Cover crops reduce subsurface nutrient loads to downstream management practices improving cost-effectiveness

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Highlights

- Cover crop implementation reduced nutrient loads and concentrations in drain tile
- Nitrogen, total and dissolved reactive phosphorus removal costs of $13, $955 and $1,720 kg^{-1} ha^{-1}
- Cover crop implementation improved downstream management practice performance

Abstract

The conservation practice of cover crop adoption, expanding rapidly in the Midwest United States in recent years, has been shown to be one of the most cost-effective practices for reducing nutrient loss from agricultural landscapes. In particular, cover crops may aid in the prevention of nutrient losses through drain tile, a common and necessary agricultural practice for removing excess soil moisture. When implemented as part of an agricultural treatment train, a series of management practices placed across a landscape gradient, cover crops may also serve to improve both cost and nutrient removal efficiencies of downstream practices. Through modeling techniques and field monitoring spanning 2013-2019 at a southern Minnesotan agricultural demonstration field site, this study aims to characterize total nitrogen, total phosphorus, and dissolved reactive phosphorus concentrations and load reductions provided by cover crops. Direct implementation cost estimates and nutrient removal performance improvements provided by cover crops to a downstream treatment wetland were also analyzed. Analysis of drain tile water quality and quantity data showed annual concentration reductions of 48%, 75% and 63% and annual load reductions of 9.13, 0.12 and 0.07 kg ha^{-1} for total nitrogen, total phosphorus and dissolved reactive phosphorus, respectively. Direct cost estimates for these cover crop reductions were \$13.96, \$955, and \$1,720 kg^{-1} ha^{-1} yr^{-1}. Cover crops improved annual nutrient removal cost of a downstream wetland by \$18.47 kg^{-1} for TN and \$211.38 kg^{-1} for TP.

Key Words

Nitrogen, Phosphorus, Drainage, Treatment Train, Cover Crops

Abbreviations

TN – Total Nitrogen
P - Phosphorus
TP – Total Phosphorus
DRP – Dissolved Reactive Phosphorus

1. Introduction

The use of cover crops as an agricultural conservation management practice includes the planting of forbs, legumes or grasses that provide fall and spring coverage on otherwise bare agricultural lands (Carlson and Stockwell, 2013; Sustainable Research Agriculture and Education, 2016). This vegetative cover increases agroecosystem water and nutrient demands, through plant uptake and growth requirements, while also improving soil quality (Blanco-Canqui et al., 2015; Keesstra et al., 2018). In addition to providing economic benefits including increased yield and reduced tillage costs, cover crops have the potential to reduce subsurface nutrient losses (Drury et al., 2014; Sustainable Research Agriculture and Education, 2020; Zhang et al., 2017) . Rye winter cover crops have been shown to reduce drain tile total nitrogen (TN) loads by an average of 15.40 kg ha^{-1} and to reduce concentrations by up to 39% (Ruffatti et al., 2019; Yang et al., 2021). Erosion control provided by cover crops on otherwise bare soil may also reduce particle-bound phosphorus (P) (Liu et al., 2019; Maltais-Landry et al., 2015).

While cover crops reduce nutrient losses, subsurface drainage (i.e., drain tiles), a necessary agricultural management practice for crop yield maintenance and stress reduction, can contribute to downstream water quality impairments (Blann et al., 2009; Smith et al., 2018; Zucker and Brown, 1998). Increases in drain tile acreage, have been associated with increased dissolved reactive phosphorus (DRP) loads in agricultural tributaries with variable P dynamics observed among different cropping systems and variable agroecosystems (Hanrahan et al., 2021; Jarvie et al., 2017; Nuruzzaman et al., 2005; Smith et al., 2015). What happens when cover crops and drain tiles are used concurrently is less clear. Studies have documented a wide range of P drain tile responses to cover crop implementation, including both P concentration increases and decreases, as well as observed P reductions when implemented in association with additional management practices. (Horst et al., 2001; Lenhart et al., 2017; Ni et al., 2020; Zhang et al., 2017).

Cover crops are planted in the fall after cash crop harvest, followed by manual post-emergent herbicide termination, senescence, or other removal methods in late spring (Hanrahan et al., 2018; Rosario-Lebron et al., 2019). Direct cover crop implementation cost factors, which are required to determine impacts to land-owner profitability; include seed mix, planting, and termination (Christianson et al., 2013; Lazarus and Keller, 2018). In addition to environmental benefits, cover crops have the potential to improve farm-wide profit through crop system management alterations, yield improvements, and reduced labor, time, and machinery wear under no-till or reduced tillage practices commonly associated with cover crops (Bergtold et al., 2017; Seifert et. al., 2018; Singh et al., 2021). Cover crops may also improve nutrient removal efficacy and associated cost-benefit ratios of downstream practices.

This may be particularly true when used as part of an agricultural management practice treatment train, which is comprised of multiple management practices placed in series along a landscape gradient, designed to improve the performance of downstream practices by treating portions of the same runoff and nutrient load (Apfelbaum et al., 1995). The treatment train framework may provide greater cumulative nutrient reduction and lower per-unit cost nutrient removal than the use of a single practice (Lenhart et al., 2017; Magner, 2011). One framework may consist of an "avoiding" practice such as a cover crop, placed at higher elevation in the landscape to reduce flows and nutrient delivery to a downstream "trapping" practice, such as a pond or wetland (Lenhart et al. 2017) (Figure 1).

Few studies have documented the economic and water quality benefits of agricultural management practice treatment trains (Barber et al., 2016). This study fills this research gap through modeling methodologies and field data collection at an agricultural field research site present with a rye winter cover crop located upstream of a treatment wetland. At the research site, located in southern Minnesota, 10.12 hectares of upland cropland are present with a drain tile system that outlets at the treatment wetland, constructed in 2013. We conducted water quality and quantity monitoring at this outlet between 2013 and 2019 with rye winter cover crop use occurring between the Fall of 2015 and the Spring of 2019. Data spanning 2013-2015 allowed for the analysis of drain tile nutrient transport without cover crops and data spanning 2016-2019 for analysis with cover crops (Gordon et al., 2021).

