 days 19% (27)

Phosphorus Reduction Efficiency Recommendation

Using a statistically driven approach to devalue and evaluate phosphorus reduction efficiencies, a 23% manure incorporation reduction efficiency was determined (Figure 1). This 23% reduction efficiency is applied for all eligible manure incorporation practices meeting the definition above, and it should be highlighted that there is no distinction made between high and low disturbance in Vermont.

In the Chesapeake Bay watershed, there are two separate reduction efficiencies for high disturbance and low disturbance incorporation. The Chesapeake Bay Expert Panel adopted an overall 30% total phosphorus reduction efficiency for low disturbance manure incorporation in the Coastal Plain and Upland regions (CBP 2016, Section 4.6), but the final report provides no specific justification for the 30% value other than the panel believed the value should be more conservative than manure injection. For high disturbance incorporation, the Chesapeake Bay Expert Panel assigned a conservative reduction of 30% for Coastal Plain. For the Upland regions, the Expert Panel originally did not assign a reduction efficiency because the potential for increased erosion and TP loss was likely with intensive tillage, but this was later amended to a 15% reduction efficiency based on input from the New York Department of Agriculture and Markets.

Altogether, our 23% reduction efficiency for Vermont is within the range of low (30%) and high (15-30%) disturbance incorporation reduction efficiencies in the Chesapeake Bay watershed. The devalued dataset has less variation than the original phosphorus dataset, which also provides added confidence in the median value of 23% (Figure 1). When comparing the Vermont and Chesapeake Bay reduction efficiencies, however, it should be noted that the Chesapeake Bay literature review was conducted several years ago, and the Vermont literature review includes the results of some additional studies completed since the publication of the Chesapeake Bay review in 2016.



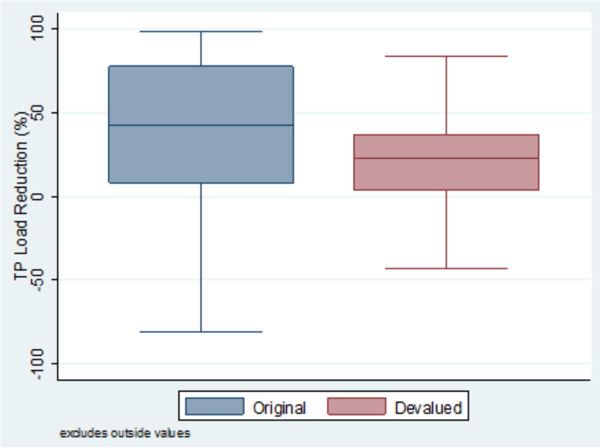


Figure 1. Comparison of phosphorus load reduction data spreads form the original phosphorus dataset (blue) and devalued dataset (red). The plot on the right removes outliers. The devalued dataset is characterized by a lower median phosphorus reduction efficiency and lower overall variability.

Table 2. Comparison of phosphorus load reduction data spreads between original and devalued phosphorus datasets graphed above in Figure 1.

	Median	**Mean**	**Number**	**Min**	**Max**	**SD**
Original	42%	25%	43	-243%	98%	67%
Devalued	23%	14%	43	-207%	83%	46%

Limitations

As with any nutrient reduction efficiency, there are limitations associated with the 23% phosphorus reduction efficiency determined here. To begin, this analysis was limited by the manure incorporation studies identified in the original literature review. There may be other reputable manure incorporation studies that could be relevant to conditions in Vermont, but this analysis assumes that the studies identified in this literature review are a good representation of manure incorporation research. In addition, although a statistical approach was used to determine an efficiency, quantitative evaluations were also complemented with best professional judgement to evaluate the appropriateness of the result.

Lastly, it should again be noted that subsurface flow and leaching were not assessed or assigned a load reduction efficiency from manure incorporation in Vermont. The Lake Champlain TMDL only applies to the surface component of total runoff, so all BMP efficiencies in the Lake Champlain basin must only apply to the surface runoff component. The Workgroup expressed some concern in not considering tile drainage when determining a reduction efficiency from manure incorporation in Vermont. While it is possible that there are some subsurface load reductions associated with manure incorporation in Vermont, BMP reduction efficiencies must be consistent with the assumptions in the original Lake Champlain TMDL model. Altogether, the 23% phosphorus reduction efficiency for manure incorporation in Vermont was based on the best available literature at the time, a statistical methodology, and the knowledge of the Workgroup.

References

Chesapeake Bay Program Phase 6.0 Manure Incorporation and Injection Expert Review Panel. 2016. *Manure incorporation and injection practices for use in Phase 6.0 of the Chesapeake Bay Program Watershed Model.* Report Prepared for the Chesapeake Bay Program.

Appendix C: Grazing Management Phosphorus Reduction Efficiency

This appendix outlines the methods used to determine a phosphorus reduction efficiency for the Grazing Management BMP. The Grazing Management BMP is defined as: A range of pasture management and grazing techniques to improve the quality and quantity of the forages grown on pastures and reduce the impact of animal travel lanes, animal concentration areas or other degraded areas. Pastures under the Grazing Management BMP need to have a vegetative height of 3 inches or greater, which is consistent with the Vermont Agency of Agriculture, Food, and Markets (AAFM) and Vermont Natural Resources Conservation Service (NRCS) requirements.

Literature Review

Don Meals, an agricultural researcher with Tetra Tech, conducted an extensive literature review of the effects of grazing management on nitrogen and phosphorus runoff from agricultural fields. Don identified 18 relevant studies, covering various study scales, study time frames, and types of soil, runoff components, and nutrient components. Don extracted data from these studies to produce 70 individual records of phosphorus reductions/increases. These individual records represented single measurement events within a study, where possible.

Don provided a summary of the literature review to the Vermont Agricultural BMP Tracking and Accounting Workgroup (hereafter Workgroup) in spreadsheet format. Don also presented an overview of his literature review to the Workgroup, where he provided the following recommendations:

8) Consider giving no P reduction credit at all given the variability, trade-offs, and uncertainty reported in the literature.
9) Focus on median efficiency values or select the results most relevant to Vermont or the Lake Champlain basin.
10) Devalue nutrient reduction efficiencies from plot studies and studies without full annual or seasonal monitoring, as these are not representative of natural field conditions.
11) Condition efficiency values only on the surface runoff component of phosphorus loss.

The Workgroup agreed with many of Don's recommendations and selected the results most relevant to Vermont.

Phosphorus Dataset Development

The original literature review dataset developed by Don was narrowed down to include only studies relevant for determining a grazing management phosphorus efficiency in Vermont. The following conditions and methods were applied to the original literature review dataset.

