TILLAGE, RESIDUE AND WINTER MANURE APPLICATION EFFECTS ON RUNOFF AND NUTRIENT LOSSES FROM AGRICULTURAL FIELDS

By

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Abstract

Agricultural tillage and residue management is widely practiced across the US and worldwide. Applying manure to snow-covered frozen soils (winter manure application) is a common practice in cold agricultural regions (e.g., Midwestern states of the US) where dairy, poultry and other animal production are intensive. In cold agricultural regions, soils also undergo seasonal freezing and thawing that could affect runoff transport processes. However, the overall effectiveness of tillage, residue, and winter-manure application practices and their relationship to freeze-thaw cycles challenge water quality protection. This research investigated tillage, residue, and winter-manure application management effects along with their relationship to surface runoff and associated nutrient losses through field experiments (Chapter 1), meta-analysis (Chapter 2), and characterizing and statistically analyzing soil freeze-thaw cycle relationship to runoff and nutrient losses (Chapter 3).

Field experiments evaluated wintertime (Nov-Apr) surface runoff and nutrient losses on soils with chisel tillage (fall chisel plow and spring finisher) and no-tillage receiving three manure types (liquid, solid, and un-manured controls) as a late winter application on snow-covered frozen soils. The surface roughness from chisel tillage resulted in the greatest reduction in nutrient loads by reducing runoff volumes through depressional storage of snowmelt and rain, thus providing additional time for infiltration. Solid manure, irrespective of tillage or no-tillage, can be physically present on the surface for a longer period and release nutrients every time it interacts with runoff, compared to liquid manure. Chisel tillage with liquid manure application demonstrated the greatest potential to reduce wintertime runoff and nutrient losses across all tillage and manure type managements studied. Overall, results from the field experiments challenged general perceptions as mechanically disturbed soils (fall chisel tillage in this study) resulted in significantly less runoff and nutrient losses compared to no-tillage. Therefore, a meta-analysis was conducted to further understand tillage effects on an annual scale across different sites and years. The analysis included 1,571 site-years of data from published research on tillage and residue management across the US (21 states) and Canada (4 provinces). Data were categorized into tillage, no-tillage, tillage with residue cover (>30%), and no-tillage with residue cover (>30%). Tillage and no-tillage management with >30% residue cover were generally superior to the same management with <30% residue cover in controlling runoff, sediments and nutrients. Overall, no-tillage with >30% surface cover was the most effective management with largely positive performance effectiveness in controlling sediments, particulate nitrogen and phosphorus, total nitrogen and phosphorus losses in runoff compared to other tillage and residue managements.

Lastly, an approach to characterize soil freeze-thaw (FT) cycles was developed and relationships between FT cycles and wintertime runoff and associated nutrient losses were explored. Depressional storage of fall chisel tillage trapped more snow, increased snowmelt infiltration, and thus reduced the number of seasonal FT-cycles (not significantly different in both years of study; $p<0.05$) compared to no-tillage. Winter liquid manure application did not affect the FT-cycles compared to un-manured controls. The number of FT-cycles had the strongest positive correlation to wintertime runoff ($r = 0.72$) and then to nitrogen (NH_4^+ and TKN) losses ($r = 0.44$ to 0.47), suggesting FT-cycles could be used as a parameter in water quality models to predict wintertime runoff and nutrient losses.

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Chapter 1

Tillage and manure type effects on nitrogen and phosphorus losses through surface runoff from winter manure application

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Abstract

In cold regions, nutrient losses from dairy agroecosystems are a longstanding and recurring problem, especially when manure is applied during winters over snow-covered frozen soils. While many different factors affect nutrient losses from winter manure applications, this study evaluated two tillage (fall chisel and no-tillage) and three manure-type [un-manured/control, liquid (<5% solids) and solid (>20% solids) manure] management treatments. The six management treatments were field-tested in south-central Wisconsin during the winters (Nov-Apr) of 2017-18 and 2018-19 with a complete factorial design. Seasonal runoff depth and associated sediment and nutrient losses were 12 times higher in no-tillage treatments than fall chisel tillage. Solid manure treatment had up to 23 times higher normalized nutrient losses than liquid manure. Manure type physical characteristics had an important role in their nutrient losses. Irrespective of tillage and multiple runoff events, solid manure was present on the surface for longer periods, potentially releasing nutrients each time it interacted with runoff. Liquid manure applied infiltrated and remained in snowpack and lost with snowmelt. When compared across all treatment combinations, no-tillage with solid manure application had the highest nutrient losses, while chisel tillage with liquid manure had the lowest losses. Overall, this study found that wintertime manure applications over snow-covered frozen soils pose a risk of nutrient loss irrespective of tillage and manure type, but in unavoidable situations, prioritizing tillage × manure type combination can help reduce losses.

Keywords: Tillage, manure, winter, runoff, nutrient losses, and frozen soil

1. Introduction

In dairy agroecosystems, livestock manure management (collection, processing, storage, transport, and land application) is a longstanding major challenge (Sharara et al., 2018). Advances in engineering, research, and capital investment on manure handling equipment are providing solutions to some of these challenges (Aguirre-Villegas et al., 2014, Holly et al., 2017, Sharara et al., 2017, Sharara et al., 2018). However, there are many scenarios when manure needs to be applied during winter months due to lack of storage capacity or emergency applications. Land application of manure in cold regions (e.g., Great Plains, Great Lakes, northern Europe and Asia), especially during winter months, is associated with elevated runoff risks and manure nutrients losses because of conditions of frozen soils, snowmelt, and rain-on-snow events (Fleming and Fraser 2000; Srinivasan et al., 2006, Liu et al., 2018). Such nutrient losses can lead to fish kills, eutrophication, degraded freshwater quality and many other environmental issues (Carpenter et al., 1998).

In the midwestern and northeastern states of the US, regardless of the environmental risk, manure is often land applied during winter months to avoid problems associated with storage infrastructure, handling logistics, and economy (Williams et al., 2011; Smith et al., 2017). Increasing the number and size of structures for long-term storage requires an additional investment that may not be economical for farmers. A recent survey conducted in Michigan found that a total ban on winter manure application would cost $30 million US dollars per year on small livestock farms (Miller et al., 2017). Other factors appear to affect runoff losses risks. For example, an 11-year watershed-scale modeling study found that 12 months of storage and applying all the manure in one application (spring) did not reduce annual phosphorus loads compared to six months storage and two (fall and spring) manure applications or three months storage and four (fall, winter, spring and summer) applications (Liu et al., 2017), signifying that long-term storage does not benefit the environment. Logistically, performing winter manure application avoids the challenge of farm labor availability and provides more time for planning growing season field activities (Srinivasan et al., 2006). Also, driving manure-spreading equipment during winter when the soil is frozen reduces the risk for soil compaction (Srinivasan et al., 2006; Smith et al., 2017). Recent research advances and processing technologies are providing solutions to manure management through anaerobic digestion, solid-liquid separation and granulating the manure (Aguirre-Villegas et al., 2014, Holly et al., 2017, Sharara et al., 2017, Sharara et al., 2018). However, these technological solutions are not immediately available to all farmers, and winter manure application may not be avoided but rather needs to be facilitated by carefully considering the farmer's needs and simultaneously conserving environmental quality.

Nutrient loss from winter manure application has been a research topic since Midgley and Dunklee (1945) first identified that spreading manure on snow-covered fields leads to contamination of water bodies. Since then, studies have been conducted at different experimental (laboratory, field, watershed) and time scales, and in different regions to identify appropriate management practices for winter manure application. Most research was conducted before 1980 (Hensler et al., 1970; Converse et al., 1976; Klausner et al., 1976; Young and Mutchler, 1976; Young and Holt, 1977; Phillips et al., 1981; Steenhuis et al., 1981), with some more recently (Hansen et al., 2000; Ulen et al., 2003; Lewis and Makarewicz, 2009; Komiskey *et al.*, 2011; Owens et al., 2011; Williams et al., 2011; Williams et at., 2012a,b; Singh et al., 2017; Vadas et al., 2018; Stock et al., 2019a).

Laboratory-scale studies mainly investigated nutrient release characteristics of manure types (liquid, semi-solid, and solid) by varying their placement (below the snow, in between snow layers, and on top of snow), snowpack depths, surface slopes, and air and snowmelt temperatures (Steenhuis et al., 1981; Williams et al., 2011; Vadas et al., 2018). These laboratory studies also provided essential winter manure application strategies. However, field studies that evaluated similar conditions had contrasting results. For example, slope had minimal effect on nitrogen losses of a frozen soil under laboratory conditions (Steenhuis et al., 1981). However, field-scale studies found a significant slope effect on snowmelt and rainfall-induced runoff volumes (Lewis and Makarewicz, 2009). Similarly, snowmelt temperature and manure placement within the snowpack had no effect on nutrient release in a laboratory study (Vadas et al., 2018), but some field studies found that applying manure before snowpack accumulation resulted in less nutrient losses than applying it on top of the snowpack (Williams et al., 2011; Stock et al., 2019a) while other studies found applying solid manure on top of the snowpack resulted in less nutrient losses than applying on frozen ground without snowpack (Hensler et al., 1970; Converse et al., 1976; Kalushner et al., 1976; Young and Mutchler 1976). The lysimeter study of Williams et al., 2011 also suggested that incorporating manure into the middle of the snowpack could provide similar benefits to incorporating it into the soil. The discrepancies between laboratory and field studies are because of varying environmental conditions and suggest that replicating experiments at different spatial and temporal scales is necessary to provide strong evidence-based guidance on winter manure application.

Field studies (plot and watershed scale) have investigated interaction effects of winter manure application and tillage management while understanding underlying hydrological and nutrient transport processes (Plach et al., 2019; Good et al., 2019; Hoffman et al., 2019; Stock et al., 2019a; Vadas et al., 2019). Studies focused on fall tillage with winter manure application found that mechanically disturbed soil surfaces significantly reduced snowmelt and rain-on-snow runoff and their corresponding nutrient losses compared to no-tillage with winter manure application; differences were attributed to higher surface roughness of tilled surfaces providing more opportunity time for snowmelt infiltration and reduced subsequent runoff losses (Young and Mutchler 1976; Hansen et al., 2000; Iwata et al., 2010; Starkloff et al., 2017; Stock et al., 2019a). Results from tillage with manure timing studies (early winter/fall vs late winter/spring application) are mixed. Fall nutrient applications (injection or surface broadcast) before the soil starts freezing reduced surface nutrient losses in some studies (Stock et al., 2019a; Vadas et al., 2019), while spring applications reduced nutrient losses in others (Young and Mutchler 1976 ; Young and Holt 1977; Randall and Vetsch 2005; van Es et al., 2006; Liu et al., 2017). The effects of manure type (solid manure vs liquid manure) along with tillage and timing of application have also been widely studied, and contrasting information is available regarding nutrient losses. Kongoli and Bland (2002) found that solid manure (>20% solids) applied on snowpack absorbed shortwave radiation and reflected it into the atmosphere as longwave radiation, turbulent flux and latent heat. This phenomenon significantly retarded the snowmelt rate and provided more time for snowmelt and manure nutrients to infiltrate into the soil. However, in this study, snow was completely covered with an even thick solid manure layer (3.5 cm) which is an unusual application method. Solid manure applications typically leave areas with and without manure at short spatial scales (<0.5 m^2) and not a continuous blanket of manure (personal communication, F.J. Arriaga, Associate Prof., UW-Madison). Also, the Kongoli and Bland (2002) study was not statistically replicated nor compared to liquid manure (<5% solids) since the main focus of their work was to describe the energy exchange. Komiskey et al. (2011) compared nutrient losses from dairy liquid and solid beef manure on no-tillage fields and found no differences. Young and Mutchler (1976) and later Young and Holt (1977) investigated the effects of solid manure application timing and found that spreading manure on top of snowpack rather than before snowfall resulted in less runoff and nutrient losses. They noted that solid manure acts as a “mulch” that disperses the force of raindrops in the spring season and reduces runoff losses.

All the above-discussed studies investigated a wide range of scenarios/managements and added substantial knowledge for guiding land application of winter manure. However, the contradicting results among different studies are because of differences in study designs, dynamic site-specific weather and soil conditions, and a lack of normalization/statistical methods to analyze the hydrologic, timing of application, and manure property controls on wintertime nutrient losses. Also, comparisons of wintertime nutrient losses from different manure types of the same animal species and their interactions with tillage management are lacking. Understanding how solid and liquid manure of the same animal species interact with snow and soil, and how nutrients are lost in runoff during winter conditions will help guide recommendations and farmers strategize winter manure applications. Overall, this study aims to increase knowledge of and quantify wintertime surface nutrient losses from frozen and snow-covered soils that receive late winter manure. The specific objective of this field study is to compare tillage (chisel tillage and no-tillage) and winter manure type (liquid, solid, and un-manured) effects on wintertime (November to April) surface runoff, nitrogen, and phosphorus losses. Here, we hypothesized that fall chisel tillage would reduce runoff through increased surface roughness, and solid manure applications would result in greater nutrient losses than liquid manure.

2. Materials and methods

2.1 Experimental site and Treatments

A field study was conducted in south-central Wisconsin at the University of Wisconsin-Arlington Agricultural Research Station (AARS; 43˚17' N 89˚21' W). The study site was under alfalfa (2011-14) before transitioning into the experimental research site. Since the conversion (2015 onwards), the site has been under corn silage production with all field operations performed along the contour. The site consists of 18 plots (5 x 15 m each) with a 5.8% slope and a south-facing aspect on silt-loam soil (Saybrook-Ringwood-Griswald series association). Prior to this study (2015-17), the plots were used to investigate the effects of tillage (chisel vs. no-tillage) and winter liquid manure application timing (early December vs. late January application) on surface runoff and associated nutrient losses (Stock et al., 2019a).

In the current study, two tillage types and three manure types were evaluated in a complete factorial design. Fall chisel tillage (CT), and no-tillage (NT) treatments were evaluated as the main plot treatments and the three manure-type treatments (liquid manure, solid manure, and un-manured control) were evaluated as subplot treatments. Plots for tillage treatments were paired for field operations purposes, resulting in nine pairs. However, because of field layout constraints, one of the pairs was split into independent plots. Tillage treatments were assigned randomly to each pair. Similarly, manure type treatments were randomly assigned within each tillage pair. All tillage and manure type treatment combinations were conducted in triplicate (2 tillages x 3 manure types x 3 replications).

Data were collected during the 2017-18 and 2018-19 winter seasons (Nov-Apr). Each year, CT plots were tilled using a chisel plow to create a rough surface (elevations and depressions), and no-tillage plots were not disturbed. In all plots, little residue remained on the soil surface after corn silage harvest with only 20-30 cm stalks left behind. Manual manure applications were performed in January. The date of application in both experimental years was chosen based on when the following conditions were met, i) snowpack depth on the plots was between 12-15 cm, and ii) no snowmelt or rain-on-snow runoff event was forecast within five days following manure application. The liquid (<5% solids) and solid (>20% solids) manure types used in this study had different nutrient contents due to their physical characteristics (Lorimor et al., 2008; Wang et al., 2019). The manure samples were analyzed by the University of Wisconsin Soil and Forage Analysis Laboratory (Marshfield, WI) following standard methods adopted from the Association of Agricultural Chemists (AOAC) Official Methods of Analysis and Environmental Protection Agency (Peters et al., 2003). The liquid manure was applied at 37.6 Mg ha^{-1} (kL ha^{-1}), and solid manure at 20.6 Mg ha^{-1}. The total nitrogen (TN) and total phosphorus (TP) application rates for both manure types ranged from 55.5 to 102.1 kg ha^{-1} and 28.5 to 41.3 kg ha^{-1}, respectively. The application dates were Jan 18, 2018, and Jan 24, 2019. Liquid and solid manure were collected from a dairy cow (*Bos taurus*) milking operation both years. Liquid manure was collected from storage lagoons, and solid manure was scraped from the animal barn on the day of application.

2.2 Field measurements and analysis

The field site was equipped with an onsite weather station to measure air temperature and precipitation (snow water equivalent and rainfall). The snow water equivalent within each experimental plot was measured with snow cores were collected daily during precipitation events and equivalent water depth was calculated following the methods proposed by the U.S. Army Corps of Engineers (2021) (Missouri Basin Water Management Division and Omaha District Method). After fall harvest and before performing tillage operations, intact soils cores (10 cm deep) were collected from each experimental plot and oven-dried to measure dry bulk density. Snow depth inside the experimental plots was measured by installing three snow sticks equidistant along the length of each plot. The average depth measured at the three sticks was considered to be the depth of snow in each plot. Soil frost formation and depletion depths were monitored weekly at a fixed location in each plot using frost tubes. Each plot was also equipped with a storm-integrated, discharge-weighted runoff collection system (Pinson et al., 2004; Bonilla et al., 2006; Vadas and Powell, 2013) to facilitate capture of up to 760 mm of runoff per event. The runoff depths were measured, and runoff samples were collected at the end of each event. Half of each collected sample was filtered (0.45µ filters) and analyzed for dissolved reactive P (DRP) calorimetrically (Murphy and Riley, 1962) on a spectrophotometer and ammonium (NH_4^+) on a Lachat automated analyzer (Hach Company) using Quick Chem Methods 12-107-06-2-A. The unfiltered samples were analyzed for total solids (TS), volatile solids (VS) (APHA 1995), and total Kjeldahl nitrogen (TKN) and phosphorus (TKP) calorimetrically using an AQ2 Discrete Analyzer (SEAL Analytical Brand, Mequon, WI; Seal, 2017).

2.3 Statistical analysis

Surface runoff, sediments (TS and VS), nitrogen (NH_4^+ and TKN) and phosphorus (DRP and TKP) losses of individual runoff events were summed to obtain seasonal losses (Nov-Apr). Statistical analyses were performed on the seasonal losses of each experimental year separately. Data were modeled using linear and mixed-effects models in R software (R Core Team-2020). For facilitating the statistical analysis, two adjacent treatment pairs were treated as a block (Figure S1). Each block consisted of a pair of CT and NT plots which were randomly assigned with manure-type treatments. Tillage, manure type and their interactions were treated as fixed effects. Block and block x tillage were treated as random effects. Logarithmic data transformations were performed on variables not normally distributed. Residual plots of modeled data were developed to demonstrate the randomly distributed error and homogeneous variances. Fixed effects of tillage, manure type, and tillage x manure type were assessed separately by the differences of estimated marginal means using Kenward-Roger degrees of freedom at 95% significance level ($\alpha = 0.05$). Additionally, pairwise comparisons were made between tillage, manure type and tillage x manure type treatment pairs at 95% significance level ($\alpha = 0.05$). To further explore nutrient loss dynamics between the two manure types, seasonal nutrient losses were normalized to account for differences in the applied nutrient content of the two manure types and potential losses contributed by the soil. Nutrient losses from the tillage-control treatment were subtracted from the corresponding tillage-manure type treatment and divided by the amount of nutrient applied through manure (Equation 1). For example, DRP losses of CT-Control treatment were subtracted from the DRP losses of CT-Liquid manure treatment and divided by the amount of phosphorus applied through liquid manure. The normalized nutrient losses were statistically analyzed, similar to the seasonal nutrient losses. All significance tests were conducted on logarithmically transformed data, and the actual treatment means (not back-transformed means) are presented in the tables and figures.

$$Nutrient\ loss_{normalized} = \frac{Nutrient\ loss_{treatment}(g\ ha^{-1}) - Nutrient\ loss_{control}(g\ ha^{-1})}{Nutrient\ applied\ (kg\ ha^{-1})} \quad (1)$$

3. Results and Discussion

3. 1 Weather

Table 2 presents the monthly mean temperature and total precipitation for Arlington, WI (NOAA, U.S. Department of Commerce). The normal (1991-2020 average) precipitation and temperature from November to April are 347 mm and 1.1^{o}C, respectively. Therefore, the experimental seasons (2017-18 and 2018-19) were colder and drier than normal for the monitoring period (Nov-Apr). In 2017-18, average monthly air temperatures were 2.4 to 6.1 ^{o}C colder than normal. Similarly, 2018-19 air temperatures were colder by 0.8 to 5.9 ^{o}C. Air temperatures started dropping below 0^{o}C earlier in 2018-19 than in 2017-18 (Figure 1). However, Dec and Apr of 2017-18 were 3.8^{o}C and 5.2^{o}C colder than 2018-19, respectively. In both study years, 44 to 49% of total precipitation occurred in the form of snowfall, and the remaining 51 to 56% occurred as rainfall and rain-on-snow. The total precipitation in 2018-19 was 54% higher than in 2017-18. However, both years had 43% and 11% less precipitation than normal, respectively.