The primary objective of this study was to characterize cover crop benefits at a working field demonstration site within the context of an agricultural best management practice treatment train. The first objective of this study was to estimate drain tile nutrient load and concentration reduction rates in the presence of cover crops and the associated cost of nutrient removal. Quantifications of changes in subsurface nutrient concentrations and loads and the association of implementation costs from a long-term field study will aid in the development of state and federal water quality implementation planning (Lenhart et al., 2017, Wall et al., 2020).

We hypothesized that TN, total phosphorus (TP) and DRP drain tile concentrations with cover crops would be less than those without cover crops. Additional research objectives included quantification of cover crop nutrient load reductions in kilograms per hectare per year and direct cover crop implementation cost in dollars per kilogram per hectare per year. The final objective was to quantify nutrient reduction and cost benefit improvements provided by cover crops to a downstream treatment wetland.

2. Materials and methods

2.1 Study site

The research site is located in Martin County Minnesota near the Iowa border within the Blue Earth River Watershed, draining to Elm Creek (AUID 07020009-502). The site has been extensively studied and serves as an agricultural BMP demonstration site (Gordon et al., 2021; Lenhart et al., 2016; Ross, 2014). Cropland, covering 10.12 ha, is present under a bi-annual corn and soybean rotation with conservation tillage. Crop yields averaged 187-bushel units for corn and 52-bushel units for soybean between 2013 and 2019. Average annual crop yields in Minnesota are 192-bushel units for corn and 49-bushel units for soybean (USDA, 2021). Phosphorus fertilizer application rates were consistent, averaging 90 kg ha^{-1}, slightly passing regional rate recommendations (Kaiser et al., 2011). Nitrogen fertilizer application rates averaged 18 kg ha^{-1} between 2013 and 2017 increasing to an average rate of 170 pounds per acre in 2018 and 2019, surprising region rate recommendations (Kaiser et al., 2011). A drain tile system is present with a spacing of 24 m, and a depth of 1.2 m, within loam and clay loam soils consisting of 22% clay, 42% sand and 36% silt. Drain tile flow outlets at an Agri Drain control structure located at the inlet of a subsurface treatment wetland covering .10 ha, where water quality and quantity sampling was conducted between 2013-2019 (43° 45' 4''N, 94° 20' 51''W; Figure 2).

The use of a rye winter cover crop began in the Fall of 2015 allowing for pre-cover crop analysis between the years of 2013-2015 and post-cover crop analysis between the years of 2016-2019. The cover crop mix consisted of 96.55% fall rye (*Secale cereale*), 1.16 % tillage radish (*Raphanus sativus*), 1.14% purple top turnips (*Brassica rapa*) and 1.15% trophy rapeseed (*Brassica napus*). Cover crops were aerial applied between late August and early September and terminated in early May.

Cost for establishment of cover crops on site was \$118.24 ha^{-1}. We obtained seed mix costs from the La Crosse Seed Company based out of La Crosse, WI, for the specific mix used on site at a rate of \$35.95 ha ^{1}. Costs for aerial seed application and spring herbicide application were provided by the University of Minnesota Extension Service at rates of \$42.01 and \$40.28 ha^{-1}, respectively (Lazarus and Keller, 2018). Direct cover crop costs per unit installation have been reported at \$205 ha^{-1} by Lenhart et al. (2017), \$151 ha^{-1} by Roley et al. (2016) and at \$115 ha^{-1} by Christianson et al. (2013).

2.2 Hydrology

We mounted Solinst Levelogger monitoring devices and paired Solinst Barologgers in an Agri Drain water control structure located at the treatment wetland inlet, to capture drain tile outlet flow. A known stage-discharge relationship calibrated by the Minnesota Department of Agriculture enabled for the calculation of flow rate based on water level over a v-notch weir in the control structure recorded in 10-minute time intervals. Flow rate was calculated as follows in Equation 1:

$$\text{Equation 1. } Q = 0.98x^{2.08}$$

where Q is the flow rate in cubic feet per second and X is water stage above the v-notch weir in feet. We then converted flow rate intervals to cubic meters per minute, multiplied by ten and summed to obtain annual and seasonal drain tile outlet volumes. Solinst Leveloggers have an estimated accuracy of ±0.05% from which the error ranges for field monitored tile outflow volumes were generated (Chun and Cooke, 2008).

We utilized annual flow volumes to calculate annual subsurface nutrient loading rates and cover crop load removals. Growing season flow volumes were then calculated between April 1st and September 30th and further divided into early and late period volumes. Early period flow volumes were compared to late period volumes to demonstrate the proportion of total drain tile flow occurring and available for treatment during the time frame of cover crop influence. Early flow volumes were calculated from April to June and late flow volumes from July to September.

2.3 Nutrient Concentration and Load Analysis

Depending on study year, we collected weekly, bi-weekly, or monthly water quality grab samples at the drain tile outlet between April and November. Samples were analyzed at the Minnesota Valley Testing Laboratory in New Ulm, MN, for TN, TP and DRP, methods EPA 365.1 for P and EPA 300.0 for N. Total nitrogen was measured as NO_3^{-1} as previous studies on site and in the region showed this to be the predominant form of N (Nustad et al., 2015). A one-way analysis of variance was utilized to test for significant differences in drain tile constituent concentrations under the presence and absence of cover crops.

Within the FLUX32 software program, we calculated annual flow weighted mean concentrations and loading volumes for each constituent (Minnesota Pollution Control Agency, 2021). FLUX32 software provides the coefficient of variation (CV) for each annual flow weighted mean concentration to compare annual concentration variation around the mean. A flow weighted mean concentration value was also calculated for years without cover crops and years with cover crops. Flow weighted mean concentration values for each constituent both with and without cover crops were multiplied by the average annual site drain tile volume to determine annual loading rates. Loading rates with cover crops were subtracted from those without to estimate annual nutrient load reductions. Annual load reductions were further divided by the study site area to calculate cover crop nutrient reduction benefits in kilograms per hectare per year.