11. Only surface runoff and total phosphorus (TP) data. The Lake Champlain TMDL model is limited to the surface component of total phosphorus runoff, so subsurface flow and leaching data were removed from the dataset. The model also only applies to total phosphorus, so particulate phosphorus and soluble phosphorus data entries were removed. If data were classified as surface runoff and subsurface flow ("Both" in dataset), the data were excluded since the surface component could not be classified.
12. All significant and non-significant findings. The literature on grazing management varies greatly in statistical significance, with some studies not even reporting the significance of findings. To avoid narrowing down the dataset too much, all results were included regardless of statistical significance.
13. All soil types. Including all these data captures the wide range of possible grazing management practices in Vermont.
14. For studies with multiple measurement events, one phosphorus reduction value was calculated as the difference between the summed control loads and summed treatment loads. Calculating summed differences minimizes the variability that arises from multiple measurement events across various time scales when comparing to other articles that only reported averaged multiple events.
15. Studies where the total phosphorus load reductions reported were due to a reduction in streambank erosion by livestock were removed. Streambank erosion is more closely tied to the Livestock Exclusion BMP and not the Grazing Management BMP, which focuses on in-field grazing management practices, such as rotational or prescribed grazing rather than access to adjacent surface water or the quality of streambanks.
16. Studies not directly measuring the impact of grazing management practices were eliminated. Three studies indirectly assessing grazing management were removed, including (1) Butler et al. (2008) simulating grazing management by adding feces and urine to plots, (2) Alfaro et al (2008) comparing livestock density differences between plots, and (3) McDowell et al. (2005) comparing hours of grazing per day between plots.

The research on grazing management was more limited than the literature available on manure injection, manure incorporation, and soil aeration. The filters listed above resulted in a phosphorus dataset consisting of 3 different studies with a total of 4 individual records of phosphorus reductions.

Phosphorus Reduction Efficiency Recommendation

As the phosphorus dataset sample size was small for grazing management, the remaining three studies were further analyzed for their applicability to grazing management systems in Vermont.

1. Chaubey et al. (2010) was a SWAT modeling study that simulated 171 combinations of agricultural BMPs in the Lincoln Lake watershed in northwest Arkansas and eastern Oklahoma. For grazing management, the study simulated no grazing, optimum grazing, and over-grazing scenarios at various manure application rates. Overall, grazing management was associated with a 51% TP load reduction when averaged across all manure application rates. As this was a modeling study and not a monitoring study, the Workgroup used this result mainly for comparison purposes.
2. Lambert et al. (1985) tested three livestock treatments - rotational grazing with sheep, rotational grazing with cattle, and set stocking with sheep - using high and low fertilizer application rates. The only valid control-treatment comparison was between rotational and set stocking sheep. The total phosphorus load reductions were calculated as the percent reduction from the summed control and summed treatments to arrive at a 28% TP load reduction for the low fertilizer treatment and 15% for high fertilizer treatment across three years. Please note that this study was conducted over 35 years ago in New Zealand.
3. Haan et al. (2006) compared continuous cattle stocking (5 cm forage height, 7-10-day rest period) to rotational stocking (5 cm and 10 cm treatments, 35-day rest period) on study fields in Iowa. Rotational stocking with 5 cm forage height was associated with a 24% TP load reduction compared to continuous stocking, while the 10 cm forage height was associated with a 64% load reduction compared to continuous stocking.

Overall, for both direct monitoring studies, the TP load reduction efficiencies were 15%, 24%, 28%, and 64%. There is greater confidence in the Haan et al. (2006) study than the Lambert et al. (1985) due to its very well-documented methods, more recent time frame, and applicability to Vermont grazing management standards. The Rotational Grazing practice under the AAFM FAP program requires a minimum 3 inch (7.62 cm) residual perennial vegetative height and NRCS technical staff are encouraging a 4-6-inch residual vegetative height (10.16-16.24 cm) for their Prescribed Grazing practice. To be conservative with the Vermont grazing management requirements, the Workgroup has adopted the 24% TP reduction efficiency from the 5 cm rotational grazing treatment practice in Haan et al. (2006).

Although the 24% reduction efficiency was determined using the results of one study, this value is in line with the results from Lambert et al. (1985) and is conservative compared to the Chaubey et al. (2010) modeling study and the 10 cm vegetative height treatment in Haan et al. (2006). Furthermore, the 24% reduction efficiency agrees with the Chesapeake Bay Program's 24% reduction efficiency for Precision Intensive Rotational/Prescribed Grazing BMP (CBP 2018).

Limitations

As with any nutrient reduction efficiency, there are limitations associated with the 24% phosphorus reduction efficiency determined here. To begin, this reduction efficiency is based mainly on the results of just one study, which may not be as robust as taking the median from dozens of grazing management studies but there are additional lines of evidence supporting this value. This analysis was also limited by the grazing management studies identified in the original literature review. There may be other reputable grazing management studies that could be relevant to conditions in Vermont, but this analysis assumes that the studies identified in this literature review are a good representation of grazing management research. Further local and regional research and analysis into the phosphorus reductions resulting from rotational grazing is recommended in order to augment this reduction efficiency review and determination process.

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Appendix D. Precision Agriculture Literature Review

Introduction

The Vermont *Agricultural TMDL Tracking & Accounting Workgroup* (the *Workgroup*) requested assistance from Tetra Tech, Inc. in conducting a literature review on aspects of precision nutrient management (NM) for the purpose of establishing a science-based phosphorus (P) reduction credit for use in Lake Champlain Phosphorus TMDL tracking and accounting. Preliminary exploration of the available scientific literature indicated that little published data exist on specific effects of precision NM on P loss from agricultural land. Therefore, the scope of the review expanded to include nitrogen (N) as well as P and to search for data on indirect response metrics of relevance to water quality, including changes in nutrient application rates, changes in soil test P, and changes in crop yields attributable to precision NM. Each of these often has an indirect relationship to nutrient loss from agricultural land and may serve as a surrogate for changes in P loss in response to precision NM.

Literature Review Process

A set of potential references was generated using several search engines, including *Web of Science*, *AGRICOLA*, the USDA *National Agricultural Library*, and *Google Scholar*. The following sets of keywords were used in each of these search engines:

- Precision agriculture AND nutrient management;
- Precision agriculture AND water quality;
- Precision agriculture AND runoff;
- Precision agriculture AND phosphorus;
- Precision agriculture AND nutrient loss; and
- Variable rate manure application.

More than 2,000 individual references were returned through this process; these were screened (by title and abstract) for further review using the following criteria:

- Results (either monitored or simulated) from correctly defined Variable Rate (VR), application (i.e., true spatially variable rate application based on soil and crop criteria);
- No specifically geographic criteria, but obviously inappropriate crop/ecoregion types (e.g., ornamental plants in nurseries) excluded;
- Evaluated either P or N from either inorganic (commercial fertilizer) or organic (manure) sources;
- NOT papers exclusively addressing VR technologies, approaches to quantifying spatial variation of characteristics like soil test P within a field, or broad policy discussions of precision agriculture (PA);

- Broad categories of response metrics:
    - Water quality (runoff or leaching) response to VR application, either monitored or simulated;
    - Differences in net P or N application rates under VR vs. uniform rate (UR);
    - Differences in crop yields under VR vs. conventional; and
    - Differences in soil test P after VR vs. conventional
- Some economic (e.g., change in $ returns) data included if part of broader analysis, but NOT if that was the sole topic addressed.

After initial screening, 48 potential references were identified; of these, 32 were determined to contain relevant information and were included in the review. Fourteen papers did not include useful information and were excluded. Two papers could not be obtained for review. Full citations for all of these 48 papers are listed in Appendix A; abstracts of included papers are given in Appendix B. Full digital copies of all papers have been provided to the Workgroup.

The Issue

It is generally observed that many agricultural fields have high internal soil test P (STP) variability. In an overview of PA concepts and technologies, Mallarino and Schepers (2005) stated that STP variability can be very large, even within fields that seem uniform in other soil properties. In regions with long histories of fertilizer or manure application, within-field variability usually encompasses STP values that range from values much lower to much higher than optimum values for crop production. Fields with average STP levels near optimum usually have areas testing very low and areas testing very high. Application of manure to very high testing areas leads to over-enrichment with P and increases P loss potential.