3.2 Soil frost dynamics

In seasonally frozen soils, soil frost strongly affects surface runoff characteristics by blocking soil pores with ice and reducing infiltration rates (Kane et al., 1980; Appels et al., 2020). In both years, soil frost formation and depletion responded similarly to air temperatures despite differences in snowpack amount. Snowpack on the ground insulates the soil and can reduce the frost penetration rate depending upon its thickness and density. No significant differences (analysis not presented) were observed in either frost formation or depletion rates (depth day^{-1}) or average depth of frost among tillage and manure type treatments. Therefore, average depths from all experimental treatments are presented (Figure 2) as representative of that season and only seasonal differences are discussed here. In 2017-18, soil started freezing in Dec, with the earliest frost observed on Dec 9, 2017. In 2018-19, soil started freezing earlier than 2017-18, on Nov 8, 2018. Despite the later onset, the soil froze faster and deeper in 2017-18 than in 2018-19 (Figure 2). The maximum frost depth observed was 73 cm in 2017-18 and 48 cm in 2018-19. The maximum frost depth was observed after 45 and 112 days after the onset of frost in 2017-18 and 2018-19, respectively. The frost depletion was faster than formation, and all the frost disappeared within ten days after the average air temperatures started recording >2^{o}C. In 2017-18, frozen and unfrozen layers were observed within the soil profile. During the period of Feb 18 to 28, 2018, soil thawed to a depth of 16 cm from the surface and remained frozen below 16 cm. Starting Mar 6, 2018, soil started re-freezing from the surface and from Mar 6-10, 2018, the soil had a frozen layer at the surface (0-11 cm), an unfrozen layer at 11-20 cm and another frozen layer at 20-38 cm. These dynamic soil conditions (frozen-unfrozen-frozen) are rarely reported in studies of seasonally frozen soils. Most studies report freezing and thawing as a one-dimensional process (soil freezes from the surface and thaws from both the surface and subsurface) and do not report a series of frozen and unfrozen layers at one point of time irrespective of geographic location (Lindstorm et al., 2002; Iwata et al., 2010; Stock et al., 2019a). Such layering can strongly affect the hydrology (runoff and infiltration) of frozen soils and emphasizes rigorous monitoring of soil frost to improve understanding of frozen soil hydraulic characteristics for modeling and predicting wintertime runoff in cold regions.

3.3 Surface runoff

In both years of study, precipitation and tillage combined influenced runoff losses. In 2017-18, five runoff events were recorded, and seven events in 2018-19. Surface runoff was observed from all treatment plots during each event, but event-based runoff depths differed among treatments. Total seasonal runoff depth (Nov-Apr) was higher in 2018-19 than in 2017-18, irrespective of tillage and manure-type treatment (Figure 3a and 3b). This was expected because precipitation in 2018-19 was 54% greater compared to 2017-18. In both years, statistically significant differences in runoff depths were observed among the tillage treatments (p-value = 0.03; Tables 3 and 4). The NT system produced 2 and 3 times higher runoff depths than CT in 2017-18 and 2018-19, respectively. Moreover, NT produced 21-100% greater runoff depths in 9 out of 12 events across the two experimental seasons than CT, indicating that NT was more prone to wintertime runoff losses. Similar results were observed in previous studies and mainly attributed to ridges and furrows in mechanically disturbed (chisel tillage, moldboard tillage, etc.) soil holding rainfall and snowmelt water and providing more time for infiltration. Whereas the relatively smoother surface in no-tillage systems accelerates surface runoff before it has an opportunity to infiltrate (Young and Mutchler 1976; Hansen et al. 2000; Stock et al., 2019a; Zopp et al., 2019). In 2017-18, two out of five runoff events occurred on frozen soil (Figure 2a). In 2018-19, four out of seven runoff events occurred on frozen soil (Figure 2b). Though we did not measure the soil infiltration rates during runoff events, depending upon the soil moisture contents prior to freezing, the frozen soil is most likely to have minimal infiltration capacities making surface storage an important factor for controlling runoff. In our experimental plots, we consistently observed 15-52% higher soil moisture content prior to soil freezing (data not shown) in NT systems than CT at 8 cm depth from data collected prior (2016-17) to the beginning of the current study along with current (2017-19) data. The higher soil moisture content likely leads to higher pore-ice formation and blockage of pores (soil water expands by 9-10% when frozen similar to pure/free water (Anderson and Tice, 1973), thereby reducing infiltration, compared to drier soils (Roy et al., 2020).

In addition to surface roughness, soil frost and moisture content, differences in runoff can be attributed to differences in soil bulk density between CT and NT plots. The average bulk density (0-10 cm) measured during the experimental period (2017-19) prior to summer seeding was higher in NT (1.2 g cm^{-3}) than CT (1.0 g cm^{-3}). The higher bulk density may have negatively impacted hydraulic conductivity (Nawaz et al., 2013), further contributing to the higher runoff from NT systems.

Application of manure on top of the snowpack can affect snowmelt rates and subsequent runoff volumes depending upon the physical characteristics of the manure (Kongoli and Bland, 2002; Stock et al., 2019a). During 2017–18, manure application occurred on soil frozen to a depth of 69 cm and covered with 127 mm of snow (Figure 2a). Similarly, in 2018–19, manure application occurred on 152 mm of snow-covered soil frozen to a depth of 27 cm (Figure 2b). In this study, differences in seasonal runoff depths across different manure-type treatments were found, however, the differences were not statistically significant or consistent across experimental years (Tables 3 and 4). In 2017-18, seasonal runoff depth was higher from the un-manured control treatment compared to the liquid and solid manure treatments, while in 2018-19, liquid manure treatment had higher runoff than control and solid manure treatments. Similarly, runoff differences between liquid and solid manure types contrasted across years. The frequency of runoff collection did not allow estimation of snowmelt rates. However, field observations combined with event-based runoff volumes revealed some manure effects on snowmelt runoff. Liquid manure, when applied was relatively warmer than snow and infiltrated and mixed with the snowpack at the time of application. Solid manure, because of its higher solids content, did not infiltrate into the snowpack at the time of application but rather remained on the surface and interacted with snowmelt, rain, and rain-on-snow later in the season. Liquid manure treatments, despite lower seasonal runoff in 2017-18, resulted in higher runoff volumes in the first (seven days after manure application) and second (12 days after manure application) runoff events than solid and control treatments. For the remaining runoff events (3, 4 and 5) in 2017-18, solid and un-manured treatments had higher runoff than liquid manure treatments. The higher volumes for liquid manure in events 1 and 2 can be partially attributed to the dark color of infiltrated liquid manure absorbing more radiative energy into the snowpack and melting more snow. This phenomenon corroborates the findings of Stock et al. (2019b), who observed lower albedo and accelerated snowmelt from snowpack that received liquid manure compared to fresh snow or snowpack without liquid manure.

In 2018-19, no effect of liquid manure on runoff volumes was observed. After manure application on Jan 24, 2019, consecutive snowfall events covered the treatment plots with 200 mm of snow before any melting event occurred, resulting in similar melting patterns across all treatments irrespective of manure type.

There were no significant differences in runoff depths with the combined effects of tillage and manure type in either year of the study (Figure 3a and 3b). Also, no consistent trend was observed between the tillage and manure type treatments. In 2017-18, CT -liquid manure had the lowest seasonal runoff compared to other treatment combinations. While, in 2018-19, CT-solid manure had the lowest runoff compared to the other treatments.

Tillage management can strongly affect wintertime surface hydrology of cold region dairy agroecosystems, especially fields with corn silage which typically leaves <30% surface residue. As previously mentioned, NT can accelerate and produce greater runoff during frozen ground periods because soil pores can get plugged with ice, and the surface lacks depressional storage. Tillage systems (chisel, moldboard etc.) that create surface roughness and depressional storage can decelerate and infiltrate runoff, thereby reducing runoff losses. However, tillage operations need to be conducted along the contour taking surface slopes and susceptibility to sediment loss into account. Irrespective of tillage management, winter manure applications on snowpack can influence snow melting patterns and subsequent runoff volumes by changing the absorbing radiative energy. However, in extreme situations, such as greater precipitation than normal, dynamic fluctuations in diurnal temperature and saturated soil prior to freezing, neither management (tillage and manure type) will have the main control on wintertime hydrology.

3.4 Sediment and nutrient losses

While previously described differences in runoff hydrology were not statistically significant among manure type and tillage × manure type treatments (section 3.3), differences in nutrient contents between the manure types, physical characteristics of the manure, and the presence (or lack) of manure on the soil surface when runoff occurred lead to some differences in sediment (TS and VS) and total nutrient losses (NH_4^+, DRP, TKN and TP).

In both years of study, except for TS losses in 2017-18, NT had up to 12 times higher sediment and nutrient losses than CT. However, significant tillage effects ($p < 0.03$) were observed only among nutrient losses (NH_4^+, DRP, TKN and TP) in 2017-18 and TP losses in 2018-19 (Tables 5 and 6). Greater losses from NT are attributed to lower surface and subsurface storage capacities and subsequent higher runoff volumes and transport capacities than CT (Young and Mutchler 1976; Mueller et al., 1984; Stock et al., 2019a). Despite three times higher runoff volumes in 2018-19, nutrient losses in NT were as much as two times less than in 2017-18. While CT also had two times higher runoff in 2018-19 than 2017-18, its nutrient losses were similar to 2017-18. This might be partly due to the lower (6-10 kg less) nutrients applied in 2018-19 (Table 1), but runoff differences are likely driven largely by the environmental/field conditions. These interannual differences also indicate a need for long-term experiments and modeling efforts to understand the dynamic nature and variability of wintertime surface hydrology and subsequent nutrient losses across tillage types. The manure type effect did not lead to significant differences in sediment losses (TS and VS) (Tables 3 and 4). However, significant differences ($p<0.02$) were observed for some nutrients (NH4+, DRP, TKN and TP), between control and manured (liquid and solid) treatments (Tables 5 and 6). In 2017-18, manured treatments had 3-19 times higher nutrient losses than control treatments. While, in 2018-19, up to six times higher nutrient losses were observed in manured treatments compared to control. In both years of study, no significant differences were observed between liquid and solid manure treatments despite their differences in nutrient contents (Table 1). In 2017-18, N and P applied through liquid manure were 45% and 47% higher than N and P applied through solid manure, respectively. While in 2018-19, 84% and 4% higher N and P were applied through the liquid manure than solid manure. Given the higher N and P contents in liquid manure, nutrient losses are expected to be higher from liquid manure treatments than solid manure. However, in 2017-18 other nutrient losses were 29 to 58% higher in solid manure than liquid manure, except for DRP. This may have been influenced by similar runoff depths between liquid and solid manure treatments (Table 3) and also emphasizes that without sufficient runoff to mobilize the nutrients, higher losses are not solely a result of higher nutrient content (Vadas et al., 2019). In 2018-19, except for TKN, liquid manure had 24 to 36% higher nutrient losses than solid manure. Inconsistent differences between liquid and solid manure treatments across the seasons indicate the complex interactions of manure physical characteristics and field conditions partly influenced by tillage and environment as drivers of nutrient losses (Azmatch et al., 2012; Stock et al., 2019a). In both years of study, irrespective of tillage type, solid manure applied on snowpack did not wash away with runoff but remained on the surface, allowing for potential nutrient release each time it interacted with runoff. After its application, the solid manure was present on the surface until the summer planting (Figure 6).

The sediment and nutrient losses assessed considering the combined effect of tillage x manure type also revealed important information. The sediment and nutrient loss trends were inconsistent among the tillage and manure type treatments (Figures 3c to 3f and Tables 5 and 6). In 2017-18, CT-liquid manure had higher sediment losses, and except for DRP, NT-solid manure had higher nutrient losses than any other tillage and manure type combination. While in 2018-19, NT-liquid manure had higher sediment and nutrient losses. Due to different TN and TP contents, nutrient losses from liquid and solid manure treatments are not directly comparable within a tillage type. However, nutrient losses from CT-liquid manure can be compared to those from NT-liquid manure. Similarly, CT-solid manure is comparable to NT-solid manure. No significant differences were observed between CT-liquid manure and NT-liquid manure treatments. Similarly, CT-solid manure and NT-solid manure treatments are also not significantly different. Except for sediment losses in 2017-18, the other nutrient and sediment losses of NT-liquid manure and NT-solid manure were 2-11 times and up to 11 times greater than CT-liquid manure and CT-solid manure treatments, respectively. As previously explained, greater nutrient losses from NT treatments (Liquid and Solid manure) were driven by greater runoff volumes and their capacity to mobilize the nutrients than CT treatments (Vadas et al., 2018). The reduced losses in CT-liquid manure can be attributed to the physical form of liquid manure combined with the depressional storage capacity of CT likely allowing nutrients to infiltrate into the soil along with snowmelt and rain-on-snow. Similar to our results, others have observed fall tillage benefits in reducing wintertime nutrient losses compared to no-tillage at the plot (Stock et al., 2019a; Vadas et al., 2019) and field scales (Zopp et al., 2019).

3.5 Normalized nutrient losses

Nutrient losses from tillage × manure type treatments were normalized in an attempt to remove artifacts introduced by differences in total nutrients added with the two manures and to make a more direct comparison of nutrient losses. Normalized nutrient losses represent the grams of nutrient lost in the runoff per kilogram of nutrient applied through manure minus losses from the no manure control treatment. Except for the DRP losses in 2017-18, tillage × manure type had no significant effect on normalized nutrient losses (Figures 4 and 5). In both years of study, NT-solid manure exported more NH_4^+, DRP, TKN, and TP nutrients for every kilogram of TN and TP applied compared to the other treatments (NT-liquid, CT-liquid and CT-solid). Similarly, CT-liquid manure had the least nutrient exports in both years of study compared to the other treatments. The normalized nutrient losses from different manure types had similar trends within each tillage treatment. In both years of study, within CT and NT, solid manure had higher nutrient losses than liquid manure for every kilogram nutrient applied. Within CT, solid manure had 5 to 17 grams of nutrient losses (NH_4^+, DRP, TKN, and TP), and liquid manure had up to 4 grams of nutrient losses for every kilogram of TN and TP applied. Similarly, within NT, solid manure had 25 to 108 grams and liquid manure had 7 to 21 grams of nutrients lost for every kilogram of TN and TP applied. The higher losses from solid manure can be attributed to its physical characteristics (>20% solids) and potential to release nutrients over each time it interacts with runoff. Solid manure can behave similar to a slow-release fertilizer especially when applied on frozen agricultural fields with no active crop (for nutrient uptake) and minimal soil microbial activity (for decomposition). During the study period, we did not explicitly measure the nutrient release characteristics of solid manure, but depending upon environmental conditions, solid manure can remain frozen after its application restricting its nutrient release. In a laboratory study, Williams et al. (2011) found that manure remained frozen when applied on frozen soil (below the snowpack) and was less susceptible to phosphorus losses. Also, in cold agricultural regions during winters, solid manure needs a medium (water) to release and transport its nutrients (runoff and infiltration). While liquid manure, because of its physical state (<5% solids), can be easily lost and infiltrated without a medium. As discussed earlier, despite 5 to 7 runoff events during the study years, solid manure applied on snowpack did not wash away completely with runoff but remained on the surface, allowing for potential nutrient release each time interacted with runoff. In a controlled laboratory study, Vadas et al. (2018)

observed liquid manure (4.6% solids) applied on snowpack (1400 ml of water equivalent; without soil) had complete interaction with snowmelt and released more DRP and NH_4^+ than semi-solid manure (11.6 to 12.6% solids), which had incomplete interaction with snowmelt (1250 ml). Vadas et al. (2018) further suggested that solid manure may release less phosphorus during snowmelt than liquid manure. Similarly, in modeling field-scale runoff, Vadas et al. (2017) found that only 20% of snowmelt water interacted with solid beef manure. The findings of Vadas et al. (2017 and 2018) combined with our field observations support our theory that solid manure releases nutrients slowly depending upon the runoff volume it interacts with each time. Overall, irrespective of tillage type, solid manure is prone to nutrient losses for longer periods and may have higher losses than liquid manure during winters. However, soil (frost, surface storage and infiltration capacities) and environmental conditions (snowmelt and rain on snow volume), during runoff events play an important role in differentiating nutrient losses between solid and liquid manure types.

4. Conclusions

In cold region-dairy agroecosystems, especially fields managed with corn silage, both tillage and winter manure applications can influence wintertime runoff, sediment, and nutrient losses. Fall chisel tillage that creates depressions on the surface can reduce wintertime (Nov-Apr) runoff and its associated nutrient losses by providing more infiltration opportunity time for snowmelt and rain. However, such tillage operations may pose the risk of erosion, especially during non-winter periods. This suggests a need for practices like crop residue management (>30%) that can help decrease soil erosion during non-winters and increase water infiltration during winter.

Irrespective of manure type (liquid or solid), winter manure applications on snow-covered frozen soils pose the risk of manure nutrient losses. Solid manure can behave similar to a slow-release fertilizer and needs a medium (water) to transport (infiltration and runoff) its nutrients. While liquid manure can be easily infiltrated without additional water. Liquid manure applied on tilled surfaces can infiltrate into the soil depending on the surface (depressions) and sub-surface (soil moisture content) storage capacities, soil hydraulic characteristics, and runoff volumes. Solid manure, irrespective of tillage or no-tillage surface, can be physically present on the surface for a longer period and release nutrients every time it interacts with runoff. Therefore, in unavoidable situations when winter manure applications need to occur on snow-covered frozen fields, manure type could be prioritized depending on field conditions to regulate manure nutrient losses. On chisel tillage surfaces, applying liquid manure will be beneficial as it has more favorable characteristics for infiltration than solid manure. Finally, if winter manure applications on snow-covered frozen soils could be avoided, it reduces the risk of wintertime nutrient loss to the environment.