2.4 Concentration-Discharge Values

Utilizing individual water quality grab samples and associated instantaneous drain tile discharge data, we developed concentration-discharge relationships for comparing nutrient loss trends under no cover crop and cover crop conditions. We then used the power function equation to draw conclusions about the movement of constituent solutes under a range of discharge values, specifically mobilization and sources of constituents, following Equation 2:

$$\text{Equation 2. } C = aQ^{b}$$

where a is the curve coefficient, C is the drain tile concentration in mg l^{-1}, and Q is the flow rate in cubic meters per second. The component "b" serves to quantify the per unit concentration increase relative to a per unit discharge increase. Values of $b < 0$ suggest concentrations follow a diluting pattern, values of $b > 0$ suggest constituent mobilization with flow increases, and values of $b = 0$ suggest chemostatic behavior, or no significant concentration changes in association with discharge (Dolph et al., 2019; Godsey et al., 2009).

2.5 Prioritize, Target and Measure Application Treatment Train Analysis

The Prioritize, Target and Measure Application is a water quality model that leverages geospatial data and information systems to characterize nutrient, sediment, and hydrologic loading by field scale catchments. The application calculates hydrologic travel times, runoff volume and peak flow to characterize landscape TN and TP load and yield for a 10-year, 24 hour storm events. Locations are identified in the landscape that are feasible for various agricultural management and conservation practices. Nutrient reductions and implementation costs associated with feasible practices are calculated, both for single practice and treatment train scenarios. Costs for treatment wetland construction and annual cover crop implementation were taken from model outputs for use within this analysis (Houston Engineering, 2016). Cumulative treatment train load reductions are estimated through calculation of both the localized flow volume in addition to flow volumes and loads delivered from upstream best management practices to downstream best management practices (Houston Engineering, 2015).

We modeled the .10 ha treatment wetland at the field site within the Prioritize, Target and Measure Application to estimate TN and TP load reductions and implementation cost as a standalone practice. This practice was then modeled as part of a treatment train with 10.12 ha of upland cover crop. Wetland nutrient reduction efficacy, defined as kg ha^{-1} yr^{-1} of reduction, was utilized in association with the additive load reduction resulting from the treatment train scenario to calculate what size reduction could be applied to the wetland to achieve the same cumulative site nutrient reduction. Finally, we calculated the new cost associated with the reduced wetland size, in addition to the cost for cover crop implementation to determine the cost of nutrient reduction, defined as dollar kg^{-1} of nutrient reduction, associated with using cover crops as part of an agricultural best management practice treatment train.

3. Results

3.1 Drain Tile Flow Volumes

Annual growing season drain tile volumes ranged from 5,583 m^3 to 19,289 m^3, averaging 12,173 m^3 across the study period. Proportions of the total growing season drain tile volume occurring during the early period of April 1 through June 30th ranged from 55% to 96%, averaging 80% across the total seven-year study period. Alternatively, drain tile volumes during the late period of July 1 through September 30th ranged from 4% to 45% of the total drain tile volume averaging 20% across the total seven-year study period. The average proportion of the total growing season drain tile volume during the early period was 84% in years without cover crops and 77% in with cover crops (Figure 3). Rainfall depth during the growing season averaged 61.50 cm between 2013 and 2019, with 54% occurring during the early period and 46% occurring during the late period.

3.2 Concentration-Discharge Relationships

Parameter “b” of the log-log concentration discharge relationship for TP with cover crops was -.32, indicating source limitation and concentration dilution at high flows. Parameter “b” of the log-log concentration discharge relationship for TP with no cover crops was .23, indicating constituent mobilization at higher flows through erosional processes. Similarly, parameter “b” of the log-log concentration discharge for DRP was -.46 with cover crop and .22 without cover crops (Figure 4). Parameter “b” of the log-log concentration discharge for TN was close to zero both with and without cover crops, indicating minimal concentration changes relative to variation in discharge (Dolph et al., 2019).

3.3 Annual Drain Tile Nutrient Concentrations

Annual TN flow weighted mean concentration ranged from 6.9 mg l^{-1} to 23.3 mg l^{-1}, with a flow weighted mean concentration of 11.3 mg l^{-1} across all study years (Figure 5). TN flow weighted mean concentration across study years without cover crops was 17.13 mg l^{-1} and 8.97 mg l^{-1} across study year with cover crops, resulting in a TN flow weighted mean concentration reduction of 48%. Results of a one-way analysis of variance test found a significant difference at the 99% level between TN concentrations in years without cover crops and years with cover crops ($F(1, 113) = 80.02$, $p < .00$).

Annual TP flow weighted mean concentration ranged from 0.02 mg l^{-1} to 0.15 mg l^{-1} , with a flow weighted mean concentration of 0.04 mg l^{-1} across all study years (Figure 6). TP flow weighted mean concentration across study years without cover crops was .12 mg l^{-1} and .03 mg l^{-1} across year with cover crops, resulting in a TP flow weighted mean concentration reduction of 75%. Results of a one-way analysis of variance test found a significant difference at the 99% level between TP concentrations in years without cover crops and years with cover crops (F(1, 110) = 12.29, $p < .00$).

Annual DRP flow weighted mean concentration ranged from .02 mg l^{-1} to .12 mg l^{-1} , with a flow weighted mean concentration of .04 mg l^{-1} across all study years (Figure 7). DRP flow weighted mean concentration across study years without cover crops was .08 mg l^{-1} and .03 mg l^{-1} across study years with cover crops, resulting in a DRP flow weighted mean concentration reduction of 63%. Results of a one-way analysis of variance test found a significant difference at the 99% between DRP concentrations in years without cover crops and years with cover crops (F(1, 85) = 25.81, $p < .00$).

3.4 Drain Tile Nutrient Load Analysis

Annual TN loads ranged from 8 kg ha^{-1} to 170 kg ha^{-1}, with a mean load of 64 kg ha^{-1} across all study years (Table 1). The average TN load in years absent of with cover crops was 22.81 kg ha^{-1} and 13.69 kg ha^{-1} in years present with cover crops, accounting for a cover crop TN reduction benefit of 9.13 kg^{-1} ha^{-1} yr^{-1} (Table 2).