For example, Bermudez and Mallarino (2007) reported that among a group of Iowa corn-soybean fields, median STP (Mehlich-3) was ≤ 20 mg P/kg, while minimum and maximum STP values within each field were 4 – 18 and 22 – 62 mg P/kg, respectively. Fu et al. (2010) reported that STP varied by two orders of magnitude within an Irish dairy farm.

For P, assessment of sub-field nutrient needs often relies on intensive grid-sampling for STP and subsequently follows recommended P rates (e.g., from University of Vermont) appropriate within each specific STP zone. For N, within-field N needs are sometimes based on soil N tests (e.g., PSNT or post-harvest soil nitrate) but can also be based on identification of zones of different leaching potential, yield history, or data on denitrification (Zebarth 2009).

Definitions

Definitions of the activities that constitute precision agriculture (PA) or precision NM are variable and sometimes misleading. It is therefore critical to consider an appropriate definition both to assemble data in support of attributing practice effectiveness and to consider issues of practice tracking and accounting.

Campbell (1994) defined "precision nutrient management" as *the appropriate application of fertilizer…or technology to meet the plant's varying nutrient requirements and to achieve the best quality product under the constraints of optimizing productivity and enhancing or maintaining the environment.* This definition was early recognition of the need to go beyond a simple uniform nutrient application across an "average" field.

Later definitions highlighted the importance of moving from uniform to variable management and accounting for spatial variability within a field. Mallarino and Schepers (2005) defined PA as *the application of technologies and principles to manage spatial and temporal variability associated with all aspects of agricultural production for the purpose of improving crop performance and environmental quality*. Schepers (2008) noted that key elements of PA involve *a transition from uniform treatments to variable-rate treatments in an attempt to compensate for the effects of spatial and temporal variability in fields.*

In 2013, the Chesapeake Bay Program noted the need for detailed site data and special technology for advanced NM and defined "precision/decision agriculture" as *a management system that is information- and technology-based, is site specific and uses one or more of the following sources of data: soils, crops, nutrients, pests, moisture, or yield for optimum profitability, sustainability, and protection of the environment.*

In New Zealand, Hedly (2015) indicated that for effective PA, a significant knowledge base is required, e.g., yield maps, soil and climatic data, crop agronomy, and equipment type, to assess the needs and capabilities for precision management. The underlying principles of PA were defined as *measure, monitor, then manage*.

Most recently, the Maryland Department of Agriculture (2021) offers a highly specific definition of PA as a system used to *improve the agronomic, environmental and economical management of crop production in accordance with in-field variability. This management requires the use of a GPS (Global Positioning System) and information management tools such as GIS (Geographic Information System) to input field conditions, assess management information and understand variable management requirements. Precision soil sampling, variable rate nutrient application and record keeping/yield monitoring using GPS/GIS software are implemented by agricultural operations to ensure the most efficient production is achieved.*

The literature also reports on agricultural practices that **do not** constitute PA or precision NM in the context of this review. Tullo et al. (2018) discussed an approach called *precision livestock farming* that involved the application of process engineering waste management principles and techniques to livestock farming to automatically monitor, model and manage animal production, but did not include activities to manage land application of manure. Baffaut et al. (2020) presented data from a "precision agriculture system" in MO that implemented PA as a combination of multiple, mainly traditional BMPs: no-till + cover crop + herbicide management + split N applications + variable P fertilizer rates. Reported results could not, therefore, be attributed to a single PA BMP. Wilson et al. (2020) reported data from what was labeled Variable Rate N fertilizer, but was rather a uniform split application/side-dress N fertilizer application at a low rate, compared to a pre-plant uniform N application. None of these versions of PA or precision NM proved relevant to this review.

Early in the process, members of the *Workgroup* indicated that the element of precision NM currently most used or applicable in VT is variable rate (VR) application of manure P to cropland. VR nutrient application typically involves application of varying rates of P within the same field based on soil or crop characteristics determined by detailed assessment of the field.

Based on this premise and the definitions reported in the literature, this review is based on the following definition of Variable Rate Nutrient Management:

> *Within the context of a comprehensive farm-scale NMP, for each application event on each field, manure application rate is varied on a sub-field spatial scale based on crop nutrient needs assessed by contemporary testing of soil, plant tissue, or other soil/crop parameters.*

General aspects of PA and VR nutrient management

As noted by several authors (e.g., Campbell 1994, Wang et al. 2003, Schepers 2008, Zebarth 2009, Chen et al, 2014), VR fertilizer application based on within-field variability in soil or crop properties has the potential to reduce under- and over-application of fertilizers and thereby improve fertilizer use efficiency, crop yields and net farm returns. Improved fertilizer use efficiency could reduce adverse environmental impacts of crop production, such as N and P contamination of surface and ground water by reducing the prevalence of excessive STP levels and the consequent promotion of P runoff losses.

In Iowa, Wittry and Mallarino (2002) concluded that although use of VR technology may not increase crop yield and economic benefits for producers compared with a UR method, VR allows for better manure management and can reduce the risk of P delivery from manured fields to water resources.

In evaluating soil testing data in several northern European countries, Haneklaus et al. (2016) reported that most soils were in the >optimum STP range and that continuation of current manure application practices will further aggravate nutrient surpluses and export to water bodies. The authors present algorithms for VR manure application, based on detailed knowledge of soil nutrient status, applying at rates that match the lowest N, P, or K demand, based on conditions of no manure application if soil P exceeds the sufficiency range.

Hedley (2015) published a review article discussing the introduction of PA to New Zealand. The author cites technical, economic, and social studies on the feasibility and performance of PA techniques for different agricultural systems in New Zealand, including VR irrigation management to minimize nutrient leaching losses.

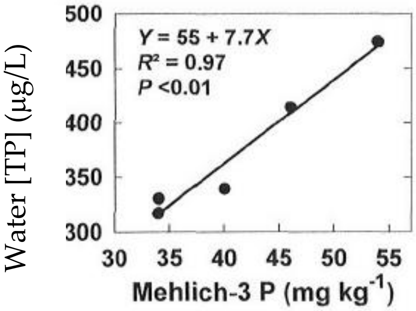
Higgins et al. (2019) noted that controlled traffic farming and VR fertilizer application have potential environmental and economic benefits, but that there is currently insufficient research into this new technology. The authors also presented some assessments of adoption attitudes among farmers in Ireland and the UK.

Water quality and related responses to VR nutrient management

Scant data exist on edge-of-field nutrient losses from VR NM. Thus, discussion of potential water quality responses to VR NM will also consider indirect metrics that potentially indicate water quality effects.

Changes in net nutrient application rates

Because VR NM would reduce or eliminate P application to field zones with greater than optimum STP levels, the practice could potentially reduce the total amount of P applied to a field. This could subsequently reduce potential P losses from the field, particularly losses of dissolved P in surface runoff or tile drainage either directly through transport of residual manure nutrients or by decreasing STP. For example, Klatt et al. (2003) reported that 46 – 83% of soils in an Iowa agricultural watershed tested above optimum STP. Rates of P applied in manure and fertilizer averaged 15 kg P/ha and 40% of the high-testing STP areas received P fertilizer. Coupled with a demonstrated strong association between increasing STP and runoff TP concentration, the authors concluded that increases in stream P levels were directly related to unwarranted increases in STP due to overapplication of P fertilizer.