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Tables and Figures

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Table 2: Mean monthly temperature and precipitation for Arlington, WI for the two study seasons and the 30-year historical record (i.e. Normal)

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Table 5: Seasonal nutrient loads and p-values for comparison of tillage, manure type and tillage × manure type effects during the 2017-18 monitoring season

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Figure 4: Normalized seasonal nitrogen loads (±standard error) by tillage×manure type during 2017-18 (4a and 4c) and 2018-19 (4b and 4d) monitoring seasons. Figures 4a and 4b present grams of NH_4^+-N lost per kilogram of total nitrogen applied through manure. Figures 4cand 4d present grams of TKN lost per kilogram of total nitrogen applied through manure

Figure 5: Normalized seasonal phosphorus loads (±standard error) by tillage×manure type during 2017-18 (5a and 5c) and 2018-19 (5b and 5d) monitoring seasons. Figures 5a and 5b present grams of DRP lost per kilogram of total phosphorus applied through manure. Figures 5cand 5d present grams of TP lost per kilogram of total phosphorus applied through manure

Figure 6: a)Solid manure on the experimental plot during the first melt event (Feb 2019) after its application. b) Solid manure on the experimental plot before summer planting (May 2019)

Table 1: Details of manure application and its associated nutrient contents

Season	Application date	Type	Density kg m^{-3}	Application rate Mg ha^{-1}	Dry matter (DM), %	Nutrient content % of DM	
						TN	TP
2017-18	18 Jan, 2018	Liquid	1006.5	37.6	5.8	2.1	0.9
		Solid	1080.0	20.6	25.3	0.7	0.3
2018-19	24 Jan, 2019	Liquid	998.1	37.6	5.8	2.1	0.8
		Solid	1247.0	20.6	35.8	0.4	0.2

TN-total nitrogen; TP-total phosphorus

Table 2: Mean monthly temperature and precipitation for Arlington, WI for the two study seasons and the 30-year historical record (i.e. Normal)

Month	2017-18		2018-19		1991-2020 (Normal)*	
	Temperature °C	Precipitation mm	Temperature °C	Precipitation mm	Temperature °C	Precipitation mm
Nov	0.9	18.3	-1.1	38.6	4.7	56.9
Dec	-6.3	14.7	-2.5	39.9	-1.4	47.8
Jan	-8.2	37.8	-9.2	53.6	-4.4	45.5
Feb	-7.0	43.7	-8.7	76.2	-2.7	42.9
Mar	0.1	19.1	-1.8	26.2	2.4	55.9
Apr	1.9	65.5	7.1	74.4	7.9	98.0
Seasonal average/total	-3.1	199.1	-2.7	308.9	1.1	347.0

*Information collected from NOAA, U.S. Department of Commerce

Table 3: Seasonal runoff depth and sediment losses of tillage and manure type treatments during 2017-18 monitoring season

Effect	Treatment	Runoff mm	TS kg ha^{-1}	VS
Tillage	CT	17.8a†	388 ns	26.0 ns
	NT	30.5b	299	115.0
Manure type	Control	25.3 ns	197 ns	48.7 ns
	Liquid	22.7	548.0	522.0
	Solid	24.5	181.0	8.1
	Analysis of variance p-value			
	Tillage	0.03	0.64	0.35
	Manure type	0.68	0.73	0.42

†Different letters in the same column and within the same factor indicate a significant difference at the 0.05 probability level. ns – not statistically significant. [CT-Chisel tillage, NT-no-tillage, TS- total solids, VS- volatile solids]

Table 4: Seasonal runoff depth and sediment losses of tillage and manure type treatments during the 2018-19 monitoring season

Effect	Treatment	Runoff mm	TS kg ha^{-1}	VS
Tillage	CT	31.1a†	26.9a	23.7a
	NT	95.7b	81.9b	74.7b
Manure type	Control	57.5ns	56.5ns	41.9ns
	Liquid	70.0	60.1	58.5
	Solid	62.6	46.7	47.2
	Analysis of variance p-value			
	Tillage	0.03	0.06	0.07
	Manure type	0.32	0.69	0.70

†Different letters in the same column and within the same factor indicate a significant difference at the 0.05 probability level. ns – not statistically significant. [CT-Chisel tillage, NT-no-tillage, TS- total solids, VS- volatile solids]

Table 5: Seasonal nutrient loads and p-values for comparison of tillage, manure type and tillage × manure type effects during the 2017-18 monitoring season

Treatment Effect	Treatment	NH_4^+-N	DRP	TKN	TP
		-------------- g ha^{-1}		----------------	
Tillage	CT	314.0a†	140.0a	968.0a	320.0a
	NT	2006.0b	710.0b	5212.0b	1030.0b
Manure type	Control	58.3b	54.5b	785.0b	228.0b
	Liquid	1491.7b	645.5b	3285.0b	742.0b
	Solid	1930.0a	574.9a	5200.0a	1061.0a
Tillage x Manure type	CT-Control	163.1a	100.0a	754.0a	162.0a
	NT-Control	40.0a	126.5a	816.0a	295.0ab
	CT-Liquid	253.6b	198.7a	783.0a	176.0ab
	NT-Liquid	2729.8b	1092.4a	5787.0ab	1307.0ab
	CT-Solid	524.6c	239.3b	1366.0bc	623.0b
	NT-Solid	3335.4c	910.5b	9034.0c	1499.0b
ANOVA p-value	Tillage	<0.01	<0.01	0.01	0.03
	Manure	<0.01	<0.01	0.01	0.02
	Tillage x Manure	0.02	0.03	0.07	0.45

†Different letters in the same column and within the same factor indicate a significant difference at the 0.05 probability level. [CT-Chisel tillage, NT-no-tillage, NH4$^+$-N – ammonium nitrogen, NO_3^-N- nitrate nitrogen, DRP- dissolved reactive phosphorus, TKN- total kjeldahl nitrogen, TP- total phosphorus].

Table 6: Seasonal nutrient loads and p-values for comparison of tillage, manure type and tillage × manure type effects during the 2018-19 monitoring season

Treatment Effect	Tillage	$NH4^{+}$-N	DRP	TKN	TP
		------------ g ha^{-1} ---------------			
Tillage	CT	378.0 ns†	126.0 a	973.0 ns	179.0a
	NT	1310.0	549.0 a	3006.0	699.0b
Manure type	Control	150.0 ns	43.9 b	731.0 ns	133.0b
	Liquid	1380.0	537.1 a	2523.0	657.0a
	Solid	1010.0	432.2a	2715.0	528.0a
Tillage x Manure type	CT-Control	114.0 ns	37.0 ns	327.0 ns	122.0 ns
	NT-Control	185.0	50.8	1135.0	144.0
	CT-Liquid	324.0	174.9	912.0	192.0
	NT-Liquid	2429.0	899.4	4134.0	1121.0
	CT-Solid	695.0	167.4	1681.0	224.0
	NT-Solid	1318.0	696.9	3748.0	833.0
ANOVA p-value	Tillage	0.19	0.05	0.06	0.03
	Manure	0.06	<0.01	0.07	0.01
	Tillage x Manure	0.54	0.38	0.93	0.78

†Different letters in the same column and within the same factor indicate a significant difference at the 0.05 probability level. ns – no statistically significant differences. [CT-Chisel tillage, NT-no-tillage, $NH4^{+}$-N – ammonium nitrogen, NO_3^{-}-N- nitrate nitrogen, DRP- dissolved reactive phosphorus, TKN- total kjeldahl nitrogen, TP- total phosphorus].

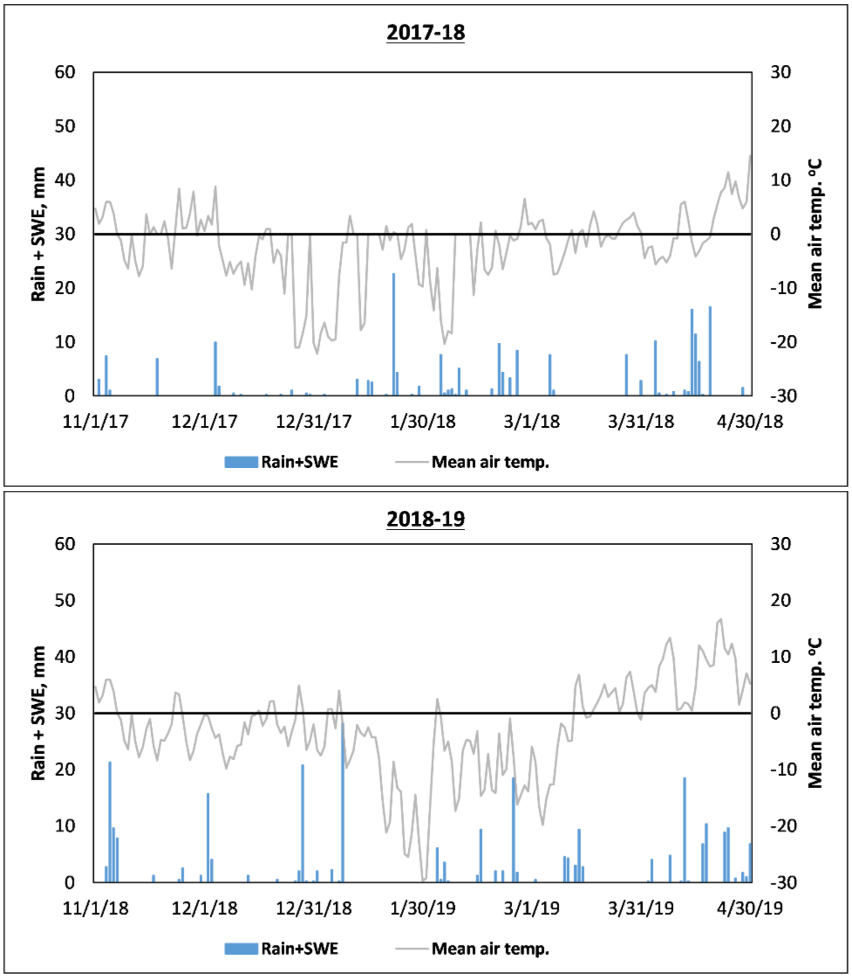

Figure 1: Average daily air temperature and total daily precipitation as rainfall or the liquid-equivalent of snowfall (SWE) during Precipitation and runoff events during the two experimental seasons (2017-18 & 2018-19)

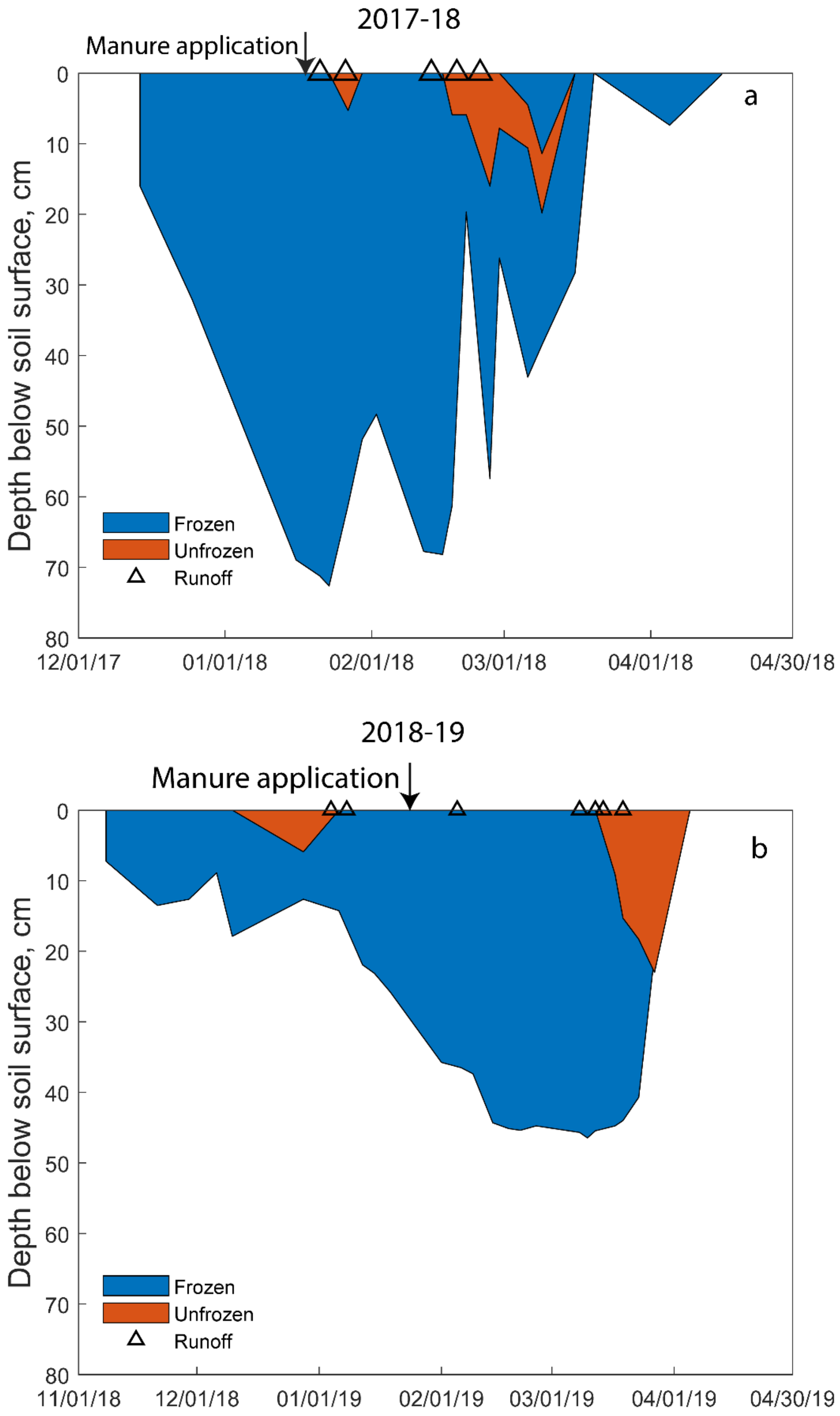

Figure 2: Soil frost formation and depletion during the 2017-18 (a) and 2018-19 (b) monitoring seasons. [Arrow presents the day of manure application. Triangle presents the day runoff event occured]

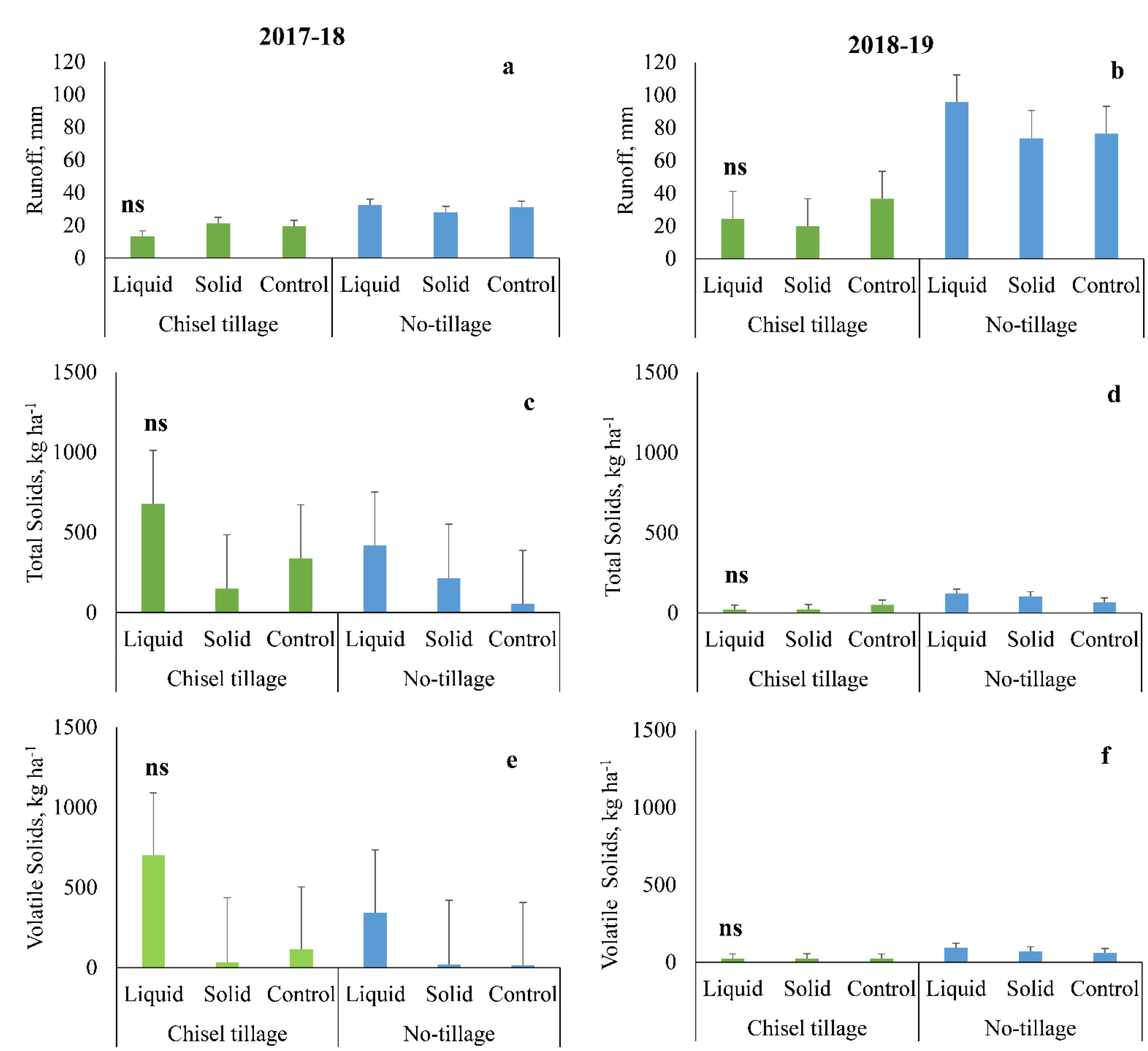

Figure 3: Tillage ×manure type treatments seasonal (Nov-Apr) mean (±standard error) runoff depth (a-b) and total solids (c-d), and volatile solids (e-f) losses for the two experimental seasons. ns- no statistically significant differences among the treatments at 0.05 probability level

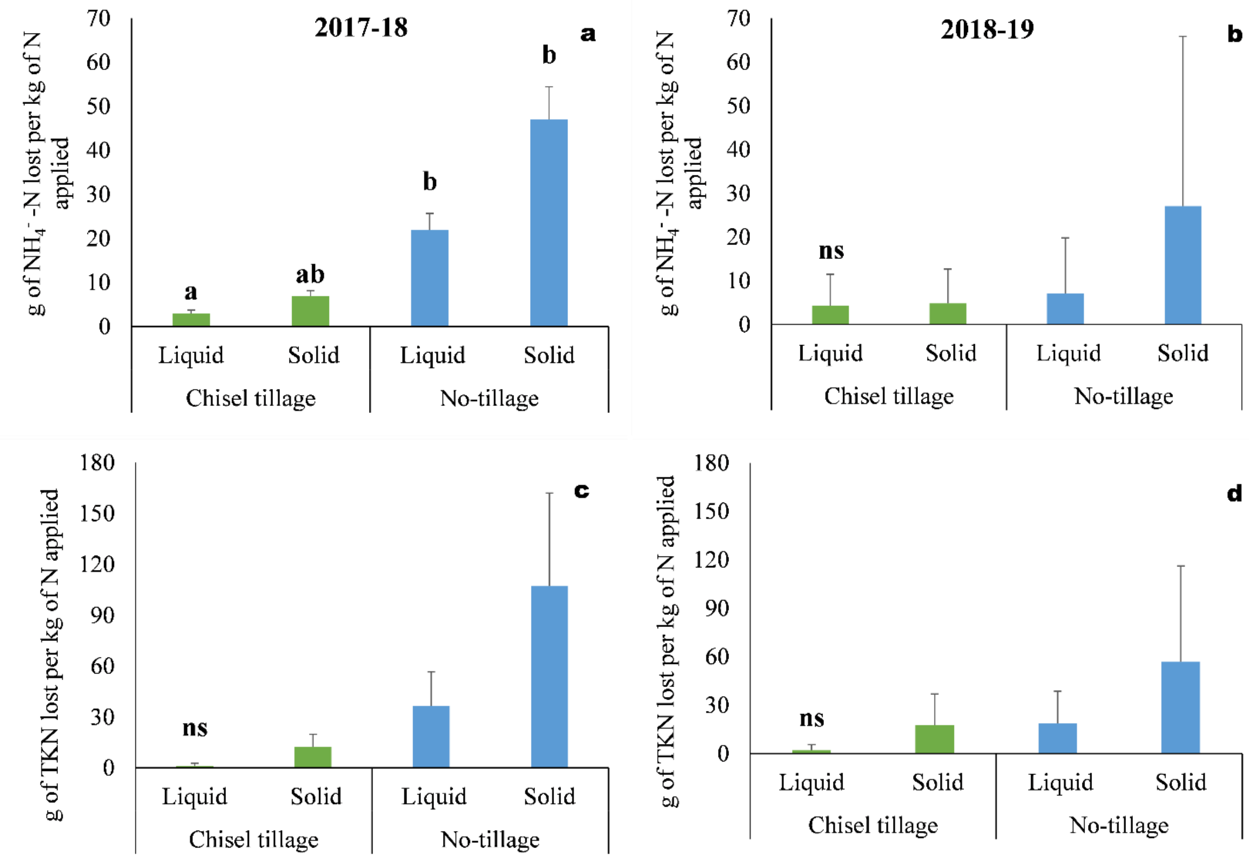

Figure 4: Normalized seasonal nitrogen loads (±standard error) by tillage×manure type during 2017-18 (4a and 4c) and 2018-19 (4b and 4d) monitoring seasons. Figures 4a and 4b present grams of NH_4^+-N lost per kilogram of total nitrogen applied through manure. Figures 4cand 4d present grams of TKN lost per kilogram of total nitrogen applied through manure [NH_4^+ – ammonium; TKN- total Kjeldahl nitrogen; N-nitrogen].