Annual TP loads ranged from .02 kg ha^{-1} to .24 kg ha^{-1} with a mean load of .09 kg ha^{-1} across all study years (Table 1). The average TP load in years absent of with cover crops was .16 kg ha^{-1} and .04 kg ha^{-1} in years present with cover crops, accounting for a cover crop TP reduction benefit of .12 kg^{-1} ha^{-1} yr^{-1} (Table 2).

Annual DRP loads ranged from .02 kg ha^{-1} to .16 kg ha^{-1} , with a mean load of .07 kg ha^{-1} across all study years (Table 1). The average DRP load in years absent of with cover crops was

.11 kg ha^{-1} and .04 kg ha^{-1} in years present with cover crops, accounting for a cover crop DRP reduction benefit of .07 kg^{-1} ha^{-1} yr^{-1} (Table 2).

3.5 Cost Benefit Analysis

Nutrient removal cost was defined as the dollar per unit of consistent nitrate (?) removal over a unit area. Annual removal rates provided by cover crops were determined to be 9.13 kg ha^{-1} , .12 kg ha^{-1} and .07 kg ha^{-1} for TN, TP and DRP, respectively. Based on a direct cover crop implementation cost of $118.24 ha^{-1} on site, annual cost efficiencies were $12.96 kg ha^{-1}, $955.92 kg ha^{-1} and $1,720.66 kg ha^{-1} for TN, TP and DRP respectively (Table 3).

3.6 Prioritize, Target and Measure Application Treatment Train Analysis

Prioritize, Target and Measure Application modeling results showed that the .10 ha wetland provides a TN load reduction of 141.49 kg and a TP load reduction of 10.56 kg, both to the catchment outlet, for a 24-hour, 10-year storm event at a construction cost of $5,110. Planting and termination of 10.12 ha of cover crops upstream of the wetland provides additional event load reductions to the catchment outlet of 106.69 kg of TN and 6.34 kg of TP, at a cost of $838. With these additive reductions, the wetland size could be reduced to .04 hectares at a new construction cost of $2,040 while providing the same annual cumulative nutrient reductions as the original standalone wetland (Figure 8). Construction of this smaller wetland area would also preserve .06 ha of cropland for production.

The construction cost for the .04 ha wetland and for planting and termination of 10.12 ha of cover crop would be $2,878 proving cumulative treatment train load reductions of 163.19 kg and 10.56 kg for TN and TP, respectively, to the catchment outlet during a 24-hour, 10-year storm event to (Figure 8). Nutrient removal cost of the standalone wetland would be $36.11 kg^{-1}

for TN and \$483.97 kg^{-1} for TP, while nutrient removal cost of the treatment train system would be \$17.64 kg^{-1} and \$272.59 kg^{-1} for TN and TP, respectively.

4. Discussion

Significant drain tile nutrient concentration reductions were observed with the implementation of cover crops at reduction rates of 48%, 75% 63% for TN, TP and DRP, respectively. These reductions were likely driven by the presence of cover crops on previously bare land between April and June, when the largest volume of drain tile flow occurred on site. In addition to nutrient uptake and soil stability, cover crops reduce deep drainage and improve soil water storage during the early crop growth period of April-June, serving to retain nutrients otherwise lost in drain tile (Yang et al., 2019). An average of 84% of the total annual drain tile volume occurred on-site between April and June of 2013-2015 with no cover crops, dropping to an average of 77% between April and June of 2016-2019 with cover crops. Cover crops contribute to reduced soil moisture storage and increased evapotranspiration rates, serving to decrease drain tile volumes (Meyers et. al., 2018).

The greatest CVs around annual flow weighted mean concentrations for both TP and DRP were observed in 2014 and 2018, driven by high drain tile concentrations during storm events. A 3.8-inch rain event in June of 2014 produced TP and DRP concentrations of .40 mg l^{-1} and .25 mg l^{-1}, respectively. A 2.21-inch rain event in June of 2018 produced TP and DRP concentrations of .19 mg l^{-1} and .09 mg l^{-1}, respectively. Rain events in 2018 resulted in a lower CV around the annual mean flow weight concentration relative to 2014. While drain tile TP and DRP losses are associated with large storm events, this provides evidence for added cover crop soil stability and soil water storage. P reductions are largely driven by erosion control during large storm events while nitrogen reduction is driven primarily by water retention, accounting for greater observed P removal rates on site. (Pease et al., 2018; Trentman et al.; 2020).

Variation in concentration-discharge relationships on site between cover crop and without cover crop provide additional evidence for cover crop reduction of drain tile phosphorus losses. TP and DRP relationships with no cover crops follow a concentrating pattern, indicating constituent mobilization at high flows through erosion or landscape connectivity. TP and DRP relationships with cover crops follow a diluting pattern, indicating concentration dilution occurring at high flows resulting from constituent source limitation (Godsey et al., 2009).

No significant difference in nitrogen concentration-discharge relationships were observed with and without cover crops. Annual nitrogen flow weighted mean concentrations increased in 2018 and 2019 following reductions in 2016 and 2017 after cover crop implementation. Increased in nitrogen drain tile flow weighted mean concentration were associated with large fertilizer rate increases on site, consistent with nitrogen fertilizer observations in previous studies (Jaynes, et al. 2001). Concentrations, however, were still lower than those observed previously under no cover crops and with lower fertilizer application rates.

Results quantifying cover crop nutrient load reduction rates and direct implementation costs will benefit Midwestern cover crop implementation efforts. The Minnesota Nutrient Reduction Strategy is a multi-agency initiative begun in 2014 as part of a larger 12 state task force to working to reduce nutrient loading to the Gulf of Mexico. Initiative efforts included cover crop expansion and called for 12% phosphorus and 25% nitrogen reductions prior to 2025 (Anderson et al. 2016). It was recognized within the strategy that there was no realistic way to demonstrate reduction achievement without the advancement of research on cover crop implementation and success (Wall et al., 2020). The plan called for 1,900,000 additional acres of cover crop implementation seeing 200,000 acres achieved in the first five years, with minimal progress on corn and soybean rotations specifically.