Although reductions in overall nutrient applications are often suggested as benefits of VR NM (e.g., Campbell 1994, Prato and Kang 1998, Haneklaus 2016, Schepers 2008, Higgins et al. 2019), literature reports on actual changes in nutrient application rates attributable to VR NM are inconsistent.

Some researchers have documented substantial decreases in net nutrient application under VR. On irrigated corn in Colorado, Koch et al. (2004) reported that 6 – 46% less N fertilizer was applied under site-specific management zone (SSMZ) management with variable yield goals, compared to uniform N management.

In strip trials in an Iowa corn-soybean rotation, Wittry and Mallarino (2004) evaluated P fertilizer applied in a single application to meet P requirement of the 2-yr rotation based on Iowa guidelines for STP and expected P removal in harvested grain. The authors reported that VR P application based on intensive grid sampling for STP within the VR strips gave an average application rate of 39 kg P/ha (range 35 – 48 kg P/ha) compared to an average uniform rate (determined by the median STP value for each strip) of 53 kg P/ha (range 45 – 70 kg P/ha), an average 26% reduction.

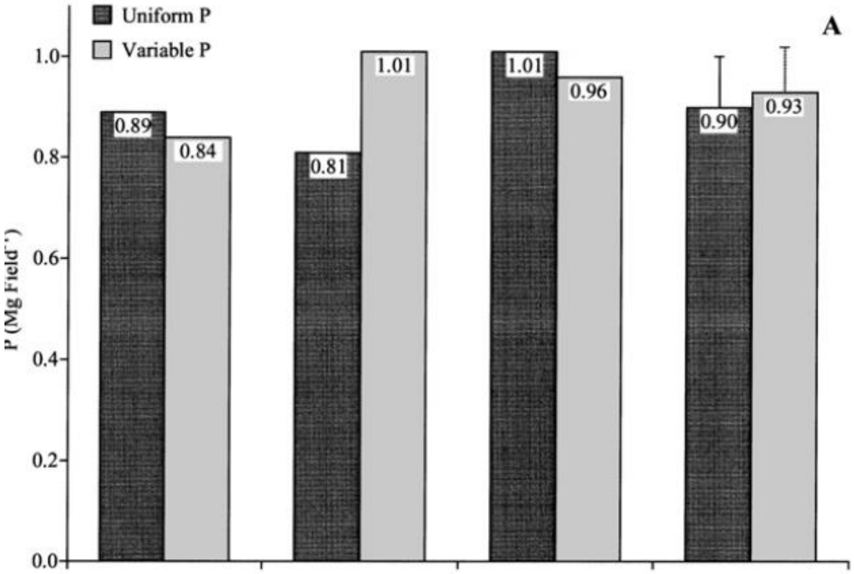
Gowda et al. (2005) reported an average VR P fertilizer rate of 27.2 kg P/ha to a Minnesota corn field, compared to a typical regional uniform application rate of 40 kg P/ha, a net reduction of ~32%.

In Iowa, Bermudez and Mallarino (2007) reported that VR application of P fertilizer to corn-soybean rotations led to an average 12.4 % lower P application rate compared to UR over 4 years. The authors concluded that VR P fertilizer management showed potential for reducing P loss from fields through reduced P application rates.

Other researchers have reported only minor changes in net nutrient application with VR NM. In Iowa strip-trials on a corn-soybean rotation, Mallarino et al. (1998) found that differences in net P application between VR and UR treatments were small. The average amount of P fertilizer used with the VR treatment compared with the UR treatment were 2 kg P/ha more at the Corn 1 trial, 2 kg P/ha less at the Soybean 1 trial, 8 kg P/ha less at the Corn 2 trial, and 11 kg P/ha less at the Soybean 2 trial.

In field-sized trials on irrigated corn in Colorado, Khosla et al. (2002) reported that except for treatments that intentionally applied N at rates exceeding recommendation, net N application rates did not vary dramatically between VR and UR management.

Weisz et al. (2003) reported little difference in the total amount of P applied between application methods in any given year to North Carolina soybeans. Net VR P application rates of 80 – 96 kg P/ha compared to UR application rates of 85 – 97 kg P/ha; VR rates were as high as 139 – 161 kg P/ha in some plots.



In a Texas paired-watershed study of VR N fertilizer applications to corn, Harmel et al. (2004) observed that VR N rate resulted in average N rates of 125 and 129 kg/ha applied within the VR subwatershed, 4–7% less than would have been applied under uniform N rate application.

However, the authors pointed out that VR fertilizer application will not always result in reduced total fertilizer application over a field as was the case in their study. The VR field contained a higher proportion of poor yield potential areas that received lower N rates compared to best potential areas; therefore, less overall fertilizer was applied to the field,

Mallarino and Wittry (2006) conducted strip trials on 11 Iowa fields for 3 cycles of a corn-soybean rotation, comparing VR P fertilizer based on dense grid soil sampling to UR fertilizer based on average field STP. The amount of P fertilizer applied by each method varied considerably among fields, and was often but not always less for the VR method. The VR method applied less P than the UR method on ~50 % of the fields (6 - 60 lb P_20_5/ac), the two methods applied about the same amount of fertilizer to ~25% of the fields, and the VR method applied more than the UR method to the reminder of the fields (12 – 22 lb P_20_5/ac). On average across fields, the VR method applied just 9 lb P_20_5/ac less than the UR method.

Fabiani et al. (2020) assessed the sustainability of VR fertilizer technology on wheat production based on case studies in Greece and Czech Republic. All sites had the same net P application rate under VR and UR. Only in one Greek site did the N fertilizer application rate differ between VR and UR (131 kg N/ha vs. 212 kg N/ha); all other sites had same N rate.

There have been some reports of increased net nutrient applications under VR. Yang et al. (2001) tested N fertilizer application to field plots of grain sorghum in Texas, comparing conventional UR N and P to VR N and P applications. The N fertilizer rates for the UR treatment were almost the same as the average rates for the VR treatment, while average P fertilizer rates for the VR treatment were ~40% higher than the P rates for the UR treatment. This is because some of the soil P_2O_5 values were higher than the total P_2O_5 needed. These higher values increased the overall means of soil P levels for the UR treatment, reducing the fertilizer P requirement, while the higher STP zones did not help reduce fertilizer P requirements in low STP zones.

In strip trials on corn-soybean rotations, Witry and Mallarino (2002) reported that VR application of swine manure applied 11% more manure than UR management.

In Iowa, Mallarino and Wittry (2010) compared UR manure treatment to corn-soybean rotations of 51 kg P/ha set by the farmer and the mean STP of initial soil samples (initial mean STP of both fields was in the "low" interpretation range) to VR manure application rates defined by STP sampling of 0.1 – 0.3 ha grid cells. Individual VR application rates were 85 kg P/ha for very low STP, 68 kg P/ha for low STP, 42 kg P/ha for optimum STP, and no P for high or very high STP. Overall VR manure P applications of ~48-64 kg P /ha exceeded those under UR application.