Columns with different lowercase letters indicate statistically significant differences among treatments at the 0.05 probability level.

Columns with similar lowercase letters indicate treatments are not statistically significant.

ns- not statistically significant difference among the treatments

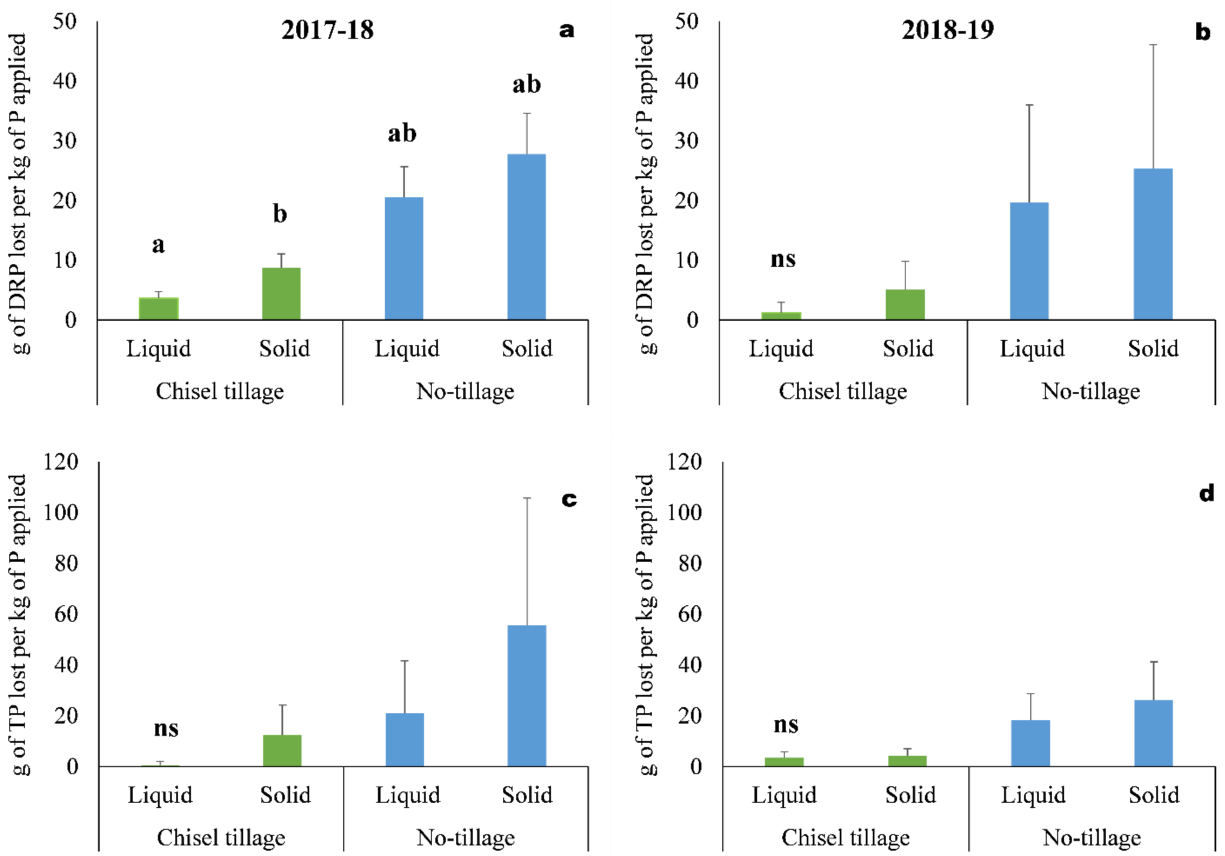

Figure 5: Normalized seasonal phosphorus loads (±standard error) by tillage×manure type during 2017-18 (5a and 5c) and 2018-19 (5b and 5d) monitoring seasons. Figures 5a and 5b present grams of DRP lost per kilogram of total phosphorus applied through manure. Figures 5cand 5d present grams of TP lost per kilogram of total phosphorus applied through manure [DRP-dissolved reactive phosphorus; TP- total phosphorus; P-phosphorus].

Columns with different lowercase letters indicate statistically significant differences among treatments at the 0.05 probability level.

Columns with similar lowercase letters indicate treatments are not statistically significant.

ns- not statistically significant difference among the treatments

Figure 6: a)Solid manure on the experimental plot during the first melt event (Feb 2019) after its application. b) Solid manure on the experimental plot before summer planting (May 2019)

Chapter 2

Effectiveness of tillage and residue management on runoff reduction from agricultural systems

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Abstract

Tillage and residue management conservation practice standard (NRCS 345) is widely practiced in agricultural management, however, the overall effectiveness of this practice for water quality protection is challenged. A meta-analysis was conducted to understand and quantify tillage and residue management effectiveness on runoff reduction and its associated constituents from agricultural fields. Annual runoff, sediment, and nutrient loads were compiled from published literature across the United States and Canada. A total of 61 research articles were reviewed, and 1575 site-years of data were categorized into four management practices (tillage, no-tillage, tillage with residue cover, and no-tillage with residue cover). Across the site years (1968-2019) studied, median runoff depth for no-tillage and no-tillage-residue were 40% and 45% greater than tillage and tillage-residue management, respectively. No difference in median runoff was observed between no-tillage and no-tillage-residue managements, while the median runoff for tillage-residue management was 25% lower compared to tillage. Irrespective of residue cover, tillage systems (with and without residue) had 70% greater sediment losses than no-tillage-residue management. Dissolved nitrogen and phosphorus losses were higher in no-tillage systems than tillage systems, while total nutrient losses were higher in tillage systems than in no-tillage systems. Maintaining greater than 30% residue cover reduced dissolved nitrogen and phosphorus losses by 39% and 33%, respectively, across tillage and no-tillage systems. Particulate nutrient losses followed trends in sediment loss. Similar to dissolved nutrients, greater than 30% residue cover decreased total nutrient losses by ~50% irrespective of tillage management. These results indicate that over the long-term, no-tillage and tillage, combined with greater than 30% residue cover, can effectively reduce sediment and nutrient losses. However, no-tillage can be effective in reducing sediment and particulate nutrient losses in field conditions with a high risk of erosion.

Keywords: Tillage, No-tillage, Conservation tillage, Residue cover, and water quality

1. Introduction

Natural Resource Conservation Service (NRCS) practice standards, “Residue and Tillage Management, No Till” (NRCS code 329) and “Residue and Tillage Management, Reduced Till” (NRCS code 345), are agricultural conservation practices (ACPs) that "limit soil disturbance to manage the amount, orientation, and distribution of crop and plant residue on the soil surface year-round" (NRCS, 2017). “Tillage” in this context is defined as the mechanical manipulation of soil for the purpose of crop production, "No Till" in this context means that no method of tillage is applied during any part of the year or growing season, and "Reduced Till" refers to a reduced frequency of tillage or a less disruptive tillage method compared to conventional tillage practices, such as moldboard plowing. Both practices attempt to preserve plant residues on the ground surface in order to prevent soil erosion and nutrient losses via surface runoff.

Increasing residue cover reduces evaporation and increases infiltration, which leads to less runoff and can reduce soil erosion and sediment loss, which reduces sediment-bound nutrient transport in surface runoff (Lascano & Baumhardt, 1996; Baumhardt et al., 2001). Conservation tillage practices increase infiltration by leaving intact root channels and other near-surface voids created between soil aggregates because of a reduction in soil disturbance from fewer and less aggressive field operations (Busari et al., 2015). Additionally, crop residues left on the soil surface protect soil particles from detachment from raindrop impact, which decreases the formation of surface seals and crusts (Sharpley and Smith, 1991; Blanco-Canqui and Lal, 2009). Similarly, many studies have shown that tillage significantly affects the physical, chemical, and biological properties of soil over time (Busari et al., 2015). Conservation and reduced tillage practices preserve residue cover which benefits soil by increasing organic matter content and soil microbial productivity, as the supply of organic material left on the soil surface is decomposed by a healthy soil microorganism population (Busari et al., 2015). These practices can benefit soil health by reducing organic carbon oxidation, which increases soil organic matter content. In fact, any tillage system that leaves at least 30% of the soil surface covered with crop residue after planting can improve soil quality by increasing or maintaining organic matter (Maetens et al., 2012). Tillage and residue management go together in practice, since reducing the frequency and intensity of tillage can leave crop residue intact in the soil with root systems undisrupted. Tillage and residue management practices are also commonly applied with other ACPs, such as Conservation Crop Rotation, Nutrient Management, Pest Management, and Irrigation Water Management.

Numerous peer-reviewed articles have documented the benefits soil received from conservation tillage and residue cover (Blanco-Canqui and Lal, 2009; Brusar et al., 2015; Carretta et al., 2021). Studies have also assessed the water quality benefits provided by the practice (Shipitalo and Edwards, 1998; Montgomery, 2007; Armand et al., 2009; Leys et al., 2010; Maetens et al., 2012; Wang et al., 2015). However, studies also identified the increased runoff and dissolved nutrient losses from conservation tillage and residue management practices than conventional tillage (Darynto et al., 2017a; Daryanto et al.,2017b; Baumhardt et al., 2020). These results were generally attributed to compaction and nutrient stratification, making tillage and residue management benefits for water quality protection debatable (Carretta et al., 2021). Also, most of the information on tillage and residue management effectiveness in reducing water pollutants from agricultural fields is available at seasonal scales.

The goal of this paper was to develop a systematic understanding of tillage and residue management as a conservation practice for water quality improvement Specific objectives were to: (1) synthesize peer-reviewed literature information available at an annual scale on the impact of tillage and residue management on surface water quality; (2) compare the effect of crop residue management by tillage management on surface water quality parameters in the United States and

Canada with a meta-analysis approach. The information gained from this meta-analysis can be used to help inform the selection of conservation tillage and residue management practices for water quality improvement.

2. Materials and Methods

2.1 Literature Search

A search of peer-reviewed literature was performed between April and September 2020 to gather data from relevant research articles that reported on the effects of tillage and residue management on water quality either as a primary or secondary treatment. Primary treatment indicates that the article's main focus was on investigating tillage and/or residue management. Whereas secondary treatment refers to articles in which the main focus was not on tillage and/or residue management, but either tillage and/or residue management were evaluated (section 2.2). For example, Bormann et al. (2012), evaluated the runoff measurement scale effect on phosphorus losses by collecting runoff from agricultural fields of varying sizes (0.0001–12 ha) that had undergone different tillage and residue management practices. While their primary focus was not on tillage and residue management, the study provided information related to tillage and residue management effect on water quality. The collected articles were segregated based upon the geographical region (North America vs. non-North America/international) and timescale of data collection (seasonal vs. annual). For the purposes of this literature review and its applicability, only field studies conducted within the United States (US) and Canada were included in the database. Next, articles with information were screened, and studies with only seasonal (i.e., not year-round), rainfall simulation, and modeling data were excluded. Therefore, the literature considered for this work included annual scale data pertaining to precipitation, surface runoff, sediment, nitrogen (N) and phosphorus (P) losses. To avoid extraction errors which could lead to additional uncertainty in the dataset, no software or other methods were used to extract information from figures. Only information presented in tables and text was manually extracted from the selected articles and used for the analysis. A summary of articles reviewed in this study is presented in Appendix A.

2.2 Data collection

Using the criteria described above, 61 research articles published between 1968-2019 were identified that reported experimental methods and site conditions in detail. The extracted runoff and nutrient loss data were further categorized into five management categories for analysis. These management categories were selected to help determine the impact of soil disturbance and residue cover somewhat individually. The five categories used were,

I. Tillage (T): Any form of soil disturbance operation comprising moldboard, chisel, disk, subsoiler, vertical, and reduced tillage leaving <30% of surface cover.

II. No-tillage (NT): No soil disturbance following harvest, with the only soil disturbance happening during seedling/planting stage with < 30% of surface cover. This category applies for cropping systems that leave little crop residues after harvest, such as corn (*Zea mays* L.) silage production.

III. Tillage-residue (T-R): Any form of tillage operation listed in T but with >30% of surface cover. Fields with a summer-winter crop rotation system were considered a form of residue management because the standing crop covers the soil for most of the year.

IV. No-tillage-residue (NT-R): As defined under NT, no soil disturbance other than during seeding operations with >30% of residue cover and any summer-winter crop rotation system.

V. Pasture (PA): Any rangeland, improved pasture, and hay land, all of which may or may not be used for animal feeding.

2.3 Data analysis

The geographical distribution of the data was mapped, and the number of site-years for each tillage and residue management category were calculated. Precipitation, runoff, sediment and nutrient loss data for each management category were analyzed using descriptive statistics and then compared using box-and-whisker plots. The nutrient loss data were grouped into dissolved, particulate, and total forms (Table 1) to evaluate the effect of tillage and residue management on specific nutrient losses. Runoff loss as a percentage of precipitation was computed using precipitation and surface runoff data to normalize the effects of climate, soil type, and management (other than tillage and residue) on runoff losses.

For comparisons, T management (<30% residue) is considered as a baseline practice and the other management practices were evaluated with respect to this baseline by calculating the "percent effectiveness" (Smith et al., 2019).

$$Percent\ Effectiveness_{x} = \frac{Baseline\ practice_{x} - other\ practices_{x}}{Baseline\ practice_{x}} \times 100 \qquad (1)$$

Where *x* represents runoff volume or depth, sediment load, or the nutrient load of interest within each management category.

For example, the percent effectiveness of NT was calculated by subtracting the nutrient and sediment loads of NT from those of T, and then dividing by the load of T for each site year within the studies that directly compared the practices (Equation 1). A negative percent effectiveness value indicates that NT increased nutrient loads (less effective), whereas a positive value indicates that NT decreased nutrient loads and thus improved water quality (more effective). Confidence intervals for the mean percent effectiveness were also computed at $\alpha = 0.05$ to assess the statistical significance of the results, and boxplots of percent effectiveness and confidence intervals were plotted for visual comparison. Due to data constraints, not all combinations of tillage and residue management practices were able to be evaluated for effectiveness.

3. Results and Discussion

3.1 Data overview

A total of 61 peer-reviewed research articles spanning 20 states in the conterminous US and four provinces in Canada were identified that reported annual data on precipitation, runoff, and sediment and nutrient losses, comprising a total of 1575 site-years (Figure 1). The sediment and nutrient loss data from these studies included annual loads (mass per area) and concentrations (mass per volume). The loads and concentrations were measured through various methods, mainly based on the collection and chemical analysis of water samples from experimental plots, edge of fields, and watersheds. Experimental unit size ranged between 0.0009 and 103 ha, with 64% of the total site-years coming from sites of <1 ha, 33% from sites between 1 and 30 ha, and 3% from sites larger than 30 ha. Most data came from studies conducted in Southern and Midwestern states of the US. In the Midwest, Ohio alone accounted for 14% of total site-years. In the southern US, Texas and Oklahoma contributed to 10% and 16% of total site-years, respectively. Except for California, no data were found for states in the West and Pacific Northwest. Four provinces in Canada (British Columbia, Manitoba, New Brunswick, and Ontario) contributed 7% of the total site-years.

T and PA managements accounted for 72% of site-years, with the remaining 28% distributed among NT, T-R, and NT-R. NT had the least amount of data (73 site-years) (Figure 2), and it appeared that NT management was practiced either with residue cover (>30%) or with summer-winter crop rotations (increasing ground surface cover throughout the year), making it challenging to obtain data for strictly no-tillage systems (without residue cover). In the 521 site-years of PA data, Texas and Oklahoma contributed to 47% of the site-years and 47% site-years were evenly distributed among states in the Midwest and Southeast. The remaining 6% of PA data were contributed by California and Canada (Ontario).

3.2 Runoff losses

Surface runoff was not normally distributed and varied considerably within and among tillage and residue management practices. The median runoff was highest in NT management (155.5 mm) and lowest in PA management (41.0 mm). The NT (155.5 mm) and NT-R (152.0 mm) management median runoff was greater than T (91.0 mm) and T-R (68 mm), respectively (Figure 3). While runoff for NT and NT-R were similar, the median runoff for T-R was 25% lower than that of T. Aggregated across all studies, residue cover in no-tillage did not affect the annual median runoff, while both tillage managements (i.e., T and T-R) were superior to both NT and NT-R in reducing runoff volumes.

The amount and timing of runoff can vary significantly because of differences in precipitation amount and intensity between locations. Since precipitation varies geographically and temporally due to climate differences, comparing the aggregated surface runoff alone can be misleading for understanding the effects of tillage and residue management. To address this, the percentage of precipitation loss as runoff was computed for the five tillage-residue categories (Figure 4). Median precipitation losses as runoff ranged from 6 to 18% among the management practices. Similar to runoff losses, NT (median of 17%) had the highest and PA (6%) has the lowest runoff losses adjusted for precipitation. The NT (17%) and NT-R (18%) had greater percent precipitation losses compared to T (12%) and T-R (11%), respectively. On an annual scale, no differences were observed for median runoff and precipitation loss among the treatment categories. Residue cover did not affect precipitation losses as runoff; that is, tillage with <30% surface residue and tillage with >30% residue categories had similar runoff volumes within a specific tillage management type. The annual surface runoff results obtained in this meta-analysis contrast with the general notion that no-tillage results in less runoff than many tillage practices (Maetens et al., 2012; Carretta et al., 2021). However, depending upon climate and site-specific conditions, no-tillage systems can produce greater runoff than tillage systems. For example, in a long-term study (27 years) conducted in Bushland, TX, annual runoff from no-tillage fields was greater than stubble mulch tillage fields in a wheat-sorghum-fallow rotation and was significantly higher during the fallow period (Baumhardt et al., 2020). Similarly, in a six-year study, greater annual runoff was reported from no-tillage watersheds than those with conventional tillage irrespective of the cropping systems (Richardson et al., 1995). Although, long-term no-tillage management improves soil pore structure and aggregate stability, eventually increasing the soil infiltration capacity and reducing runoff (Lindstrom et al., 1998; Schreiber and Cullum 1998), others have reported that soil consolidation in no-tillage can reduce infiltration (Jones et al., 1994) and the smooth/even surface can accelerate runoff (Drury et al., 1993), resulting in greater runoff volumes relative to tillage (Angle et al., 1984). In tilled fields, the disturbance of the topsoil creates a roughened surface with depressions and channels. Depending upon the soil antecedent moisture, rainfall intensity and duration, this rough surface can impede runoff flow by holding the water in place and increasing the infiltration opportunity time (Angle et al., 1984; Lindstrom et al., 1981).

Some researchers have reported that residue cover can control runoff flow and reduce runoff volumes in most cases by increasing infiltration rates irrespective of tillage management (Kenimer et al., 1987; Mostaghimi et al., 1992). The effect of residue in reducing runoff depends upon the percentage of ground area covered with residue (Balco-Canqui and Lal et al., 2009). The work presented here contradicts these findings. While a higher percentage of residue cover seems to have greater benefit in runoff reduction, higher residue cover can reduce evaporation rates and increase soil water and can eventually increase runoff (Blanco-Canqui and Lal 2009; Baumhardt et al., 2020). Further, it was also observed that residue cover had no effect on reducing runoff in no-tillage systems in rainfall simulation studies (Lindstrom et al., 1984; Baumhardt et al., 2012). In other words, it appeared that the soil properties that developed from no-tillage restricted infiltration and overpowered the beneficial effects of residue cover. Findings from this meta-analysis agree with those that reported an increase in the runoff with no-tillage.