Results of the study found average annual cover crop reduction benefits of 9.13, .12 and .07 kg^{-1} ha^{-1} at direct annual implementation costs of \$12.96, \$955, and \$1,720 kg^{-1} ha^{-1} for TN, TP and DRP, respectively. Christianson et al. (2021) noted annual reduction costs of both \$2.70 kg^{-1} and \$3.25 kg^{-1} for TN and 35.15 kg^{-1} and 47.60 kg^{-1} for TP. These cost estimates factor in cost savings associated with fertilizer, weed control, erosion repair and yield increases.

Direct implementation costs identified from a field-based study, that will be incurred by landowners, can help further refine cover crop implementation goals and inform initiative efforts. Additional cover crop implementation initiatives in Minnesota include the University of Minnesota Forever Green Initiative, the Conservation Reserve Enhancement Program, and the Working Lands Watershed Restoration Feasibility Study and Program Plan (Wall et al., 2020). The Midwest Cover Crop Council (https://mccc.msu.edu/) is also leading joint state efforts by bringing together leaders from major universities.

While cost per kg reduced for TP and DRP are orders of magnitude larger than those for TN, less phosphorus contributions are required for water body impairment and algal bloom occurrence in freshwater ecosystems, which is driven by small contributions of highly bioavailable phosphorus (Baker et al., 2014). Minnesota water quality standards are .065 mg/l and 10 mg/l for TP and TN, respectively (Minnesota Legislature, 2018). Cost for TP and DRP removals must also be placed into context of the economic implications of algal blooms relative to tourism and recreation, commercial fishing, properties values, drinking water treatment and human health (U.S. Environmental Protection Agency, 2021).

Identification of direct landowner costs and economic benefits will also aid in landowner cover crop implementation, including the potential for increased cash crop yield (Farzadfar et al., 2021). At the field site average soybean yield increased from 43 to 56-bushel units under cover crops and average corn yield increased from 182 to 191-bushel units under cover crops. Identifying beneficial uses of cover crops in a more systematic mater, such as within the treatment train approach may also encourage implementation. Modeling of cover crop implementation was shown to increased nutrient reduction rates within a downstream subsurface treatment wetland, demonstrating the potential for wetland size and cost reduction while obtaining the same cumulative nutrient reductions rates in association with cover crops.

Cover crop benefits to wetland performance could be substantial, as the main limiting factor in landowner wetland implementation in this region is cost and land area taken out of production. Landowners may not be financially able or willing to remove large areas of productive cropland for wetland implementation (Hyberg et al., 2015). As such, while treatment wetlands are effective, opportunities to place them are limited. Subsurface flow wetlands have been shown to be more effective at nutrient removal than surface flow wetlands, however, cannot treat large volumes of water (Gordon et al., 2021; Kadlec and Wallace, 2009). By reducing flow with the implementation of cover crops, subsurface flow wetlands become more economically and hydrologically feasible.

A similar study conducted by Hanrahan et al. (2021) found a monthly average drain tile load reduction of 50% for TN, TP and DRP provided by cover crops from 40 agricultural field sites in northcentral Ohio. Southern Minnesota differs from Ohio in having less intensive tile drainage and a later spring drainage season, thus making cover crops less effective. When used in associated with drainage water management, cover crops were found to reduce TP flow weighted mean concentrations by 26% with no significant effect on DRP concentrations (Zhang, Tan, et al. 2017). Waring et al., (2020) noted consistent reductions in subsurface nitrate leaching through implementation of both cover crops and no-till practices in north-central Iowa. Few long-term field studies exist that document drain tile nutrient reduction potential of winter cover crops as a standalone practice for both nitrogen and phosphorus in the Midwest.

Rural areas in the United States are experiencing more intensive water management due to regulations and increasing demand for food and fuel, presenting a strong need to maximize agricultural best management practice performance and implementation (Thompson et al., 2021). Relative to other areas of the nation, cover crop implementation is lowest in the Midwest, despite significant nutrient contributions to the Gulf of Mexico (Hamilton et al., 2017). Challenges to Midwestern cover crop implementation include a short growing season paired with primary cultivation of full season corn and soybean crop (Carlson and Stockwell, 2013). While landowner perceptions of cover crops in the Midwest are generally positive, direct net returns for implementation have been negative in many cases, highlighting a need for the development of more state or region-specific implementation recommendations (Plastina et al., 2018).

This study demonstrates the benefits of cover crop implementation in the Midwest while also quantifying associated nutrient reduction rates and direct implementation costs. The use of cover crops in a systematic manner for improved downstream conservation practice performance and cumulative nutrient reductions and cost benefits are also demonstrated. Research limitations include findings limited to only one field research site in addition to lack of continuous nutrient monitoring to capture the full influence of storm events across the study period. Results could also be improved through field monitoring data within the on-site treatment train to complement findings from modeling techniques.

Next steps include research on site- and region-specific factors including work on multiple sites to account for variations in soil, landscape, local climate, or management practices and to document the influence of various seed mixes or seeding and termination dates and methodologies. Further knowledge on economic considerations including those related to cash crop yield, accessibility and benefit of governmental cost share programs and long-term landowner return on investments will also aid in increased implementation. Finally, expansion of the treatment train framework to include additional practice types, to improve landscape positioning and to document varying hydrologic conditions will contribute to even greater cumulative conservation practice performance.