Conclusion: While substantial net decreases in nutrient application under VR NM compared to UR applications have been reported, results are inconsistent; some research has documented either very small changes in net P or N application rates or even higher rates under VR NM, compared to UR management. From discussions in the literature, it is clear that changes in actual nutrient applications with VR NM are highly dependent on initial conditions in a field – e.g., the distribution of initial STP values. If a field contains a high proportion of excessive STP compared to moderate STP areas, less P might be applied under VR than UR because no P will be added to the areas of excess STP. In contrast, a field with a high proportion of low P STP zones and a few > optimum STP areas may receive a lower UR application because the average STP will be elevated by the high STP areas, while a VR application will apply large amounts of P to the low STP soils. Therefore, it cannot be assumed that VR NM would always result in lower net nutrient application.

Changes in soil test P

In simulations of the economic and environmental implications of PA, Weiss (1997) evaluated residual STP as an environmental indicator of the effects of VR application of P fertilizers at different densities of grid sampling. Nearly all soil sampling grid densities modeled showed a strong decrease in residual STP, a result of the high initial overall field STP in the simulation. In simulated low STP fields, residual STP increased in all cases, but the increases tended to be smaller at higher grid precisions. The author concluded that while increased sampling densities drive greater reductions in residual STP in some cases, the average field STP level is important in determining whether greater precision leads to decreased excess STP. Increases in precision can lead to net decreases in excess soil P or have an insignificant effect, depending on initial STP levels in the field.

In North Carolina no-till soybean fields, Weisz et al. (2003) reported that in field areas of lowest initial STP, VR application of P fertilizer resulted in higher post-crop STP compared to UR, while in field areas of high initial STP, VR application resulted in lower STP compared to UR. These effects were statistically significant, but quantitatively small and no longer detectable after two years. The authors did not report changes in average field STP over time.

In Iowa corn-soybean field trials using P fertilizer, Wittry and Mallarino (2004) reported that within-field variability in STP decreased following VR management, because the VR method was designed to apply higher P rates to low-testing areas and no P to high-testing areas. Slight decreases in average STP were observed in VR fields after treatment, but the decrease was statistically significant in only one field.

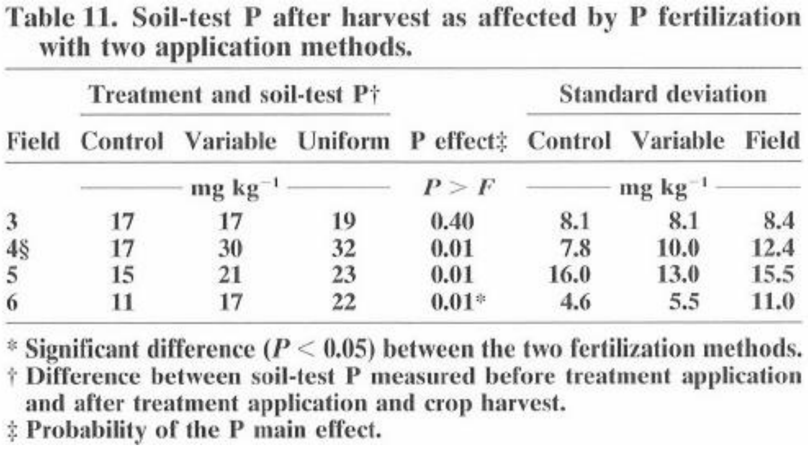


Table 11. Soil-test P after harvest as affected by P fertilization with two application methods.

	Treatment and soil-test P†				Standard deviation		
Field	Control	Variable	Uniform	P effect‡	Control	Variable	Field
	mg kg^{-1}			$P > F$	mg kg^{-1}		
3	17	17	19	0.40	8.1	8.1	8.4
4§	17	30	32	0.01	7.8	10.0	12.4
5	15	21	23	0.01	16.0	13.0	15.5
6	11	17	22	0.01*	4.6	5.5	11.0

* Significant difference ($P < 0.05$) between the two fertilization methods.

† Difference between soil-test P measured before treatment application and after treatment application and crop harvest.

‡ Probability of the P main effect.

Wittry and Mallarino (2002) compare the effects of VR and UR application of swine manure on STP in different STP-class soils on Iowa corn-soybean rotations. The use of VR reduced STP variability by increasing STP more than UR in low-testing areas and reducing or not affecting STP in high testing areas:

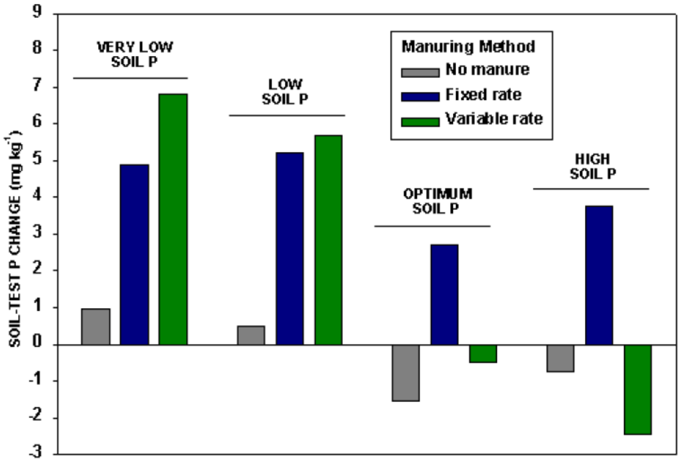


Fig. 1. Effect of the fixed-rate and variable-rate applications of liquid swine manure on soil-test P change after crop harvest for various initial soil-test P interpretation classes (means of 2 years and two fields).

Clearly, as higher rates of manure P were applied to low STP soils under VR, STP tended to increase, whereas low or zero manure P applications to high STP soils under VR tended to decrease STP.

On Iowa corn-soybean fields, Bermudez and Mallarino (2007) reported that STP (Mehlich-3) generally increased in all fields after two P fertilizer applications, but ending field average STP was generally lower where fertilizer applied at VR vs UR application. Decreases in STP ranged from 0 – 15 mg/kg (0 – 38%), averaging 6.5 mg/kg (18%).

Mallarino and Wittry (2010) observed that VR manure application to Iowa corn and soybean fields reduced in-field STP variability after just two years of VR practice. The authors noted that if VR application is used long-term, STP will eventually reach optimum levels across the field and manure P application could then be done uniformly at crop removal rates.

In one case-study site in Greece, Fabiani et al. (2020) estimated that residual soil N was reduced by ~50% in VR treatment (8 vs. 15 mg/kg soil) compared to UR application of N fertilizer, but no differences between VR and UR treatments were observed in Czech sites.

Conclusion: Research has confirmed the fundamental outcome that VR nutrient application will tend to increase soil nutrients in deficient or low concentration areas and decrease soil nutrients in high-testing soils where less P or N is applied. In general, studies have shown that this process can reduce variability in STP across a field under VR application management and that this effect may occur fairly quickly. Based on our understanding of the influence of STP on P loss in runoff or tile drainage, it seems likely that reductions of STP, especially in high STP field areas, can lead to decreases in P loss from the field. As a field moves toward a more homogeneous STP, overall P application may be able to be done at a basic crop removal rate, potentially reducing the total P application rate to the field and facilitating optimum NM.

However, it is clear that these effects are variable and highly dependent on initial conditions. Thus, it is difficult to generalize the effect of VR NM on soil nutrients.

Changes in crop yields

Changes in crop yields may influence nutrient losses from a field by reducing surplus nutrients left in the soil after harvest (increased yields) or by leaving excess nutrients in the soil (decreased yields). Thus, changes in crop yields in response to VR NM may provide another indirect measure of the impacts of VR NM on P losses.