3.3 Sediment losses

Not all studies reviewed as part of this meta-analysis reported sediment losses. Compared to the reporting of runoff and nutrients, annual sediment loss was the least reported. Only three studies were found that reported annual sediment losses for NT. The remaining four tillage and residue management categories (T, TR, NT-R and PA) have 24, 10, 13 and 13 studies that reported sediment losses, respectively. Median sediment loads varied greatly among tillage and residue management practices (Figure 5). PA had the lowest median sediment loss (97.5 kg ha^{-1}), while NT (7207.5 kg ha^{-1}) had the highest, howe, this value was from only three studies. The NT-R management median sediment loss (532.2 kg ha^{-1}) was less than NT and T (2499 kg ha^{-1}). The T and T-R (2039 kg ha^{-1}) sediment losses were greater than NT-R. The ranking for median annual sediment losses was NT > T > T-R > NT-R > PA.

Irrespective of the scale (i.e., plot, field, and watershed) of the studies (those included in this meta-analysis and others), tillage was reported to produce higher sediment losses than no-tillage in most cases. Although seasonal data were not included in this work, this effect of tillage on sediment losses was especially evident in seasonal studies (e.g., Lindstrom et al., 1998; Grandy et al., 2006). Greater sediment losses have been observed under conventional tillage as a result of major storm events occurring during early seedbed preparation and after crop harvest when the soil cover was minimal (Angle et al., 1984; McGregor and Green, 1982; Wittmuss and Swanson, 1964; Langdale et al., 1985). According to Angle et al. (1984), one or two rainfall events were responsible for 78% of annual sediment losses under conventional tillage. Though no-tillage had significantly lower sediment loss than conventional tillage, 99% of the no-tillage annual losses occurred during one storm event (Angle et al., 1984).

While any form of tillage creates soil disturbance and may increase the threat of sediment loss, in many cases, greater sediment losses could be a direct effect of precipitation intensity, runoff volume, and soil condition rather than tillage itself. Jeong et al. (2011) reported that large runoff events (>500 m^3 ha^{-1}) generated several magnitudes more total suspended solids (TSS) than small runoff events and that residue cover did not have any impact on reducing sediment losses for large runoff events. The decision of which tillage and residue management practices to implement for controlling sediment losses needs to be made based upon management effectiveness at an annual scale and site-specific characteristics.

3.4 Nitrogen (N) losses

In comparison to the four tillage management categories, PA had lower N losses irrespective of the form (i.e., dissolved, particulate and total N). Median DN losses were highest in NT (3.3 kg ha^{-1}), while PN and TN losses were greater with T (6.2 and 14.5 kg ha^{-1}, respectively; Figure 6). Overall, tillage systems with >30% surface cover (TR and NT-R) were superior in limiting N losses compared to the tillage systems with <30% surface cover (T and NT).

3.4.1 Dissolved Nitrogen (DN)

No tillage (NT) had greater losses of DN (3.3 kg ha^{-1}), and PA had the least (1.4 kg ha^{-1}) compared to other tillage and residue management categories. The T management had a greater variation in DN loss than the other four categories, with losses reported up to 45 kg ha^{-1} (Figure 6). The DN loads, especially for NO_3^-, were reported to be higher in NT systems than T due to N stratification in the upper soil layers, poor drainage characteristics (in clay-rich soils), and surface sealing (Daryanto et al., 2017, Blanco-Canqui and Wortman 2020). However, it is unlikely that no-tillage systems always produce higher DN loads than tillage. Since nutrient load depends upon runoff volumes and concentrations (Randall and Mulla 2001), some studies reported no difference in NO_3^- and NH_4^+ loads between no-tillage and tillage systems but found that concentrations were significantly higher in no-tillage (Gal et al., 2007; Daryanto et al., 2017a). Also, it is not likely that the benefits of tillage in reducing runoff volumes will always result in reduced DN losses, as studies have observed significantly higher DN losses in tillage systems than no-tillage (Sharpley and Smith 1994; Drury et al., 2014). These contradicting results might be due to site-specific characteristics, including physical (e.g., rainfall variability, soil texture) and management factors (e.g., crop species, fertilizer type). However, despite these contrasting results, this meta-analysis found that tillage systems having >30% surface cover (T-R and NT-R) reduced DN losses by 52% and 39%, respectively, compared to tillage systems with <30% surface cover (T and NT).

3.4.2 Particulate Nitrogen (PN)

Particulate N losses followed a similar trend to sediment losses (Figure 7). PA produced the lowest PN losses compared to the other management categories. The PN losses of NT-R were comparable to that of P, which implies that plant surface residue cover can protect the soil from losing sediments and associated nutrients via runoff (Mostaghimi et al., 1988; Kenimer et al., 1987; Soileau et al., 1994; Torbert et al., 1999).

3.4.3 Total Nitrogen (TN)

The median TN losses were highest in T (14.5 kg ha^{-1}) and lowest in PA (1.0 kg ha^{-1}; Figure 8). In contrast to DN and PN, the TN losses had greater differences among the five tillage management categories. Also, TN loss data was consistent over different regions and periods. Compared to T, in most of the studies included in this analysis, NT was effective in reducing TN loads. The load reductions were more evident for Southern US states, where soils minimally or never undergo freeze-thaw cycles. While studies from the Midwest also reported positive effects of NT in reducing TN losses compared to T, some studies observed that NT produced more TN losses, especially during the non-growing season and when soils were frozen. Similar to DN and PN losses, this meta-analysis showed tillage systems with >30% surface cover had 52.3% and 52.6% lower TN losses, respectively, compared to the same systems with <30% surface cover. These results were similar to the findings of other studies, where residue cover reduced TN losses irrespective of the tillage system, which was attributed to lower sediment losses (Schuman et al., 1973; McDowell and McGregor 1984; Soileau et al., 1994; Blanco-Canqui and Lal 2009).

3.5 Phosphorus (P) losses

In comparison to the four tillage management categories, PA had lower P losses irrespective of the form (i.e., dissolved, particulate and total P). The median DP and PP losses were highest in NT (1.2 and 1.8 kg ha^{-1}, respectively), while TP losses were highest in T (1.9 kg ha^{-1}). Similar to N, tillage systems with >30% surface cover (TR and NT-R) were superior in limiting P loss compared to the systems with <30% surface cover (T and NT).

3.5.1 Dissolved Phosphorus (DP)

Dissolved P losses differed more among the five management categories than PP or TP (Figure 9). The magnitude of losses greatly varied within each category. The median DP losses were highest in NT (1.2 kg ha^{-1}) and lowest in T-R (0.1 kg ha^{-1}) and PA (0.1 kg ha^{-1}) managements. Compared to T, NT and NT-R had 400% and 167% higher median DP losses, respectively. Tillage systems with >30% surface cover (T-R and NT-R) had 33% and 42% less DP losses than tillage systems with <30% surface cover (T and NT), respectively.

The higher DP losses in NT systems can be attributed to insufficient sediments to sorb solution P and leaching P from the crop and weed decaying tissue (McDowell and McGregor 1980;

Langdale et al., 1985; Soileau et al., 1984; Sharpley and Smith 1994; Schreiber and Cullum 1998; Tiessen et al., 2010). Also, lower soil disturbance in no-tillage systems can increase surface soil P saturation, increasing phosphate supplying capacity of sediments and DP losses (McDowell and McGregor 1980; Tiessen et al., 2010). Reduced DP losses in tillage systems are likely due to disturbance of soil which reduces P saturation at/near the surface and incorporates plant and weed residues. While several studies have documented positive effects of NT in reducing DP loads, other studies report negative, and no effect compared to tillage systems. These mixed results stem from differences in management (other than tillage and residue), climate, and site characteristics. This meta-analysis found that tillage systems were superior in limiting DP losses over no-tillage systems regardless of field size, region of study, and management practices.

3.5.2 Particulate Phosphorus (PP)

Particulate P was the least reported nutrient form compared to others. Of the 61 articles reviewed for this meta-analysis, only eight reported nutrient losses from NT, and only one of those eight reported PP. Particulate P loss was reported for each of the other four management categories, but in fewer studies than other nutrient forms. Median PP losses varied greatly among the tillage and residue management categories (Figure10). Tillage (1.4 kg ha^{-1}) had the highest PP losses, while PA (0.1 kg ha^{-1}) had the lowest. In comparison to T, T-R and NT-R had 78% and 68% less PP losses, respectively. The reduced losses in T-R and NT-R managements are likely due to >30% surface cover, which dissipates rainfall impact energy, and traps sediments, restricting their losses from the field, and subsequently reducing PP (Langdale et al., 1985; Richardson and King 1995; Tiessen et al., 2010). Similar to PN, most of the studies in this meta-analysis correlated PP loss to sediments. Greater sediment losses will likely result in greater PP losses.

3.5.3 Total Phosphorus (TP)

Total P losses followed a similar trend to that of TN (Figure 11). The median TP losses were highest in T (1.9 kg ha^{-1}) and lowest in PA (0.2 kg ha^{-1}; Figure 8). In contrast, TP losses from NT (1.7 kg ha^{-1}) were similar to T. Tillage systems with >30% surface cover (T-R and NT-R) had 52% and 29% less TP losses than tillage systems with <30% surface cover (T and NT), respectively. Similar to TN, most studies attributed the reduction in TP losses to physical benefits of > 30% surface cover. (Schuman et al., 1973; McDowell and McGregor 1984; Soileau et al., 1994; Blanco-Canqui and Lal, 2009).

3.6 Performance Effectiveness

This section compares the effectiveness of NT, NT-R, and T-R management practices with respect to T. Most studies considered in this meta-analysis did not directly compare PA with T management. Due to this data constraint, the management effectiveness of PA with respect to T was not computed. However, PA had 40-99% less losses than other tillage and residue management categories irrespective of the variable of interest (runoff, sediments and nutrient losses).

Figure 12 presents the effectiveness of NT for runoff and its associated constituents. The impact of NT in reducing runoff was neutral, with median effectiveness close to zero (0.8%). In the 13 (n) comparisons made from six different studies, NT reduced runoff in seven, increased in five, and had a neutral effect in one. Despite the limited information (n = 2 to 4), NT was effective in reducing sediments (95%), TN (73%), PP (83%), and TP (75%) losses. However, NT negatively impacted DN and DP losses with -20% and -284% effectiveness, respectively. These results were similar to NT-conservation effectiveness reported by Smith et al., 2019.

Except for DP, NT-R had a positive effect in reducing runoff and its associated constituents (Figure 13). NT-R reduced runoff with median effectiveness of 10%. Similar to NT, NT-R largely reduced sediments (91%), PN (86%), TN (70%), PP (89%), and TP (65%) losses. For dissolved nutrient losses, NT-R median effectiveness was positive for DN (22%), but negative for DP (-67%). Leaving >30% surface cover after tillage appeared to reduce runoff and its associated losses in T-R relative to T (Figure 14). Despite the limited information, T-R was effective in reducing runoff (24%), sediment (76%), DN (10%), TN (16%), PP (71%) and TP (42%) losses.

4. Conclusions

Through meta-analysis, we quantified tillage and residue management effectiveness on runoff, sediment, and nutrient loss reduction from agricultural systems in the US and Canada. Across the 1575 site-years and five management categories (T, T-R, NT, NT-R and PA) studied, NT was the least reported management, while T was the most reported. Irrespective of the variable of interest (runoff, sediments, and nutrient losses), PA management had the lowest losses compared to all other tillage and residue management categories. The impact of tillage and residue management on runoff, sediment, and nutrient losses varies with site-specific characteristics. However, in general, tillage systems with >30% surface cover (T-R and NT-R) were superior to the tillage systems with <30% residue cover (T and NT) in controlling most runoff constituents. T and T-R managements reduced runoff and dissolved nutrients but not sediments and their associated particulate nutrients compared to NT and NT-R, respectively. In contrast, NT and NT-R managements had reduced sediments and associated nutrients but not runoff and dissolved nutrients compared to T and T-R, respectively. The performance effectiveness of NT, NT-R and T-R managements with respect to T revealed their respective % effectiveness in decreasing the runoff, sediments and nutrients losses from agricultural catchments. Overall, NT-R management was found to be the most effective management with largely positive performance effectiveness in controlling sediments, PN, PP, TN and TP losses in the runoff than other tillage and residue managements (T, NT, and T-R).

In light of these findings, it is advised to choose tillage and residue management practices based upon site-specific water pollutants of concern. T and T-R managements have the potential to decrease runoff and dissolved nutrient losses. However, these practices may need to be balanced with practices that help decrease the risk of soil erosion, and its associated nutrients. While long-term NT and NT-R managements have the potential to reduce sediments and associated nutrients, reducing runoff and dissolved nutrient losses , may require occasional tillage (once in 5-10 years) to avoid surface sealing, compaction and nutrient stratification (Balnco-Canqui and Wortman 2020; Darynto et al., 2017a). , Finally, tillage and residue management will continue to be vital agricultural management practices, therefore understanding their combined effectiveness on an annual scale through long-term monitoring across multiple sites and years would help establish robust recommendations for tillage and residue management.

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Tables and Figures

Table 1. Criteria used to group nutrient forms

Figure 1. Distribution of data collected from peer-reviewed articles on annual runoff losses across the US and Canada

Figure 2. Number of site-years of data available for each management practice category

Figure 3. Annual surface runoff losses for different tillage and residue management practice categories (T = tillage with <30% surface residue, NT = no-tillage with <30% surface residue, T-R = tilled with >30% surface residue, NT-R = no-tillage with >30% surface residue, and P = pasture, n indicates number of data values involved in each box-plot)

Figure 4. Percent of precipitation lost as surface runoff for each management practice category (T = tillage with <30% surface residue, NT = no-tillage with <30% surface residue, T-R = tilled with >30% surface residue, NT-R = no-tillage with >30% surface residue, and P = pasture, n indicates number of data values involved in each box-plot)

Figure 5. Annual sediment losses for different tillage and residue management practice categories ((T = tillage with <30% surface residue, NT = no-tillage with <30% surface residue, T-R = tilled with >30% surface residue, NT-R = no-tillage with >30% surface residue, and P = pasture, n indicates number of data values involved in each box-plot)

Figure 6. Annual dissolved nitrogen losses for different tillage and residue management practice categories (T = tillage with <30% surface residue, NT = no-tillage with <30% surface residue, T-R = tilled with >30% surface residue, NT-R = no-tillage with >30% surface residue, and P = pasture, n indicates number of data values involved in each box-plot)

Figure 7. Annual particulate nitrogen losses for different tillage and residue management practice categories (T = tillage with <30% surface residue, NT = no-tillage with <30% surface residue, T-R = tilled with >30% surface residue, NT-R = no-tillage with >30% surface residue, and P = pasture, n indicates number of data values involved in each box-plot)

Figure 8. Annual total nitrogen losses for different tillage and residue management practice categories (T = tillage with <30% surface residue, NT = no-tillage with <30% surface residue, T-R = tilled with >30% surface residue, NT-R = no-tillage with >30% surface residue, and P = pasture, n indicates number of data values involved in each box-plot)

Figure 9. Annual dissolved phosphorus losses for different tillage and residue management practice categories (T = tillage with <30% surface residue, NT = no-tillage with <30% surface residue, T-R = tilled with >30% surface residue, NT-R = no-tillage with >30% surface residue, and P = pasture, n indicates number of data values involved in each box-plot)

Figure 10. Annual particulate phosphorus losses for different tillage and residue management practice categories (T = tillage with <30% surface residue, NT = no-tillage with <30% surface residue, T-R = tilled with >30% surface residue, NT-R = no-tillage with >30% surface residue, and P = pasture, n indicates number of data values involved in each box-plot)

Figure 11. Annual total phosphorus losses for different tillage and residue management practice categories (T = tillage with <30% surface residue, NT = no-tillage with <30% surface residue, T-R = tilled with >30% surface residue, NT-R = no-tillage with >30% surface residue, and P = pasture, n indicates number of data values involved in each box-plot)

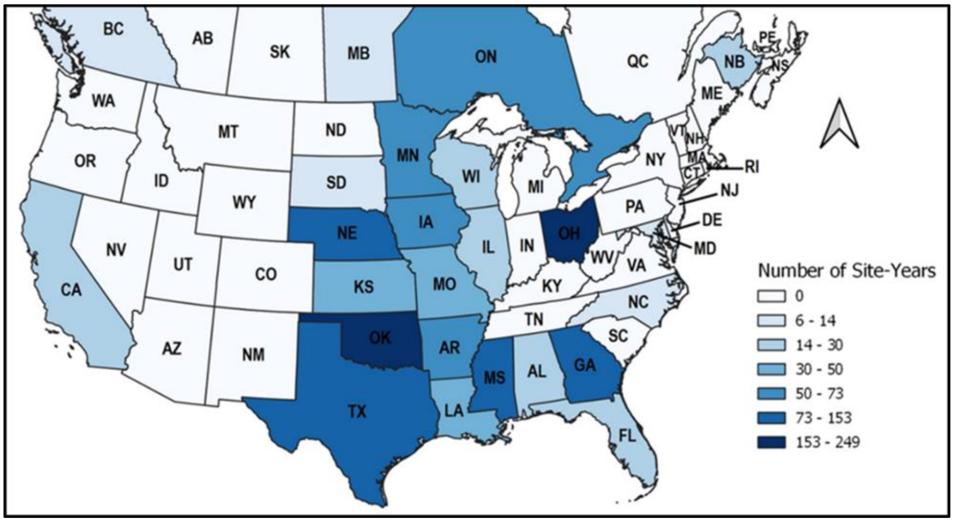
Figure 12. Practice Effectiveness of no-tillage management with respect to tillage for Runoff (R), Sediments (S), Dissolved N (DN), Particulate N (PN), Total N (TN), Dissolved P (DP), Particulate P (PP), and total P (TP). Solid black line represents 0% effectiveness; "n" indicates the number for comparisons represented by the box plot or confidence interval for a given constituent

Figure 13. Practice effectiveness of no-tillage-residue management with respect to tillage for Runoff (R), Sediments (S), Dissolved N (DN), Particulate N (PN), Total N (TN), Dissolved P (DP), Particulate P (PP), and total P (TP). Solid black line represents 0% effectiveness; "n" indicates the number for comparisons represented by the box plot or confidence interval for a given constituent

Figure 14. Practice effectiveness of tillage-residue management with respect to tillage (no residue) Runoff (R), Sediments (S), Dissolved N (DN), Particulate N (PN), Total N (TN), Dissolved P (DP), Particulate P (PP), and total P (TP). Solid black line represents 0% effectiveness; "n" indicates the number for comparisons represented by the box plot or confidence interval for a given constituent

Table 1. Criteria used to group nutrient forms

Nutrient Form	Nitrogen (N)	Phosphorus (P)
Dissolved	Nitrate Nitrate + Nitrite Ammonium Nitrate + Ammonium	Dissolved Reactive Phosphorus Soluble Reactive Phosphorus Water extractable Phosphorus
Particulate	Sediment Bound N	Sediment Bound P
Total	Dissolved N + Particulate N	Dissolved P + Particulate P