5. Conclusion

While there is a need for increased cover crop implementation in the Midwest, a lack of research exists on implementation success, nutrient reduction benefits and economic implications. In addition, a growing demand for food and fuel production while also protecting water resources has called for conservation practice performance improvements. Through field data collection at an agricultural field demonstration site in southern Minnesota, this work serves to quantify subsurface nutrient reduction benefits provided by cover crops at rates of 9.13, .12 and . kg^{-1} ha^{-1} yr^{-1} with associated direct implementation costs of \$12.96, \$955, and \$1,720 kg^{-1} ha^{-1} yr^{-1} for TN, TP and DRP. The systematic use of cover crops for conservation practice performance improvement is also demonstrated through desktop modeling on the treatment train framework. Through upstream flow reduction and nutrient retention, cover crops were found to improve nutrient reduction rates within a downstream subsurface treatment wetland. As a result, size reductions could be applied to agricultural wetlands in order to minimize the area of land taken out of production while maintaining nutrient reduction goals. Future research building upon this work would aid in the development of field and state specific cover crop implementation guidelines, while also expanding on the treatment train framework for improved conservation practice performance.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Anderson, W.P., Wall, D., and Olson, J.L., 2016. Minnesota nutrient reduction strategy. In 2016 10th International Drainage Symposium Conference, 6-9 September 2016, Minneapolis, Minnesota, pp. 1-9. American Society of Agricultural and Biological Engineers.

Apfelbaum, S.I., Eppich, J.D., Price, T., Sands, M., 1995. The prairie crossing project: Attaining water quality and stormwater management goals in a conservation development. In proceedings of the national Symposium of Using Ecological Restoration to Meet Clean Water Act Goals. Chicago, Illinois, pp. 33-38.

Baker, D.B., Confesor, R., Ewing, D.E., Johnson, L.T., Kramer, J.W., Merryfield B.J., 2014. Phosphorus loading to Lake Erie from the Maumee, Sandusky and Cuyahoga rivers: The importance of bioavailability. J. Great Lakes Res. 40, 502-517. https://doi.org/10.1016/j.jglr.2014.05.001.

Barber, N., Reaney, S.M., Barker, P.A., Benskin, C., Burke, S., Cleasby, W., Haygarth, P., Jonczky, J.C., Owen, G.J., Snell, M.A., Surridge, B., Quinn, P.F., 2016. The treatment train approach to reducing non-point source pollution from agriculture. In AGU Fall Meeting Abstracts, San Francisco, California, pp. H13D-1396.

Bergtold, J. S., Ramsey, S., Maddy , L. & Williams, J. R., 2017. A review of economic considerations for cover crops as a conservation practice. Renew. Agr. Fofod Syst. 34, 1-15. https://doi.org/10.1017/S1742170517000278.

Blanco-Canqui, H. et al., 2015. Cover crops and ecosystem services: insights from studies in temperate soils. Agron. Jour. 107, 2449-2474. https://doi.org/10.2134/agronj15.0086.

Blann, K. L., Anderson, J. L., Sands, G. R. & Vondracek, B., 2009. Effects of agricultural drainage on aquatic ecosystems: a review. Crit. Rev. Env. Sci. Tec. 39, 909-1001. https://doi.org/10.1080/10643380801977966.

Carlson, S. & Stockwell, R., 2013. Research Priorities for Advancing Adoption of Cover Crops in Agricultural-Intensive Regions. J. Agric. Food Sys. Community Dev. 3, 125-129. https://doi.org/10.5304/jafscd.2013.034.017.

Christianson, L., Tyndall, J. & Helmers, M., 2013. Financial comparison of seven nitrate reduction strategies for Midwestern agricultural drainage. Water Resour. Econ. 2, 30-56. https://doi.org/10.1016/j.wre.2013.09.001.

Christianson, R., Fox, J., Neely, L., Wong, C., 2021. Effectiveness of Cover Crops on Water Pollution Reduction from Agricultural Areas. Transactions of the ASABE. 64, 1007-1017. https://doi.org/10.13031/trans.14028.

Chun, J. A., Cooke, R. A., 2008. Technical note: Calibrating agridrain water level control structures using generalized weir and orifice equations. Appl. Eng. Agric. 24, 595-602. https://doi.org/10.13031/2013.25274.

Dolph, C. L., Boardmann, E., Danesh-Yazdi, M., Finley, J.C., Hanse, A.T., Baker, A.C., Dalzell, B., 2019. Phosphorus transport in intensively managed watersheds. *Water Resour. Res.* 55, 9148-9172. https://doi.org/10.1029/2018WR024009.

Drury, C. F., Tan, C.S., Welacky, T.W., Reynolds W.D., Zhang, T.Q., Oloya, T.O., McLaughlin, N.B., Gaynor, J.D., 2014. Reducing Nitrate Loss in Tile Drainage Water with Cover Crops and Water-Table Management Systems. J. Environ. Qual. 43, 587-598. https://doi.org/10.2134/jeq2012.0495.

Farzadfar, S. J., Knight, D. J., Congreves, K. A., 2021. Rye cover crop improves vegetable crop nitrogen use efficiency and yields in a short-season growing region. Can. J. Plant Sci. https://doi.org/10.1139/CJPS-2021-0032.

Godsey, S. E., Kirchner, J. W., Clow, D. W., 2009. Concentration-discharge relationships reflect chemostatic characteristics of US catchments. *Hydrol Process.* 23, 1844-1864. https://doi.org/10.1002/hyp.7315.

Gordon, B. A., Lenhart, C., Peterson, H., Gamble, J., Nieber, J., Current, D., Brenke, A., 2021. Reduction of nutrient loads from agricultural subsurface drainage water in a small, edge-of-field constructed treatment wetland. Ecol. Eng. 160, 106128. https://doi.org/10.1016/j.ecoleng.2020.106128.

Hamilton, A. V., Mortensen, D. A., Kammerer, A. M., 2017. The state of the cover crop nation and how to set realistic future goals for popular conservation practice. *J. Soil Water Conserv.* 72, 111A-115A. https://doi.org/10.2489/jswc.72.5.111A.

Hanrahan, B. R., King, K. W., Duncan, E. W., Shedekar, V. S., 2021. Cover crops differentially influenced nitrogen and phoshorus loss in tile drainage and surface runoff from agricultural fields in Ohio, USA. J. Environ Manage. 293, p. 112910. https://doi.org/10.1016/j.jenvman.2021.112910.

Hanrahan, B.R, Tank, J.L., Christopher, S.F., Mahl, U.H., Trentman, M.T., Royer, T.V., 2018. Winter cover crops reduce nitrate loss in an agricultural watershed in the central U.S. Agric. Ecosyst. Environ. 265, 513-523. https://doi.org/10.1016/j.agee.2018.07.004.