In the UK, Weiss (1997) modeled the effects of increasing precision of soil sampling and VR P fertilization on a number of economic and agronomic parameters. The author reported a slight tendency for estimated yield to increase with increasing soil grid sampling precision, but the effect was said to be minuscule.

In Iowa field strip-trials on corn-soybean rotations, Mallarino et al. (1998) reported that crop yields did not differ significantly between UR and VR P fertilizer applications, except for a small increase in yield in one VR field.

In Texas, Yang et al. (2001) compared UR and VR N and P fertilizer application to grain sorghum. Yield monitoring data indicated that the VR treatment resulted in significantly higher yields (8 – 17%) than the UR N and P treatments for two treatment years

In field-scale studies of irrigated corn in Colorado, Khosla et al. (2002) compared the use of site-specific management zones (SSMZ) based on soil color, topography, and yield history to the use of soil NO_3-N as guides for VR N fertilizer application. In the higher productive areas (HNH), corn yields were significantly higher from the VR treatment based on SSMZ than from UR N fertilizer application and in one study site, higher than for VR treatment based on grid-sampling for soil NO_3-N. The authors concluded that VR fertilizer application based on SSMZ can manage in-field variability better than uniform rate or yield-based N applications and is more simple and cost effective than grid-based systems.

Wang et al. (2003) evaluated economic and environmental impacts of VR N application to corn production in Missouri claypan soils through modeling. Variable N rates were based on yield targets or conventional recommended rates within management units (defined by topsoil depth and soil pH) on a grid basis within fields. Expected corn yields were generally higher for VR application than for UR application based either on management units or recommended N rates, despite slightly lower N fertilizer rates under VR application compared to either UR strategy.

In studies on a North Carolina no-till soybean field, Weisz et al. (2003) found that VR P fertilizer in areas of low initial STP did not result in a consistent increase in yield, possibly because other factors such as drought stress limited production.

Wittry and Mallarino (2004) reported that P fertilization increased corn and soybean yields in Iowa fields vs. an unfertilized control, but the method of application (UR vs. VR) did not affect crop yield in any year.

Mallarino and Wittry (2006) evaluated impacts of VR P and K fertilizer applications on yield in Iowa corn-soybean rotations. The authors reported that in spite of the obvious variation in soil-test values and responses to uniform fertilizer rates applied to the strips, there was seldom a statistically significant grain yield difference between UR and VR fertilizer application methods. The UR method increased yield more than the VR method in one-half of the instances and the opposite result was observed in the others. Yield responses to contrasting soil types within a field sometimes had a much greater effect on yields than fertilizer application method.

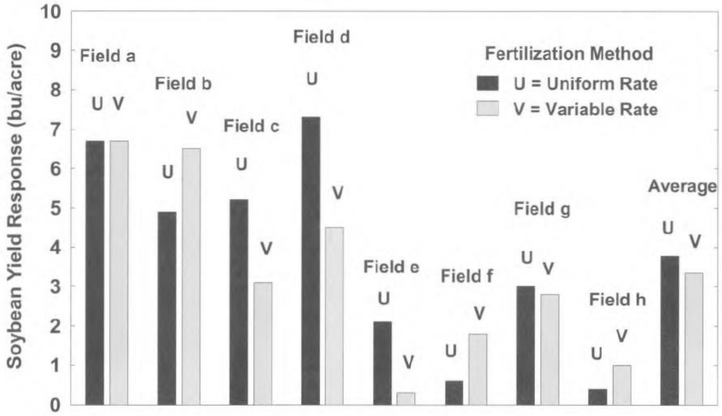


Figure 2. Soybean yield response to P fertilization with uniform and variable-rate application methods for eight representative Iowa fields (field identifiers are arbitrary codes).

In strip trials on Iowa corn-soybean fields, Bermudez and Mallarino (2007) observed that VR P fertilizer application did not significantly change corn or soybean yields, although yield variability was often decreased under VR management.

In Iowa, Mallarino and Wittry (2010) reported that swine manure application to corn-soybean rotations generally increased yields, but found no significant yield differences between UR and VR management.

Boyer et al. (2011) found no statistical difference in wheat yields in Oklahoma plots between VR and UR N fertilizer treatments

Conclusion: VR NM appears to generally maintain or slightly increase crop yields; reports of decreased yields are few. Effects on yield appear to depend on soil characteristics and initial soil nutrient levels, as well as on nutrient application strategy. To the extent that maintenance or increase in crop yield may be coupled with decreased nutrient application rate, yield may be an indirect indicator of potential water quality effects of VR NM. However, the metric is unlikely to be quantitatively large.

Monitored or modeled effects on water quality

As noted earlier, there are few studies that report direct effects of VR NM on water quality, either through monitoring or modeling.

Wang et al. (2003) evaluated economic and environmental impacts of VR N applications to corn production in Missouri using modeling; VR applications were driven by management units based on soil depth and pH. The authors estimated potential water quality benefits as a calculation of potential leachable N remaining from optimum N applications and crop yields. An index (DPLN, the difference in potential leachable N between VR and UR treatments) was used as an indicator of potential water quality benefits; absolute N concentrations or loads were not reported. VR treatment had greater water quality benefits when compared to UR, although benefits varied across fields. Sensitivity analysis indicated that water quality benefits of VR treatment increased with greater variability in topsoil depth and/or soil pH, Residual soil N was lower for all cases of VR compared to UR treatment because VR eliminated excessive N application associated with UR in some portions of fields, which resulted in water quality benefits.

Harmel et al. (2004) conducted a paired-watershed study to evaluate the impacts of VR N fertilizer application to corn in Texas. Corn yields were similar for the two fields even though less N was applied by the VR treatment. During the 2-year monitoring period, VR N treatment resulted in few water quality differences compared to UR application, but overall median NO_3-N+NO_2–N concentrations were significantly lower for the VR field in the second year of VR N application. Overall and event mean NO_3-N+NO_2–N concentrations from the VR field tended to be higher, but median concentrations tended to be lower than those from the UR field. The authors suggested that this pattern could represent a water quality improvement, but could also be attributed to dilution from increased runoff volume from the VR field. Total N loads were similar between the VR and UR fields, but the lack of significant N load increase from the VR field despite higher runoff volume suggested improvement in water quality. Dissolved P concentrations and TP loads were similar from both fields, probably because P applications were the same for both fields.

In Colorado, Delgado et al. (2005) identified specific management zones for VR N fertilization based on productivity and leaching potential; the authors used the model NLEAP to simulate soil and leached NO_3-N. Nitrate leaching was variable across the management zones, with highest leaching losses occurring in low productivity zones. As N fertilizer rate increased by productivity zone, the rate of NO_3-N leaching increased and the increases were greatest for the low-productivity zone. The authors reported that spatially variable N management based on realistic yield goals within productivity zones produced less NO_3-N leaching than uniform strategies while maintaining maximum yields. They estimated that using VR application to site-specific management zones reduced nitrate leaching losses by 25% during the first crop year.

Gowda et al. (2005) conducted a field/modeling study of VR P fertilizer application to corn in Minnesota. The authors used field data to calibrate the ADAPT model (a combination of GLEAMS and DRAINMOD) to simulate long-term P loss, including both runoff and tile drainage. Modeled P losses were 3.6 – 11% lower for VR application than those from a typical UR application. The authors concluded that a VR application strategy could produce measurable reductions in off-site P losses on similar fields, compared to UR application strategy.