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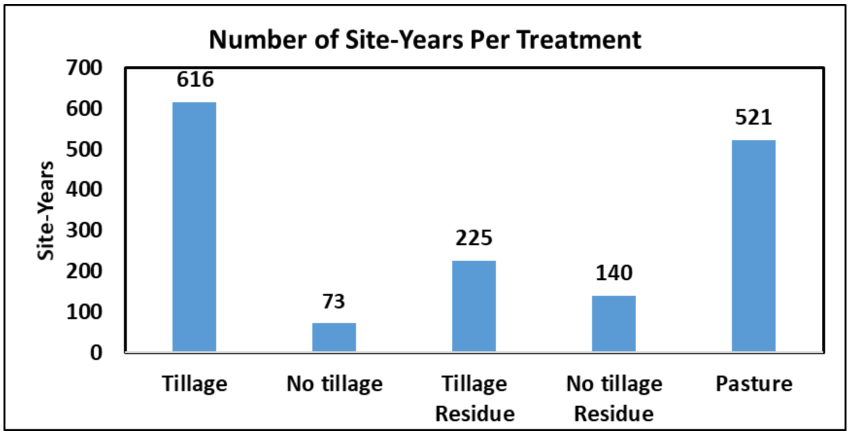

Figure 2. Number of site-years of data available for each management practice category

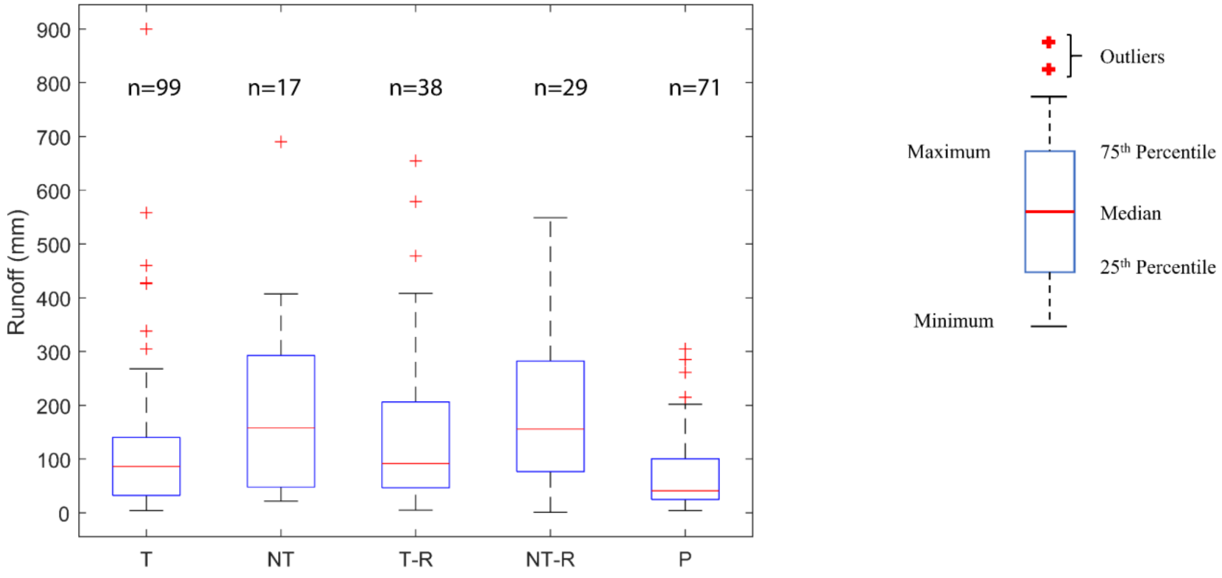

Figure 3. Annual surface runoff losses for different tillage and residue management practice categories (T = tillage with <30% surface residue, NT = no-tillage with <30% surface residue, T-R = tilled with >30% surface residue, NT-R = no-tillage with >30% surface residue, and P = pasture, n indicates number of data values involved in each box-plot)

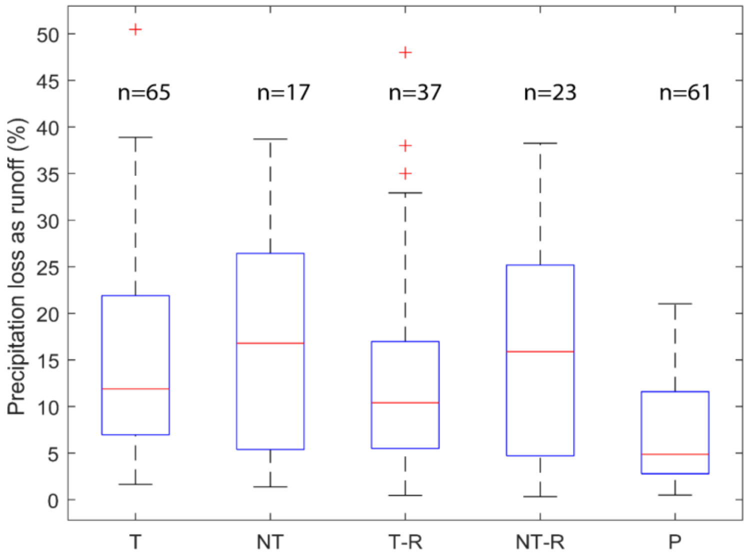

Figure 4. Percent of precipitation lost as surface runoff for each management practice category (T = tillage with <30% surface residue, NT = no-tillage with <30% surface residue, T-R = tilled with >30% surface residue, NT-R = no-tillage with >30% surface residue, and P = pasture, n indicates number of data values involved in each box-plot)

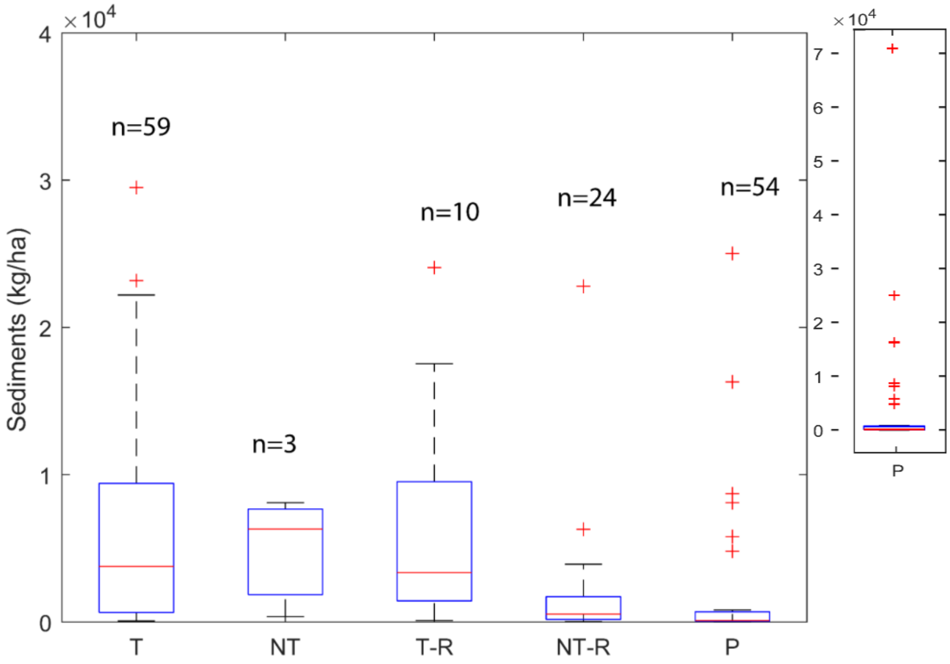

Figure 5. Annual sediment losses for different tillage and residue management practice categories ((T = tillage with <30% surface residue, NT = no-tillage with <30% surface residue, T-R = tilled with >30% surface residue, NT-R = no-tillage with >30% surface residue, and P = pasture, n indicates number of data values involved in each box-plot)

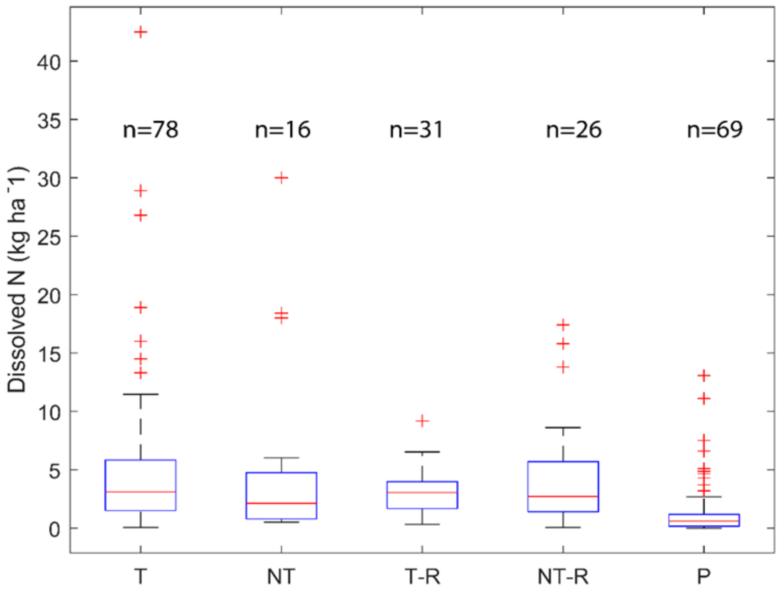

Figure 6. Annual dissolved nitrogen losses for different tillage and residue management practice categories (T = tillage with <30% surface residue, NT = no-tillage with <30% surface residue, T-R = tilled with >30% surface residue, NT-R = no-tillage with >30% surface residue, and P = pasture, n indicates number of data values involved in each box-plot)

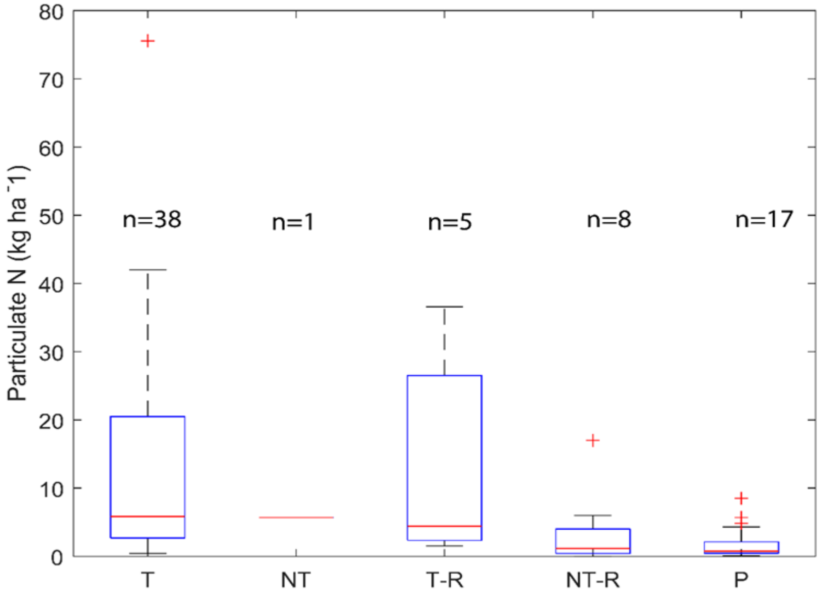

Figure 7. Annual particulate nitrogen losses for different tillage and residue management practice categories (T = tillage with <30% surface residue, NT = no-tillage with <30% surface residue, T-R = tilled with >30% surface residue, NT-R = no-tillage with >30% surface residue, and P = pasture, n indicates number of data values involved in each box-plot)

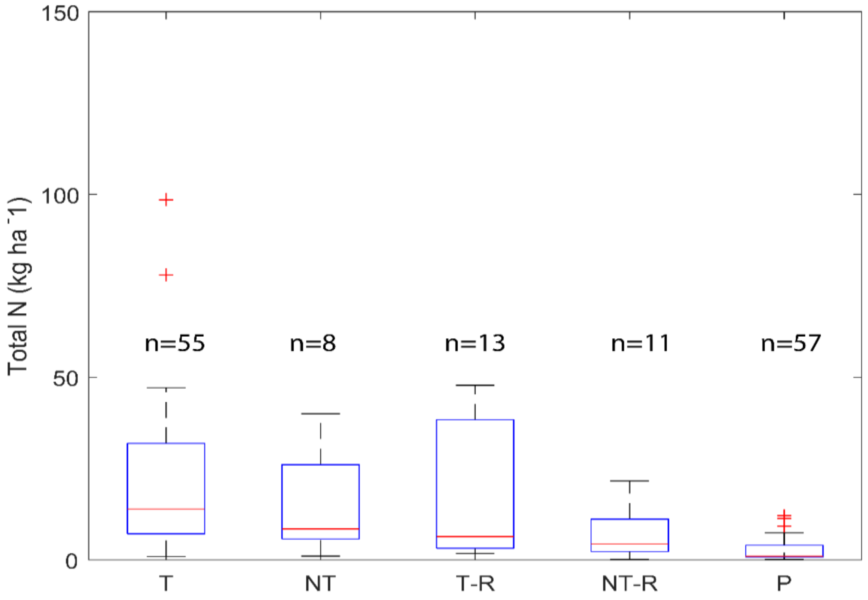

Figure 8. Annual total nitrogen losses for different tillage and residue management practice categories (T = tillage with <30% surface residue, NT = no-tillage with <30% surface residue, T-R = tilled with >30% surface residue, NT-R = no-tillage with >30% surface residue, and P = pasture, n indicates number of data values involved in each box-plot)

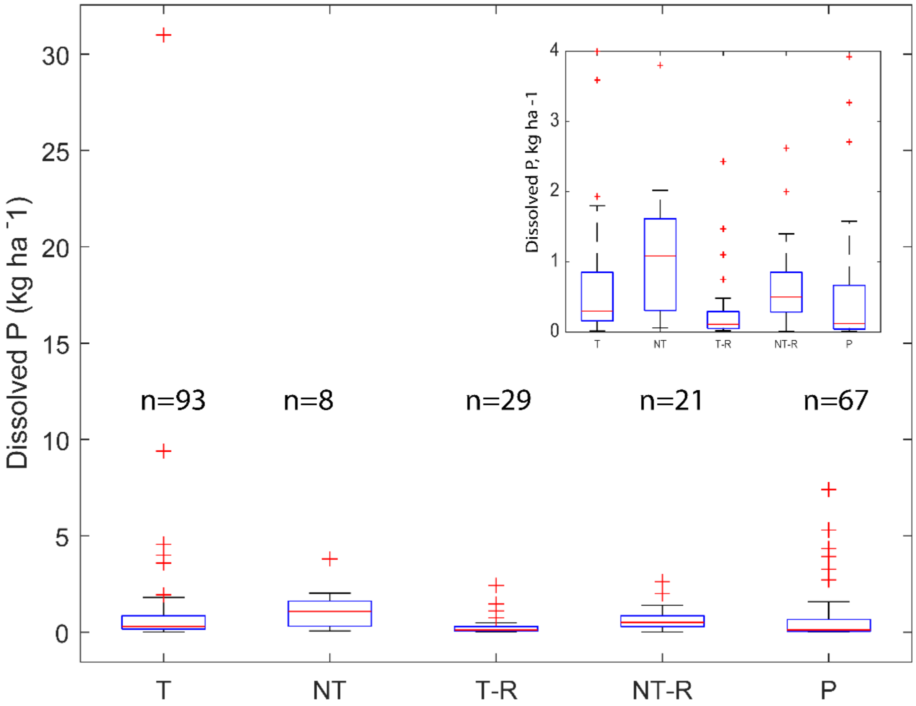

Figure 9. Annual dissolved phosphorus losses for different tillage and residue management practice categories (T = tillage with <30% surface residue, NT = no-tillage with <30% surface residue, T-R = tilled with >30% surface residue, NT-R = no-tillage with >30% surface residue, and P = pasture, n indicates number of data values involved in each box-plot)

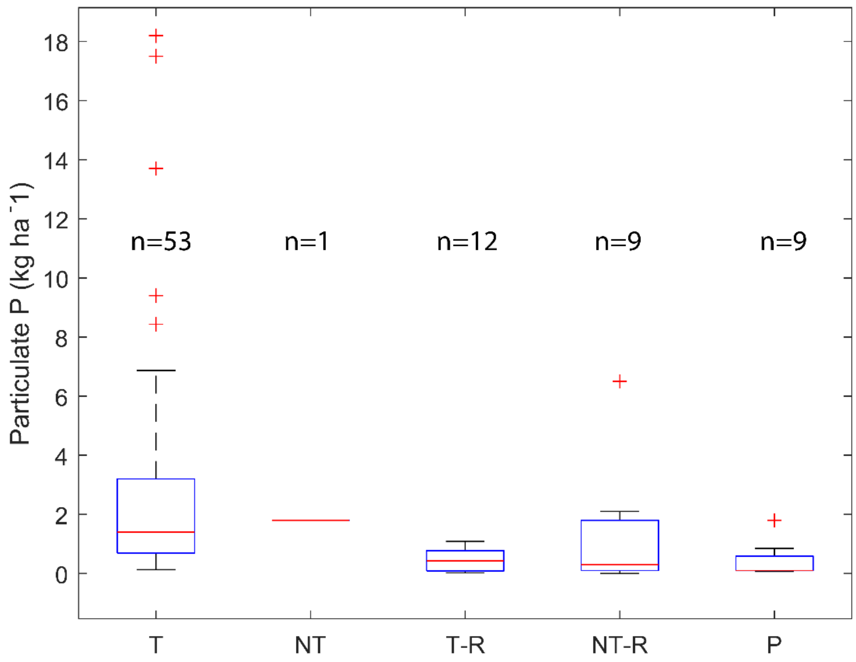

Figure 10. Annual particulate phosphorus losses for different tillage and residue management practice categories (T = tillage with <30% surface residue, NT = no-tillage with <30% surface residue, T-R = tilled with >30% surface residue, NT-R = no-tillage with >30% surface residue, and P = pasture, n indicates number of data values involved in each box-plot)

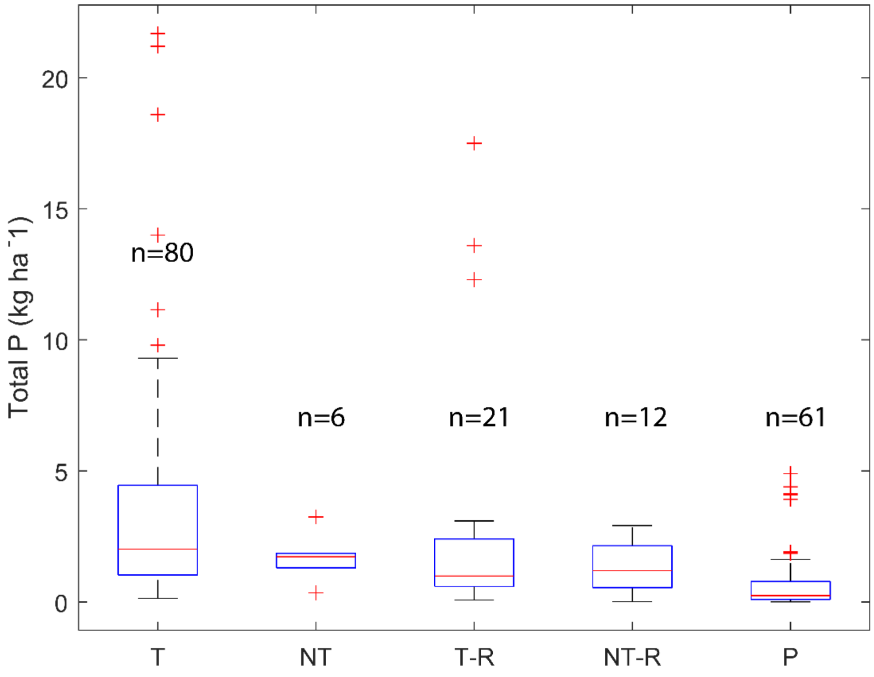

Figure 11. Annual total phosphorus losses for different tillage and residue management practice categories (T = tillage with <30% surface residue, NT = no-tillage with <30% surface residue, T-R = tilled with >30% surface residue, NT-R = no-tillage with >30% surface residue, and P = pasture, n indicates number of data values involved in each box-plot)