Horst, W. J., Kamh, M., Jibrin, J.M., Chude, V.O., 2001. Agronomic measures for increasing P availability to crops. Plant Soil. 237, 211-233. https://doi.org//10.1023/A:1013353610570.

Houston Engineering, 2016. PTMAPP: Theory and Development Documentation, HEI No. 6059_051. Minnesota Board of Water and Soil Resources. 61 p. https://ptmapp.bwsr.state.mn.us/files/04052016_PTMA_Theory_Report.pdf

Houston Engineering, 2015. Treatment Train Memo, HEI No. 4875-027. Minnesota Board of Water and Soil Resources. 7 p. https://ptmapp.bwsr.state.mn.us/files/BMPsandTreatment_Memo_FINAL_Approved.pdf.

Hyberg, S., R., Iovanna, W., Crumpton, W., Richmond, S., 2015. The cost effectiveness of wetlands designed and sited for nitrate removal: The effect of increased efficiency, rising easement costs, and lower interest rates. J. Soil Water Conserv. 70, 30A-32A. https://doi.org/10.2489/jswc.70.2.30A.

Jarvie, H. P., Johnson, L.T., Sharpley, A.N., Smith, D.R., Baker, D.B., Bruulsema, T.W., Confesor, R., 2017. Increased soluble phosphorus loads to Lake Erie: Unintended consequences of conservation practices? J Environ Qual. 46, 123-132. https://doi.org/10.2134/jeq2016.07.0248.

Jaynes, D. B., Colvin, T.S., Karlen, D.L., Cambardella, C.A., Meek, D.W., 2001. Nitrate loss in subsurface drainage as affected by nitrogen fertilizer rate. J. Environ. Qual. 30, 1305-1314. https://doi.org/10.2134/jeq2001.3041305x.

Kadlec, R. H., Wallace, S., 2009. Treatment Wetlands, second ed. CRC Press, Boca Raton.

Kaiser, D. E., Lamb, J.A., Eliason, R., 2011. Fertilizer Guidelines for Agronomic Crops in Minnesota, BU-06240-S. University of Minnesota Extension. 44 p. https://hdl.handle.net/11299/198924.

Keesstra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z., Cerda, A., 2018. The superior effect of nature based solutions in land management for enhancing ecosystem services. Sci. Total Environ. 610-611, 997-1109. https://doi.org/10.1016/j.scitotenv.2017.08.077.

Lazarus, W., Keller, A., 2018. Economic Analysis of Cover Crops on Farms Participating in the Southeastern Minnesota Cover Crop and Soil Health Initiative. University of Minnesota Extension, Environment and Natural Resources Trust Fund. 26p. https://www.lccmr.leg.mn/projects/2015/finals/2015_04e_UMN_Economics_CoverCrop.

Lenhart, C., Gordon, B., Gamble, J., Current, D., Ross, N., Herring, L., Nieber, J. and Peterson, H., 2016. Design and hydrologic performance of a tile drainage treatment wetland in Minnesota, USA. Water-Sui. 8, 549. https://doi.org/10.3390/w8120549.

Lenhart, C., Gordon, B., Peterson, J., Eshenaur, W., Gifford, L., Wilson, B., Stamper, J., Krider, L., Utt, N., 2017. Agricultural BMP Handbook for Minnesota, second ed. Minnesota Department of Agriculture, Saint Paul.

Liu, J., Macrae, M.L., Elliott, J.A., Baulch, H.M., Wilson, H.F., Kleinman, P.J., 2019. Impacts of cover crops and crop residues on phosphorus losses in cold climates: A review. J. Environ. Qual. 48, 850-868. https://doi.org/10.2134/jeq2019.03.0119.

Magner, J., 2011. Tailored watershed assessment and integrated management (TWAIM): A systems thinking approach. Water-Sui. 3, 590-603. https://doi.org/10.3390/w3020590.

Maltais-Landry, G., Scow, G., Brennan, K., Vitousek, P., 2015. Long-term effects of compost and cover crops on soil phosphorus in two California agroecosystems. Soil Sci. Soc. of Am. J. 79, 688-697. https://doi.org/10.2136/sssaj2014.09.0369.

Minnesota Legislature, 2018. Minnesota administrative rules, 7050.0222. https://www.revisor.mn.gov/rules/7050.0222/ (accessed 7 July 2021).

Ni, X., Yuan, Y., Lui, W., 2020. Impact factors and mechanisms of dissolved reactive phosphorus (DRP) losses from agricultural fields: A review and synthesis study in the Lake Erie basin. Sci. Total Environ. 714, 136624. https://doi.org/10.1016/j.scitotenv.2020.136624.

Nuruzzaman, M., Lambers, H., Bolland, M.D., Veneklaas, E.J., 2005. Phosphorus benefits of different legume crops to subsequent wheat grown in different soils of western Australia. Plant Soil. 271, 175-187. https://doi.org/10.1007/s11104-004-2386-6.

Nustad, R.A., Rowland, K.M., Wiederholt, R.G., 2015. Water-quality characteristics in runoff for three discovery farms in North Dakota, 2008-2012. Geological Survey Scientific Investigators Report 2014-5212. 31 p. http://dx.doi.org/10.3133/sir20145212.

Pease, L.A., King, K.W., Williams, M.R., LaBarge G.A., Duncan, E.W., Fausey, N.R., 2018. Phosphorus export from artificially drained fields across the Eastern Corn Belt. J. Great Lakes Res. 44, 43-53. https://doi.org/10.1016/j.jglr.2017.11.009.

Plastina, A., Liu, F., Miguez, F., Carlson, F., 2018. Cover crops use in Midwestern US agricultural: perceived benefits and net returns. Renew. Agr. and Food Syst. 35, 1-11. https://doi.org/10.1017/S1742170518000194.

Roley, S. S., Tank, J.L., Tyndall, J., Witter, J.D., 2016. How cost-effective are cover crops, wetlands, and two-stage ditches for nitrogen removal in the Mississippi River Basin? Water Resour. Econ. 15, 43-56. https://doi.org/10.1016/j.wre.2016.06.003.