Fabiani et al. (2020) published an assessment of economic and environmental sustainability of VR fertilizer application to wheat in case studies in Greece and Czech Republic. The authors reported results that provide evidence of a decrease in N losses due to lower application amounts and improved distribution according to potential productivity within fields and proposed reductions in nitrate leaching, although no quantitative data were provided.

Conclusion: There is scant quantitative evidence reported in the literature for water quality changes – especially with respect to P – in response to VR NM. While some decreases in nutrient losses have been reported under VR management, other work has reported no significant effect.

Economics of VR nutrient management

Several reviewed studies included data and analysis of the economics of PA and VR NM. While economic aspects are not directly relevant to estimating P loss reductions, the financial impacts of new NM practices will undoubtedly influence adoption by producers and thereby the extent of any potential effects on water quality. It should be noted that papers exclusively presenting economic analyses were not included in the review, so this discussion of economic impacts is undoubtedly incomplete.

Some researchers have reported positive economic returns under VR NM.

- In a modeling study, Wang et al. (2003) reported that in Missouri corn production, even with additional application costs (e.g., high-density soil testing), VR NM was more profitable than UR NM. The higher profits under VR resulted primarily from increased corn yields; N fertilizer cost savings were minimal. Profitability of VR relative to UR N application varied among fields and depended on the uniform N strategy to which it was compared, and within-field variation in soil properties. Moreover, variations in topsoil depth and soil pH were important determinants of corn yield variation and had significant impact on the profitability and water quality benefits of VR NM.
- Koch et al. (2004) tested uniform, grid-based VR and site-specific management zones (SSMZ) against UR N management on irrigated corn in Colorado. The authors reported that VR N applications using SSMZ with variable yield goals were more profitable than conventional UR application. Net returns from SSMZ treatment were \$18 - \$30/ha more than those from UR N management.
- Iho and Laukkanen (2012) presented a complex socio-economic model of P management and agriculture in the context of grain production in Finland. The model related soil P to dissolved P in runoff in a framework that addresses socio-economic damages from excess P loading to waterways and seeks an optimum solution for crop production, P management, and environmental impacts. Although the paper does not explicitly define the relationship between soil P and runoff dissolved P or cite quantitative changes in either parameter with precision P management, the authors conclude that

precision P management is a useful means to mitigate agricultural P loading and provides important socio-economic benefits.

- Fabiano et al. (2020) found limited economic benefits of VR N fertilizer application in study sites in Czech Republic and Greece, amounting to just €20 and €117/ha, respectively. The difference in economic performance was due to initial overapplication of N fertilizer at the Greek site, vs. application rates already near optimum at the Czech sites.

Other research has reported mixed results or little economic impact of VR NM.

- Prato and Kang (1998) modeled crop yields, N losses, and net economic returns using EPIC on Missouri fields under VR or UR N management. The authors found that profitability of UR and VR management varied with cropping system. UR was consistently more profitable than VR in a grain sorghum system (and resulted in less N loss), while VR was more profitable in corn. The authors concluded that among the cropping systems and watershed evaluated, VR N application is not uniformly superior to UR in terms of increasing net return and improving water quality. This result suggests that the benefits of VR relative to UR should be expected to vary by watershed.
- In comparisons of VR and UR N fertilizer application to grain sorghum in Texas, Yang et al. (2001) found that a simple economic analysis showed that VR treatment had positive relative economic returns over UR treatment, $23 - $27/ha. However, if additional costs for soil sampling, equipment, and data analysis associated with VR management were considered, these returns would be much lower or even negative.
- Mallarino and Wittry (2006) reported that in Iowa corn-soybean rotations, VR NM does reduce unnecessary P fertilizer applications to high-testing field areas. However, savings in fertilizer were usually small for reasonably well-managed fields. The authors concluded that VR NM may result in significant increases in profitability only if the philosophy of fertilization is changed to a more strict response-based or crop-removal approach.
- In studies of the profitability of VR N fertilizer application in Oklahoma wheat production, Boyer et al. (2011) reported no significant difference in net returns across VR or UR treatments. VR treatment was the most profitable management for a split-application treatment, whereas UR management was the most profitable approach for the top-dress treatment. The authors expressed doubt that VR management would be broadly adopted over conventional treatments by Oklahoma wheat producers.

Finally, there have been some reports of increased costs and reduced economic returns from the adoption of VR NM.

- Weiss (1997) used modeling to evaluate the effects of increased precision in soil sampling on economic returns to UK farmers and on net changes in STP. Cost of P fertilizer applied actually increased with increasing grid density of STP sampling points. A major increase was recorded when sampling density increased from the coarsest grid to the next level because one of the 4 coarse sampling points was in a very high STP zone and called for little P fertilizer. Even another scenario with much lower field average STP showed higher application rates with more precise STP sampling grids than with less precise ones. Combined costs of denser STP sampling grid and P fertilizer application rates drove strong increase in input costs with rising precision. STP sampling costs were main driver of this increase. A slight tendency for yield to increase was found with increasing grid precision, but the effect was minuscule. As a result, farmer's net return (gross revenue minus costs) shows consistent decrease with increasing grid precision. The author concluded that increased precision in soil sampling (and VR P fertilizer application) does not pay for itself through increased production; increased density of soil sampling in support of precision P application has a negative economic return to farmers

- In an overview of PA technologies and concepts, Mallarino and Schepers (2005) stated that a combination of increased costs with current VR fertilization methods and infrequent yield differences between VR and UR management suggest little incentive for widespread adoption of expensive grid-based soil sampling methods to guide VR NM. The authors proposed that development of VR management zones based on existing information layers (e.g., soil survey, yield maps, aerial imagery) would be more cost effective than dense grid sampling approaches.

Conclusion: based on this limited view of the economics of VR NM, it appears that VR NM does not consistently offer improved economic return to the farmer, despite any environmental or nutrient use efficiency benefits. Increased costs for soil testing and advanced equipment, coupled with inconsistent yield increases suggest that on-farm net benefits are likely to be small or non-existent. Several authors have noted that changes in profitability with VR NM are highly dependent on initial conditions of STP and NM.

Recommendations

There has been little direct evidence reported in the literature for changes in runoff/leaching losses of nutrients attributable to VR NM. Most reports based on monitoring or modeling have focused on N losses from VR N fertilizer applications and have limited applicability to VR manure application in the LCB, especially to estimating P load reductions from VR NM.

Indirect evidence – change in nutrient application rates, soil nutrients, and crop yields – is also of limited use in estimating P load reductions from VR NM.

Changes in total nutrient application rates under VR application compared to UR application have been inconsistent. Some research has reported substantial net decreases in overall nutrient application rates under VR NM, while other work has documented only very small decreases or even increases under VR NM. Changes in actual nutrient applications with VR NM appear to be highly dependent on initial conditions in a field – e.g., the distribution of initial soil test values across the field. If, for example, a field contains a high proportion of excessive STP compared to moderate STP areas, less net P might be applied under VR than UR because no P will be added to the areas of excess STP. In contrast, a field with a high proportion of low P STP zones and a few > optimum STP areas may receive a lower UR application because the average STP will be elevated by the presence of high STP areas, while a VR application will apply larger amounts of P to the extensive areas of low STP soils. Therefore, it cannot be assumed that VR NM will always result in lower net nutrient application.