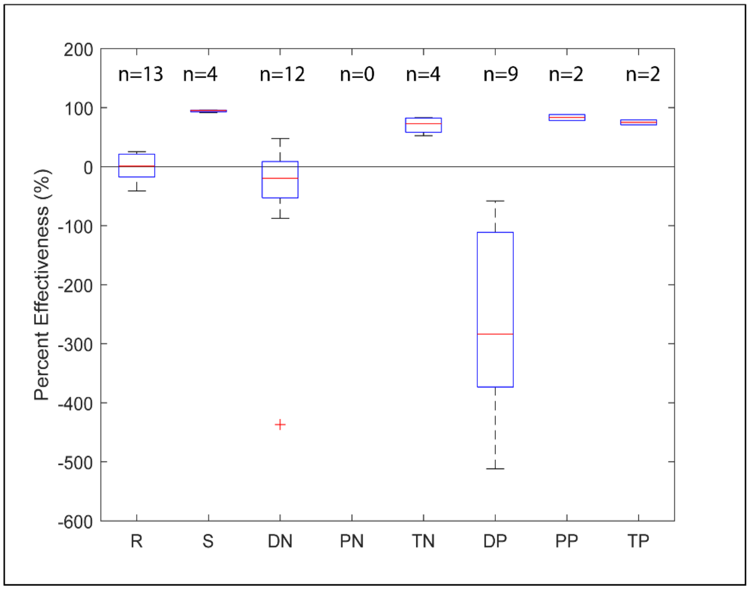

Figure 12. Practice Effectiveness of no-tillage management with respect to tillage for Runoff (R), Sediments (S), Dissolved N (DN), Particulate N (PN), Total N (TN), Dissolved P (DP), Particulate P (PP), and total P (TP). Solid black line represents 0% effectiveness; "n" indicates the number for comparisons represented by the box plot or confidence interval for a given constituent

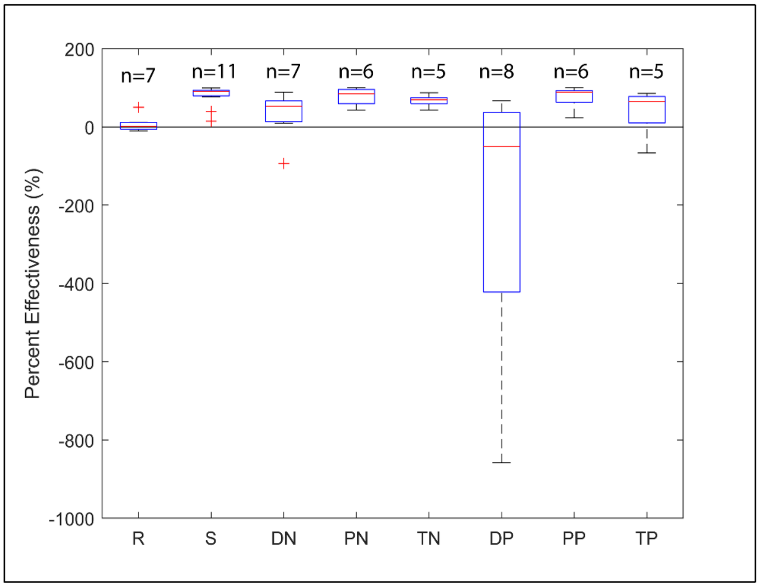

Figure 13: Practice effectiveness of no-tillage-residue management with respect to tillage for Runoff (R), Sediments (S), Dissolved N (DN), Particulate N (PN), Total N (TN), Dissolved P (DP), Particulate P (PP), and total P (TP). Solid black line represents 0% effectiveness; "n" indicates the number for comparisons represented by the box plot or confidence interval for a given constituent

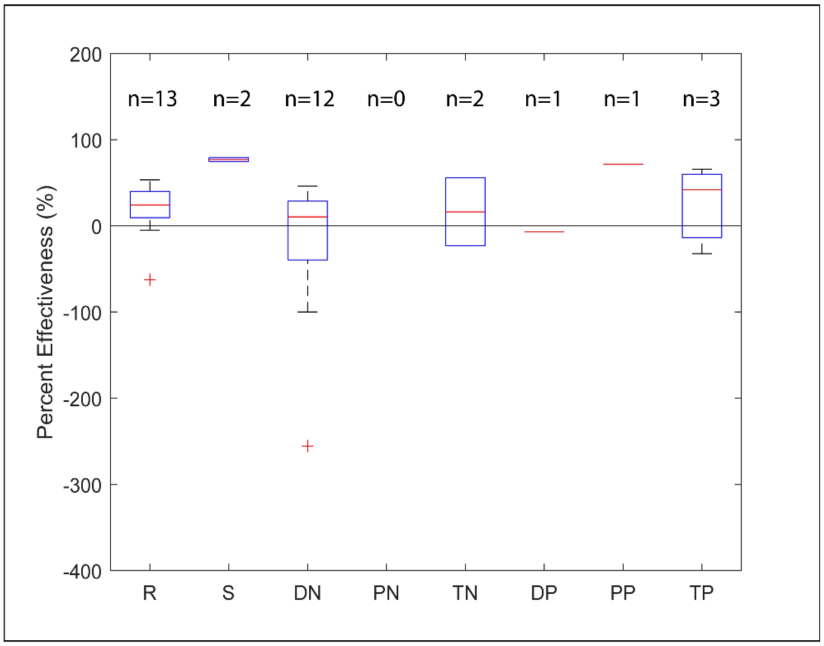

Figure 14: Practice effectiveness of tillage-residue management with respect to tillage (no residue) Runoff (R), Sediments (S), Dissolved N (DN), Particulate N (PN), Total N (TN), Dissolved P (DP), Particulate P (PP), and total P (TP). Solid black line represents 0% effectiveness; "n" indicates the number for comparisons represented by the box plot or confidence interval for a given constituent

Chapter 3

Effects of tillage and manure application on Freeze-Thaw cycles and their correlation to surface water quality parameters

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Abstract

In cold agricultural regions, tillage and winter manure management practices play an important role in influencing runoff and nutrient losses by affecting wintertime soil processes and properties. Soil freezing and thawing are unavoidable phenomena in cold regions and are known to influence wintertime runoff and nutrient losses. In this study, the effects of tillage and winter manure management on soil temperature, freeze-thaw (FT) cycles, and furthermore, the relationships between FT-cycles and wintertime runoff, nitrogen (NH_4^+, and TKN) and phosphorus (DRP and TKP) losses were studied. Two tillage [fall chisel tillage (CT) and no-tillage (NT)] and two manure type (control and liquid manure) treatments were field-tested in south-central Wisconsin during the winters (Nov-Apr) of 2016-17 and 2018-19 with a complete factorial design. From experimental plots, soil temperature at 8 cm depth, seasonal runoff, nitrogen, and phosphorus losses were monitored. FT-cycles were calculated utilizing soil temperature data and an R-programming package “FTC-Quant” developed by Boswell et al., (2020). In both years, CT soils were 1^{o}C warmer than NT due to the insulation affect of enhanced snow cover trapped in the depressions. In 2016-17, CT treatments (control and liquid manure) had a higher number of FT-cycles than NT, while in 2018-19, NT had higher number of FT-cycles CT. Liquid manure application did not affect the soil temperature and FT-cycles. Across the study years, FT-cycles had the strongest positive correlation to runoff depth (r = 0.72) and then to nitrogen losses (r = 0.44 to 0.47). The results from this study suggest that tillage can influence the wintertime soil temperatures and seasonal FT-cycles. FT-cycles constitute a positive relationship and can be helpful to improve the understanding of wintertime runoff and nutrient losses. Furthermore, FT-cycles could be used as one of the parameters in modeling wintertime runoff and nutrient losses.

Keywords: Freezing, thawing, freeze-thaw cycle, tillage, and manure

1. Introduction

In cold agricultural regions, the winter months are critical for water quality protection with most nutrient losses occurring during the spring thaw period (Gray and Landine, 1988; Plach et al., 2019; Liu et al., 2019). According to Koppen-Geiger's climate classification, average winter temperatures in cold climates fall below -3°C in the coldest months (Peel et al., 2007), causing the soil-water to freeze and minimizing microbial activity. Cold regions receive precipitation in the form of snowfall during winter months, which interacts with the landscape and affects nutrient loss processes differently than rainfall. Depending upon the weather, landscapes also undergo intermittent freezing and thawing during winter months. These conditions (no crop growth, frozen landscapes, freeze-thaw cycles, and snowfall) differentiate cold regions from warmer climates and complicate understanding and management of agricultural systems for water quality protection.

Soil freezing and thawing are natural and unavoidable phenomena in cold regions (Wei et al., 2018) that are known to influence hydrology and nutrient cycling by affecting soil properties (Bayard et al., 2005). Specifically, freeze-thaw (FT) cycles affect soil physical properties such as bulk density, hydraulic conductivity, soil aggregate stability, etc. (Müller-Lupp et al., 2003, Boswell et al., 2020). The FT-cycle effects also change with many factors, such as soil moisture content before freezing, number of FT- cycles, and freezing and thawing temperature. However, monitoring and evaluating FT-cycle effects on runoff and its associated nutrient losses are challenging because their effects on soil properties are complicated to quantify (Wei et al., 2018). For instance, Wei et al., 2018 found that the impact of FT cycles on runoff and soil loss increased with the number of FT cycles. While other studies have reported that soil water content before freezing affects soil infiltration and runoff more than the number of FT-cycles (Zhao and Gray, 1997; Roy et al., 2020).

In cold agricultural regions, management practices also affect runoff and nutrient losses (Liu et al., 2019). Many field studies have quantified management effects on wintertime runoff and nutrient losses while understanding some of the underlying hydrological and nutrient processes (Plach et al., 2019; Good et al., 2019; Hoffman et al., 2019; Stock et al., 2019a; Vadas et al., 2019). Studies focused on tillage found that mechanically disturbed soil surfaces significantly reduce snowmelt and rain-on-snow runoff because of greater surface roughness and increased time for infiltration (Young and Mutchler 1976; Hansen et al., 2000; Iwata et al., 2010; Starkloff et al., 2017). In contrast, during winter periods, no-tillage management was found to produce higher runoff volumes and nutrient losses than tillage systems (Zopp et al., 2019; Vadas et al., 2019). In cold region dairy agroecosystems (Midwestern states of the US), winter manure applications especially applied on top of snowpack also affect runoff and nutrient losses by accelerating snowmelt rates (Singh et al., 2017; Stock et al., 2019a).

Research conducted to understand and quantify wintertime runoff and nutrient loss processes from cold agricultural regions is mainly focused on management effects with some laboratory experiments focused on FT-cycles. Studies are lacking that have examined the combined effects of FT-cycles and management (e.g., tillage and manure application) on wintertime runoff and nutrient losses. Also, studies are lacking that investigated management effects on FT-cycles. This study aims to compare characteristics of FT-cycles between different management practices and identify their relationship to surface water quality parameters. Specific objectives are to i) calculate and compare the number of freeze-thaw cycles in fields managed with tillage and winter manure applications, and ii) identify the correlation between FT-cycles to runoff, nitrogen, and phosphorus losses.

2. Materials and Methods

2.1 Experimental site and Treatments

A field study was conducted in south-central Wisconsin at the University of Wisconsin-Arlington Agricultural Research Station (AARS; 43˚17' N 89˚21' W). The study site was under alfalfa (2011-14) before transitioning into the experimental research site. Since the conversion (2015 onwards), the site has been under corn silage production with all field operations performed along the contour. The site consists of 18 plots (5 x 15 m each) with a 5.8% slope and a south-facing aspect on silt-loam soil (Saybrook-Ringwood-Griswald series association). During 2015-17, the plots were used to investigate the effects of tillage (chisel vs. no-tillage) and winter liquid manure application timing (early December vs. late January application) on surface runoff and associated nutrient losses (Stock et al., 2019). During 2017-19, the same plots were used to investigate the effects of tillage (chisel vs. no-tillage) and winter manure type (liquid manure vs solid manure) on surface runoff and associated nutrient losses (Chapter 1). For this study, data collected during the 2016-17 and 2018-19 winter seasons (Nov-Apr) from fall chisel tillage (CT)-control, CT-liquid manure, no-tillage (NT)-control and NT-liquid manure treatments were analyzed. In 2015-16 & 2017-18 field seasons, there were some time periods when instrumentation problems prevented soil temperature from being continuously recorded. Since missing soil temperatures can result in underestimating the number of FT cycles, 2015-16 and 2017-18 were excluded from this study.

Each year, CT plots were tilled using a chisel plow to create a rough surface (elevations and depressions), and no-tillage plots were not disturbed. Manual manure applications were performed in January and the date of application in both experimental years was chosen based on when the following conditions were met: i) snowpack depth on the plots was between 12-15 cm, and ii) no snowmelt or rain-on-snow runoff event was expected within five days following manure application. The liquid manure was applied at 37.4 kL ha^{-1}, and no-manure was applied in control treatment plots. Liquid manure was collected from the storage lagoon of a dairy cow (Bos taurus) milking operation for both years.

2.2 Field measurements and analysis

The field site was equipped with an onsite weather station to measure air temperature and precipitation (snow water equivalent and rainfall). Hourly soil temperature data were collected from each plot at 8cm depth by installing k-type thermocouples. Each plot was also equipped with a storm-integrated, discharge-weighted runoff collection system (Pinson et al., 2004; Bonilla et al., 2006) to facilitate capture of up to 760 mm of runoff per event. The runoff volumes were measured, and runoff samples were collected at the end of each event. Half of each collected sample was filtered (0.45µ filters) and analyzed for dissolved reactive P (DRP) calorimetrically (Murphy and Riley, 1962) on a spectrophotometer, and ammonium (NH_4^+) on a Lachat automated analyzer (Hach Company) using Quick Chem Methods 12-107-06-2-A. The unfiltered samples were analyzed for and total Kjeldahl nitrogen (TKN) and phosphorus (TKP) calorimetrically using an AQ2 Discrete Analyzer (SEAL Analytical Brand, Mequon, WI; Seal, 2017).

2.3 Characterizing FT-cycles

Many studies define a FT-cycle based on a threshold of 0°C (Pakkala et al., 2013; Parkin et al., 2013; Sadeghi et al., 2018). However, depending upon soil water content and its characteristics it is unlikely that soil freezes and thaws at 0^oC. In this study, freezing point temperatures were identified using the methodology outlined by Wan et al., (2021) to define a FT cycle. The method developed by Wan et al., (2021) uses a mathematical model for determining the ice crystallization point in soils based on heterogeneous ice nucleation theory combined with the freezing point of soil water with different salt concentrations. Two freezing point temperatures identified by Wan et al. (2021) and corresponding to salt-free soils (Tf_1 = -0.4^{o}C) and soils with 1% salt content (Tf_2 = -4.0^{o}C), were used to define the freezing phase of soil.

In our experimental plots, each time soil was found unfrozen at 8cm depth, soil temperatures at that depth were analyzed to identify the range of soil temperature where soil started thawing. In both the years of study, the soil was found frozen below 0.5^{o}C and was unfrozen above 0.5^{o}C. Similar to the freezing point, the thawing point of soil also depends on various physical, chemical and thermal characteristics of soil water. However, based upon our soil frost measurements and soil temperature analysis, we assumed soil thaws at and above 0.5^{o}C, and used the criterion to define the thawing phase of soil.

The duration of the freezing and thawing phase is required to define a FT-cycle, along with freezing and thawing temperatures. Duration specifies the minimum time soil has to be below or above the freezing and thawing temperatures, respectively, to be considered in a freezing and thawing phase. A consecutive freeze-thaw phase of soil is counted as one FT-cycle (Figure 1; Boswell et al., 2020). In this study, FT-cycles were calculated for the 12 different criteria presented in Table 1. For example, in criteria 1, soil temperature must be $\leq$ -0.4^{o}C for at least 1hr to be considered in a frozen phase. Similarly, soil temperature must be $\geq$0.5 ^{o}C for at least 1 hr to be considered in a non-frozen/thawed phase. A successive freeze-thaw phase meeting this criterion is counted as one FT-cycle. The total number of FT-cycles that occurred in each treatment at 8 cm was calculated using the R-programming package FTC-quant developed by Boswell et al. (2020). Hourly soil temperatures at 8cm depth and FT-cycle criteria are supplied as inputs to FTC-quant.

2.4 Statistical analysis

Surface runoff, nitrogen (NH_4^+ and TKN) and phosphorus (DRP and TKP) losses of individual runoff events were summed to obtain seasonal losses (Nov-Apr). Detailed information related to the statistical analysis of seasonal runoff and nutrient losses are presented in chapter 1. Basic descriptive statistics were calculated to analyze differences in soil temperature among the treatments. Monthly mean soil temperatures and FT-cycles calculated in each treatment at 8cm depth were statistically analyzed using linear and mixed-effects models in R software (R Core Team-2020). For facilitating the statistical analysis, two adjacent treatment pairs were treated as a block (Figure S1). Each block consisted of a pair of CT and NT plots which were randomly assigned with liquid manure treatment. Tillage, liquid manure and their interactions were treated as fixed effects. Block and block x tillage were treated as random effects. Logarithmic data transformations were performed on data not normally distributed. Residual plots of modeled data were developed to demonstrate the randomly distributed error and homogeneous variances. Fixed effects of tillage, manure type (liquid manure and control), and tillage x manure type were assessed separately by the differences of estimated marginal means using Kenward-Roger degrees of freedom at 95% significance level ($\alpha = 0.05$). Additionally, pairwise comparisons were made between tillage, liquid manure and tillage x liquid manure treatment pairs at 95% significance level ($\alpha = 0.05$). A direct correlation analysis was performed to explore the relationship between FT-cycles and runoff and associated nutrient losses (NH_4^+, TKN, DRP and TKP).

3. Results and discussion

3.1 Weather

Table 2 presents the monthly mean temperature and total precipitation for Arlington, WI (NOAA, U.S. Department of Commerce). The normal (1991-2020 average) precipitation and temperature from November to April are 347 mm and 1.1°C, respectively. Therefore, the experimental seasons (2016-17 and 2018-19) were colder than normal for the monitoring period (Nov-Apr). In 2016-17, Nov, Feb, and Apr were up to 2°C warmer than normal. While Dec and Mar were 5°C and 2°C colder than normal, respectively. In 2018-19, the entire monitoring period was upto 6°C colder than normal. Wintertime (Nov-Apr) normal precipitation for Arlington, WI is 347 mm, and therefore, precipitation was above normal in 2016-17 (384 mm) and below normal in 2018-19 (309 mm).

3.2 Monthly and seasonal soil temperature

Soil temperature-time trends were similar at 8cm depth during the two seasons studied (Figures 2 and 3). In 2016-17, the lowest soil temperatures for all the depths monitored were observed in Jan (Figure 2), while, in 2018-19, Feb had the lowest soil temperatures (Figure 3). In both years studied, the highest soil temperatures were in Apr (Figure 3). The coldest soil temperature months did not correspond to the months with the coldest air temperatures (Figure 4). In 2016-17, Dec had the lowest mean monthly air temperature (avg = -6.1°C), while Jan had the lowest mean monthly soil temperature at 8cm depth. Similarly, in 2018-19, Jan had the lowest air temperatures (avg = -9.2°C), while soil temperature was lowest in Feb. This might be due to the insulation effect of snow. In both years, during the coldest months, the soil was covered with >6cm of snow for about 18 to 22 days. This snow cover reduced heat loss from the soil, thereby not allowing the soil temperatures to drop. Similar snow insulation effects have been observed in other wintertime field studies (Fu et al., 2017, Apples et al., 2020).