Rosario-Lebron, A., Leslie, A.W., Yurchak, V., Chen, G., Hooks, C.R., 2019. Can winder cover crop termination practices impact weed suppression, soil moisture and yield in no-till soybean [Glycine max (L.) Merr.]? Crop Prot. 116, 132-141. https://doi.org/10.1016/j.cropro.2018.10.020.

Ross, N.B., 2014. Constructed wetland used to treat nitrate pollution generated from agricultural tile drainage waters in Southern Minnesota. University of Minnesota-Twin Cities, M.S. thesis. https://conservancy.umn.edu/handle/11299/167310.

Ruffatti, M. D., Roth, R.T., Corey, L.G., Armstrong, S.D., 2019. Impacts of nitrogen application timing and cover crop inclusion on subsurface drainage water quality. Agr. Water Manage. 221, 81-88. https://doi.org/10.1016/j.agwat.2018.09.016.

Seifert, C. A., Azzari, G., Lobell, D.B., 2018. Satellite detection of cover crops and their effects on crop yield in the Midwestern United States. Environ. Res. Lett. 13, 064033. https://doi.org/10.1088/1748-9326/AAC4C8.

Singh, J., Wang, T., Kumar, S., Xu, Z., Sexton, P., David, J., Bly, A., 2021. Crop yield and economics of cropping systems involving different rotations, tillage, and cover crops. J. Soil Water Conserv. https://doi.org/10.2489/jswc.2021.00117.

Smith, D. R., King, K.W., Williams, M.R., 2015. What is causing the harmful algal blooms in Lake Erie? Soil Water Conserv. 70, 27A-29A. https://doi.org/10.2489/jswc.70.2.27A.

Smith, E., Gillette, T., Blann, K., Coburn, M., Hoppie, B., Rhees, S., 2018. Drain Tiles and Groundwater Resources: Understanding the Relations. Minnesota Ground Water Association. http://dx.doi.org/10.13140/RG.2.2.21880.60164.

Meyers, N., Bergez, J., Constantin, J., Justes, E., 2019. Cover crops reduce water drainage in temperature climates: A meta-analysis. Agron. Sustain. Dev. 39, 1-11. https://doi.org/10.1007/s13593-018-0546-y.

Minnesota Pollution Control Agency, 2021. FLUX32. https://www.pca.state.mn.us/wplmn/flux32/ (Accessed 15 March 2021).

Sustainable Agriculture Research and Education, 2016. Annual Report 2015-2016, Cover Crop Survey. United States Department of Agricultural. 42 p. https://www.sare.org/wp-content/uploads/2015-2016-Cover-Crop-Survey-Report.pdf.

Sustainable Agriculture Research and Education, 2020. Annual Report, 2019-2020, National Cover Crop Survey. United States Department of Agriculture. 63 p. https://www.sare.org/wp-content/uploads/2019-2020-National-Cover-Crop-Survey.pdf.

Thompson, N. M., Reeling, C.J., Fleckenstein M.R., Prokopy, L.S., Armstrong, S.D., 2021. Examining intensity of conservation practice adoption: Evidence from cover crop use on U.S. Midwest farms. Food Policy. 101, 102054. https://doi.org/10.1016/j.foodpol.2021.102054.

Trentman, M. T., Tank, J.L., Royer, T.V., Speir, S.L, Mahl, U. H., Sethna, LR., 2020. Cover crops and precipitation influence soluble reactive phosphorus losses via tile drain discharge in an agricultural watershed. Hydrol. Process. 34, 4446-4458. https://doi.org/10.1002/hyp.13870.

U.S. Environmental Protection Agency, 2021. A Compilation of Cost Data Associated with the Impacts and Control of Nutrient Pollution. https://www.epa.gov/nutrient-policy-data/compilation-cost-data-associated-impacts-and-control-nutrient-pollution/ (accessed 7 July 2021).

USDA, 2021. Minnesota Ag News 2020 Crop Production. National Agriculture Statistics Service, Saint Paul. 2 p.

Wall, D., Kjaersgaard, J., Drewitz, M., Graziani, M., Scheirer, L., Olmanson, R., Trojan, M., Larson, J., Wilke, A., Hong, W., Barland, J., Ganske, L., Jahnz, J., Robertson, S., Wettlauger, M., Martin, S., Engel, L., Kroening, S., Miller, D., Wagner, M., Kuehner, K., Johnson, G., Nustad, R., 2020. 5-year Progress Report on Minnesota's Nutrient Reduction Strategy, wq-s1-84a. Minnesota Pollution Control Agency, Saint Paul. 95 p.

Waring, E. R., Lagzdins, A., Pederson, C., Helmers, M.J., 2020. Influence of no-till and a winter rye cover crop on nitrate losses from tile-drained row-crop agricultural in Iowa. J. Environ. Qual. 9, 852. https://doi.org/10.1002/jeq2.20056.

Yang, W., Feng, G., Adeli, A., Tewolde, H., Zhongyi, G., 2021. Simulated long-term effect of wheat cover crop on soil nitrogen losses from no-till corn-soybean rotation under different rainfall patterns. J. Clean. Prod. 280, 124255. https://doi.org/10.1016/j.jclepro.2020.124255.

Yang, W., Feng, G., Read, J.J., Ouyang, Y., Han, J., Li, P., 2019. Impact of cover crop on corn-soybean productivity and soil water dynamics under different seasonal rainfall patterns. Agron. J. 112, 1201-1215. https://doi.org/10.1002/agj2.20110.

Zhang, T. Q., Tan, C.S., Zheng, Z.M., Welacky, T., Wang, Y.T., 2017. Drainage water management combined with cover crop enhances reduction of soil phosphorus loss. Sci. Total Environ. 586, 362-371. https://doi.org/10.1016/j.scitotenv.2017.02.025.

Zucker, L. A., Brown, L.C., 1998. Agricultural drainage: water quality impacts and subsurface drainage studies in the Midwest. Ohio State University Extension. 40 p.