Most research has confirmed the notion that VR nutrient application will tend to increase soil nutrients in deficient or low nutrient concentration areas and decrease soil nutrients in high testing soils where less P or N is applied. In general, studies have shown that this process can reduce variability in STP across a field under VR application management and that this effect may occur fairly quickly. Based on our understanding of the influence of STP on P loss in runoff or tile drainage, it seems likely that reductions of STP, especially in high STP field areas, can lead to decreases in P loss from the field. As a field moves toward a more homogeneous STP, overall P application may be able to be done at a basic crop removal rate, potentially reducing the total P application rate to the field and facilitating optimum NM. However, it is clear that these effects are variable and highly dependent on initial conditions. Thus, it is difficult to generalize the effect of VR NM on soil nutrients.

According to most research, VR NM appears to generally maintain or slightly increase crop yields; reports of decreased yields are few. Preservation of crop yield may be an important argument in support of adoption of VR NM. However, crop yields appear to depend on soil characteristics and initial soil nutrient levels, as well as on nutrient application strategy, so yield effects may be difficult to generalize. To the extent that maintenance or increase in crop yield may be coupled with decreased nutrient application rate, yield changes may be an indirect indicator of potential water quality effects of VR NM. However, the metric is unlikely to be quantitatively large.

Based on a limited review of the economics of VR NM, it appears that VR NM does not always offer improved economic return to the farmer, despite any environmental or nutrient use efficiency benefits. Increased costs for soil testing and advanced equipment, coupled with inconsistent yield increases suggest that on-farm net benefits are likely to be small or non-existent. Several authors have noted that changes in profitability with VR NM are highly dependent on initial conditions of STP and NM.

Because of the lack of convincing evidence of a measurable water quality benefit for VR nutrient application, it is recommended that no P reduction credit be given to precision agriculture/VR NM (as embodied in VR manure application) in the LCB at this time. While it is still a potentially valuable practice in improving manure P use efficiency and managing soil test P in the long term, there is no scientific basis at this time to recommend an immediate P loss reduction credit.

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Appendix E: Soil Aeration Phosphorus Reduction Efficiency

Soil aeration, or the punching of holes, pits, or slots into the soil to promote soil infiltration/adsorption of manure mainly on grassland, may be associated with reduced nutrient runoff and water quality benefits. This appendix, however, outlines why the Vermont Agricultural BMP Tracking and Accounting Workgroup (hereafter Workgroup) decided to not adopt a phosphorus reduction efficiency for soil aeration practices in Vermont.

Literature Review

Don Meals, an agricultural researcher with Tetra Tech, conducted an extensive literature review of the effects of soil aeration on nitrogen and phosphorus runoff from agricultural fields. Don identified 18 relevant studies, covering various methods of aeration, study scales, study time frames, and types of manure, soil, crops, runoff components, and nutrient components. Don extracted data from these studies to produce 67 individual records of phosphorus reductions/increases and 30 individual records of nitrogen reductions/increases. These individual records represented single measurement events within a study, where possible.

Don provided a summary of the literature review to the Workgroup in spreadsheet format. Don also presented an overview of his literature review to the Workgroup, where he provided the following recommendations:

1. Consider giving no phosphorus reduction credit at all given the variability and uncertainty reported in the literature
2. Focus on median efficiency values or select the results most relevant to Vermont or the Lake Champlain basin.
3. Devalue nutrient reduction efficiencies from plot studies and studies without full annual or seasonal monitoring, as these are not representative of natural field conditions.
4. Condition efficiency values only on the surface runoff component of phosphorus loss.

The Workgroup reviewed the literature review dataset and ultimately agreed to not assign a phosphorus reduction efficiency for soil aeration. Justification for the lack of efficiency is provided in the following sections. A nitrogen reduction efficiency will be assessed separately after all phosphorus reduction methods have been established.

Phosphorus Dataset Development

The original literature review dataset developed by Don was narrowed down to include only studies relevant for determining a soil aeration phosphorus efficiency in Vermont. The following conditions and methods were applied to the original literature review dataset.

1. <u>Only surface runoff and total phosphorus (TP) data</u>. The Lake Champlain TMDL model is limited to the surface component of total phosphorus runoff, so subsurface flow and leaching data were removed from the dataset. The model also only applies to total

phosphorus, so particulate phosphorus and soluble phosphorus data entries were removed. If data were classified as surface runoff and subsurface flow ("Both" in dataset), the data were excluded since the surface component could not be classified.

2. All significant and non-significant findings. The literature on soil aeration varies greatly in statistical significance, with some studies not even reporting the significance of findings. To avoid narrowing down the dataset too much, all results were included regardless of statistical significance.
3. All manure types, soil types, and equipment types. Including all these data captures the wide range of possible soil aeration practices in Vermont.
4. For studies with multiple measurement events, one phosphorus reduction value was calculated as the difference between the summed control loads and summed treatment loads. Calculating summed differences minimizes the variability that arises from multiple measurement events across various time scales when comparing to other articles that only reported averaged multiple events.

Based on this phosphorus dataset, the median total phosphorus reduction efficiency was 29%.

Phosphorus Reduction Efficiency Recommendation

The research on soil aeration was more variable and contradictory than for other forms of manure incorporation and injection. Many references reported no significant effect of soil aeration on nutrient loss or reported increases in nutrient losses. There was also a generally low number of studies available to identify under what conditions aeration is consistently beneficial or detrimental for total phosphorus runoff. As a result, the Workgroup was not confident to establish a phosphorus reduction efficiency based on this highly variable literature review.

As the literature review was inconclusive, Vermont agricultural researchers were contacted to see if they could provide additional insight into the effects of soil aeration in Vermont. In response, UVM Extension shared a draft manuscript on the effects of soil aeration on nutrient loss from hay fields in Vermont (Twombly et al. 2021). This paired watershed study with a calibration period and year-round edge-of-field monitoring was conducted in Chittenden County, Vermont from 2012 to 2018. Overall, soil aeration reduced TP concentrations by 32% but increased surface runoff volume by 16%, which resulted in no significant reductions in TP loads. These findings may be due to multiple factors, such as increased compaction from aeration on poorly drained soils. The literature review conducted for the introduction and discussion of the paper also found no significant TP load reductions associated with soil aeration. Some papers cited did find load reductions on well-drained soils, but the results were not always consistent.

Furthermore, the Chesapeake Bay Program (CBP) does not have a phosphorus, nitrogen, or sediment load reduction efficiency for soil aeration in the Chesapeake Bay watershed (CBP 2018). CBP (2018) and the Manure Injection & Incorporation Expert Panel did not specifically address why this practice does not receive nutrient credits, but it should be noted for comparison with Vermont TMDL tracking and accounting purposes.

Overall, multiple lines of evidence (i.e., literature review, recent Vermont-specific research study, and Chesapeake Bay TMDL program) suggest that soil aeration may not be associated with reductions in total phosphorus loads from hay fields in Vermont. As a result, the Workgroup decided to not adopt a phosphorus reduction efficiency for soil aeration practices in Vermont. This decision is further supported by the fact that AAFM is dropping cost share for soil aeration and the Vermont Phosphorus Index also does not have a reduction for this practice.

Limitations

Although the Workgroup decided to not assign a phosphorus reduction efficiency for soil aeration, there may be a water quality benefit associated with this practice. The Workgroup believed there was not enough conclusive scientific evidence to adopt an efficiency at this time, but this decision may be amended as more scientific studies relevant to Vermont are conducted.

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