Treatments (tillage, liquid manure, tillage × liquid manure) did not significantly affect the mean seasonal soil temperature except for tillage in 2016-17 (Tables 3). Across all treatments, the mean seasonal (Nov-Apr) soil temperature differed less than ±1.0^{o}C (Tables 4 and 5). However, in 2016-17, seasonal minimum and maximum temperatures were recorded in CT treatments, while in 2018-19, seasonal minimum and maximum temperatures were observed in NT treatments. In both years, CT soils were up to 1^{o}C warmer than NT soils. Within the CT, CT-liquid manure soils were warmer than CT-control. In comparison, differences between NT-liquid manure and control treatments were less than 0.5^{o}C in 2016-17 and no differences were observed in 2018-19. While not statistically significant, these temperature differences can affect the number of FT cycles counted. The warmer temperatures in CT soils could be attributed to insulation effect of snow cover trapped in the depressions of CT plots than NT. In both years, CT soils had up to 14% higher seasonal (Nov-Apr) snow cover than NT. The warmer temperatures in CT-liquid manure could be attributed to greater infiltration in CT-liquid than CT-control. Though we did not measure the seasonal infiltration depth, runoff in CT-liquid was less than CT-control, pointing to greater infiltration in CT-liquid than CT-control. A water and energy balance study (Stock et al., 2018) conducted on the experimental plots during 2015-17 estimated 28% higher seasonal (Nov-Apr) infiltration in CT-liquid than CT-control. Higher infiltration increases the soil-water content, eventually increasing the soils enthalpy and needing more energy to be lost than drier soils to decrease its temperature (Taylor and Steward 1960). Another possible reason for warmer temperatures in CT-liquid was that the average seasonal snow cover on CT-liquid plots was 5% to 30% higher than in CT-control plots. Stock et al. (2018) also found that liquid manure applied on snowpack resulted in greater radiative energy absorbed by snowpack and affected the snowmelt rates. In both years studied, the liquid manure effect on snowmelt was observed. However, the radiative energy absorbed by the snowpack was not sufficient to affect the soil temperature and resulted in no differences in soil temperature among manured and control treatments. Overall, despite the non-significant effect of treatments on soil temperature, treatments that can hold snow cover or reduce its wind redistribution can keep the soils warmer by insulating them from atmospheric heat loss. For example, mechanically disturbed soil surfaces like CT can hold the snow in depressions, and the ridges can help reduce wind drift (Stock et al., 2018). Snowmelt and rainfall infiltration may increase the enthalpy of soil and may decrease the rate of soil freezing. However, the underlying mechanisms and quantification of the heat transfer within the atmosphere-snow-soil system require further study (Fu et al., 2017).

3.3 FT-cycles

The total number of FT-cycles within a season decreased numerically by 2 to 29 as the minimum freeze-thaw duration increased (up to 6hr) and as the T_f decreased (Figures 5). Increasing the freeze-thaw duration beyond 6hr and decreasing T_f below -4.0^oC did not change the number of seasonal FT-cycles. Across all treatments, T_f and minimum freeze-thaw duration did not significantly affect the number of FT-cycles. However, the highest number of FT-cycles were observed for criteria 1 (T_f = -0.4^{o}C, T_h = 0.5^{o}C, and minimum duration =1hr) and least number of FT-cycles were observed for criteria 12 (T_f = -4.0^{o}C, T_h = 0.5^{o}C, and minimum duration =6hr). Soil and ecological processes may be differentially affected by FT-cycle characteristics, depending upon the environmental conditions. In a modeling study, Boswell et al. (2020) found that the number of FT-cycles characterized using the criteria of T_f = -0.4^{o}C, T_h= 0.3^{o}C, and minimum duration of 2.5hr had a stronger relationship ($R^2 = 0.50$) to wet-aggregate stability than FT-cycles calculated using other criteria. Similarly, criteria of $T_f = 0^oC$, $T_h = 0.3^oC$, and duration of 0.5hr had the strongest relationship ($R^2 = 0.46$) to soil N_2O emissions. In seasonally frozen soils, snowmelt or rain on snow runoff events can last from a few minutes to days depending upon the snowfall amount and melting rates. Multiple FT-cycles during runoff events change the soil structure and hydraulic properties affecting the runoff and nutrient losses (Leuther and Schluter 2021). The number of FT-cycles depends on the criteria selected, therefore it is important to understand the criteria before investigating differences in FT-cycles between managements and their effect on soil processes or ecological variables.

Treatments (tillage, manure type, and tillage x liquid manure) did not significantly affect the number of seasonal FT-cycles, except for tillage in 2018-19 (Tables 6 and 7), and the differences were also not consistent over the two years studied. In 2016-17, CT had 6 to 9 more FT-cycles than NT. While in 2018-19, NT had 6 to 38 more FT-cycles than CT. The enhanced snow cover in CT kept soil temperatures warmer than NT in both years of study, however, it did result in reduced seasonal FT-cycles in CT during 2016-17. This signifies environmental conditions other than snow cover insulation also affects the seasonal FT-cycles. In 2016-17, CT plots (30.9 mm) had higher seasonal runoff than NT (43.5). However, the difference was not significantly different (p=0.20). While in 2018-19, due to increased infiltration, CT (31.1 mm) plots had significantly (p =0.03) less runoff than NT (95.7 mm). As discussed earlier, snowmelt and rainfall infiltration may increase the enthalpy of soil, decrease the rate of soil freezing and increase the soil temperature, eventually reducing the number of seasonal FT-cycles. Similar to soil temperature, liquid manure applications did not differ in seasonal FT-cycles compared to control/unmanured treatments. In both years of study, liquid manure applications rate (37.6 Mg ha^{-1}) was 49% less than the maximum allowed for frozen or snow-covered soils in Wisconsin

(Wisconsin Nutrient Management 590 Standard). While Stock et al., (2019b) observed increased radiative energy absorbed by snow with similar application rate as in this study, further investigations are required to understand the liquid manure application effects on seasonal FT-cycles when applied greater than the application rate in this study.

Overall, tillage and manure management can affect soil structure development and hydrology (Singh et al., 2017), and naturally occurring FT-cycles can also impact the soil properties (Leuther and Schluter 2021). The number of FT-cycles among different tillage and manure type combinations were not consistent across the two study years, but tillage affected the FT-cycles for two reasons, i) The depressions developed on soil surface due to CT management trapped more snow than NT. The insulation effect of snow reduced the number of FT- cycles in CT for one of the study years but it needs more detailed investigation. ii) CT management increased the snowmelt infiltration than NT. The increased infiltration may increase the enthalpy of soil system and reduce the freezing rate. However, this phenomenon was observed only in one season and needs further studies to understand the mechanisms and quantification of the heat transfer within the atmosphere-snow-soil system.

3.4 FT-cycles relationship to seasonal runoff depth and associated nutrient loads

Statistical correlation between FT-cycles, runoff depth and nutrient loads differed depending on the FT-cycle criteria. FT-cycles calculated for criteria 1 (T_f = -0.4^{o}C and duration =1 hr) had the highest correlation to seasonal runoff depth and associated nutrient loads than FT-cycles calculated for all other criteria (Table 8). FT-cycles had the highest correlation to runoff (r=0.72) and the least co-relation to seasonal phosphorus loads [DRP (r=0.09) and TKP (r=0.08)]. This result indicates that an increase in the number of FT-cycles will likely increase seasonal runoff. In a laboratory study, Wei et al. (2018) observed that the impact of FT-cycles on runoff and soil loss increased after six FT-cycles at 10% soil moisture content. While at higher moisture contents (>10%), the impact of FT-cycles increased after only 2 to 3 FT-cycles. We did not measure soil physical properties (e.g., aggregate stability, infiltration rate) that may change due to FT-cycles and subsequently affect runoff and nutrient loss. However, other studies reported soils that underwent FT-cycles could cause runoff and nutrient losses to increase compared with the same soil that never underwent freezing and thawing (Edwards and Burney, 1987; Frame et al., 1992; Ferrick and Gatto, 2005). In general, these differences were attributed to FT cycles changing the surface soil structure, causing a decrease in macroaggregates (>0.25 mm), and resulting in decreased infiltration and increased runoff and soil loss (Oztas and Fayetorbay, 2003; Wei et al., 2018). With climate change, winter air temperatures are expected to increase over the next century and reduce the depth and duration of winter snow cover, likely causing colder soil temperatures and more frequent FT-cycles (Brown and DeGaetano, 2011). Therefore, characterizing FT-cycles following physical principles (ice nucleation theory) and studying their interactions with agricultural management practices will improve future modeling and predictions of wintertime runoff and nutrient losses.

4. Conclusion and Implications

The influence of tillage and winter manure management on soil temperature and seasonal freeze-thaw (FT) cycles were evaluated. Through correlation analysis, the relationships between FT cycles and seasonal (Nov-Apr) runoff depth, nitrogen (NH_4^+, and TKN), and phosphorus (DRP and TKP) losses were explored. FT- cycle criteria [freezing temperature (T_f), thawing temperature (T_h) and minimum freeze-thaw duration (D)] affected the number of seasonal FT-cycles. Across all treatments, FT-cycles decreased as T_f decreased and as D increased. However, decreasing $T_f <$ -4.0°C and increasing D>6hr did not change the number of FT-cycles. This finding may indicate a threshold limit for future studies that need to establish FT-cycle criteria. The approach presented to characterize FT-cycles could be used to subjectively categorize FT-cycles as “mild” (e.g. shorter duration and higher freezing temperature) and “extreme” (e.g. longer duration and lower freezing temperature) to understand what characteristics of FT-cycles have pronounced effects on soil processes or ecological variables. The rough soil surface of CT created depressional storage that trapped more snow and increased infiltration into the underlying frozen soil. Snow-cover insulates soil from heat losses and infiltration increases the enthalpy of soil-water system reducing the number of seasonal FT-cycles in CT than NT. However, increasing winter air temperature over the next 100 years and reducing depth and duration of winter snow cover (Brown and DeGaetano, 2011; Campbell et al., 2010) suggests the need for detailed investigation of the effects of tillage on soil FT-cycles. Across all the treatments, the number of FT-cycles had the strongest positive correlation to runoff (r = 0.72) and then to nitrogen losses (r = 0.44 to 0.47). This suggests FT-cycles could be used as one of the parameters in water quality models to predict wintertime runoff and nutrient losses.

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Tables and Figures

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Table 1: Criteria of Freeze-Thaw cycles to calculate the number of seasonal Freeze-Thaw cycles

Criteria	Freezing temperature (T_f), ^oC	Thawing temperature (T_h), ^oC	Duration (D), hr
1	-0.4	0.5	1
2	-0.4	0.5	2
3	-0.4	0.5	3
4	-0.4	0.5	4
5	-0.4	0.5	5
6	-0.4	0.5	6
7	-4.0	0.5	1
8	-4.0	0.5	2
9	-4.0	0.5	3
10	-4.0	0.5	4
11	-4.0	0.5	5
12	-4.0	0.5	6

Table 2: Mean monthly temperature and precipitation for Arlington, WI for the two study seasons and the 30-year historic record (i.e., Normal)

Month	2016-17		2018-19		1991-2020 (Normal)*	
	Temperature °C	Precipitation mm	Temperature °C	Precipitation mm	Temperature °C	Precipitation mm
Nov	6.3	41.1	-1.1	38.6	4.7	56.9
Dec	-6.1	33.0	-2.5	39.9	-1.4	47.8
Jan	-5.6	63.2	-9.2	53.6	-4.4	45.5
Feb	-1.2	41.4	-8.7	76.2	-2.7	42.9
Mar	0.0	71.9	-1.8	26.2	2.4	55.9
Apr	9.7	133.4	7.1	74.4	7.9	98.0
Seasonal average/total	0.5	384.0	-2.7	308.9	1.1	347.0

*Information collected from NOAA, U.S. Department of Commerce

Table 3: Analysis of variance p-values of tillage, manure type and tillage × manure type treatments on mean seasonal soil temperature at 8cm depth

Treatment effect	ANOVA P-value*	
	2016-17	2018-19
Tillage	0.01	0.54
Manure type	1.00	1.00
Tillage ×Manure type	1.00	1.00

*p<0.05-statistically significant; p>0.05- not significant

Table 4: Basic descriptive statistics of soil temperature at 8cm depth for the 2016-17 experimental season

Statistic	CC	CL	NC	NL
Mean (SE)	2.1 (0.13)	2.2 (0.13)	2.9 (0.16)	2.4 (0.14)
Range	33.6	32.2	31.4	28.2
Minimum (SE)	-11.5 (4.79)	-11.2 (1.62)	-9.5 (2.75)	-7.9 (1.31)
Maximum (SE)	22.1 (2.43)	21.1 (3.00)	21.9 (0.84)	20.3 (0.69)

CC-chisel tillage-control; CL-chisel tillage-liquid manure; NC- no-tillage control; NL-no-tillage liquid manure; SE- standard error

Table 5: Basic descriptive statistics of soil temperature at 8cm depth for the 2018-19 experimental season

Statistic	CC	CL	NC	NL
Mean (SE)	0.7 (0.45)	1.3 (0.60)	0.7 (0.45)	0.7 (0.45)
Range	25.5	20.5	40.4	36.9
Minimum (SE)	-9.8 (1.94)	-7.5 (2.74)	-13.1 (0.22)	-12.8 (0.10)
Maximum (SE)	15.7 (1.89)	13.0 (2.32)	27.3 (0.22)	24.1 (0.59)

CC-chisel tillage-control; CL-chisel tillage-liquid manure; NC- no-tillage control; NL-no-tillage liquid manure; SE- standard error

Table 6: Seasonal FT-cycles of tillage and manure type treatments during the 2016-17 monitoring season

	FT-cycle criterion	T_f = -0.4°C; T_h = 0.5°C					
	Duration	1hr	2hr	3hr	4hr	5hr	6hr
Tillage	Chisel tillage	19	17	16	15	13	12
	No-tillage	10	8	7	7	6	6
	ANOVA p-value	0.30	0.20	0.14	0.11	0.09	0.15
Manure type	Liquid manure	15	13	11	9	10	8
	Control	13	11	11	11	9	8
	ANOVA p-value	1.00	1.00	1.00	1.00	0.96	0.95
	FT-cycle criterion	T_f = -4.0°C; T_h = 0.5°C					
	Duration	1hr	2hr	3hr	4hr	5hr	6hr
Tillage	Chisel tillage	7	7	7	6	6	6
	No-tillage	4	4	3	3	2	2
	ANOVA p-value	0.21	0.21	0.21	0.19	0.03	0.06
Manure type	Liquid manure	6	6	6	5	4	4
	Control	4	4	4	4	3	3
	ANOVA p-value	0.44	0.44	0.44	0.46	0.87	0.54

T_f – freezing temperature; T_h- thawing temperature

Table 7: Seasonal FT-cycles of tillage and manure type treatments during the 2018-19 monitoring season

	FT-cycle criterion	$T_f = -0.4^{o}\mathrm{C}$; $T_h = 0.5^{o}\mathrm{C}$					
	Duration	1hr	2hr	3hr	4hr	5hr	6hr
Tillage	Chisel tillage	16	12	10	8	8	7
	No-tillage	54	49	42	38	33	29
	ANOVA p-value	0.01	0.01	0.01	0.01	0.01	0.01
Manure type	Liquid manure	27	21	18	16	15	14
	Control	32	28	25	20	18	15
	ANOVA p-value	1.00	1.00	1.00	1.00	1.00	1.00
	FT-cycle criterion	$T_f = -4.0^{o}\mathrm{C}$; $T_h = 0.5^{o}\mathrm{C}$					
	Duration	1hr	2hr	3hr	4hr	5hr	6hr
Tillage	Chisel tillage	3	2	2	2	2	2
	No-tillage	13	12	11	10	9	8
	ANOVA p-value	0.03	0.04	0.04	0.03	0.04	0.04
Manure type	Liquid manure	6	5	5	5	5	4
	Control	6	6	6	5	5	4
	ANOVA p-value	1.00	1.00	1.00	1.00	1.00	1.00

T_f – freezing temperature; T_h- thawing temperature

Table 8: Correlation of number of freeze-thaw-cycles to surface water quality parameters

	Runoff	DRP	TKP	NH_4^+	TKN
FT cycles (T_f = -0.4°C; Duration = 1hr; Depth = 8cm)	0.72	0.09	0.08	0.47	0.44
FT cycles (T_f = -4.0°C; Duration = 1hr; Depth = 8cm)	0.46	-0.10	-0.07	0.41	0.28

Note: DRP - dissolved reactive phosphorus; TKP – total Kjeldahl phosphorus; TKN – total kjeldahl nitrogen; TS- total solids; T_f – soil freezing temperature.

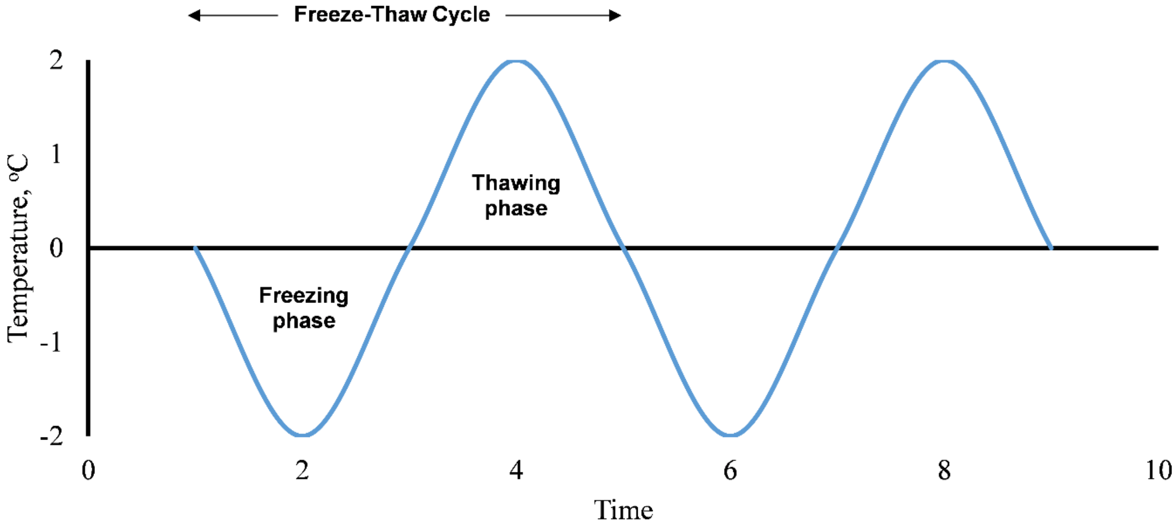

Figure 1: A general definition of the freeze-thaw cycle

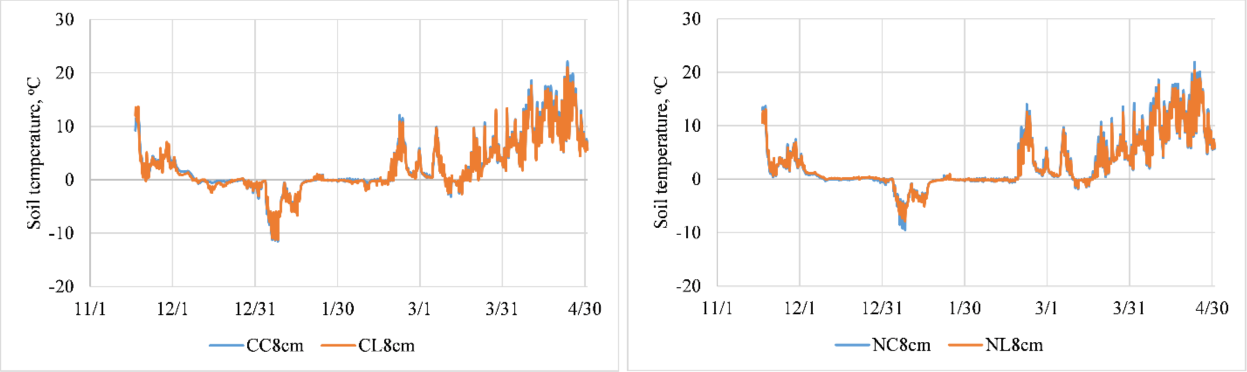

Figure 2: Soil temperature at 8 cm depth for the 2016-17 experimental season (CC-chisel tillage-control; CL-chisel tillage liquid manure; NC-no-tillage-control; NL- no-tillage-liquid manure)

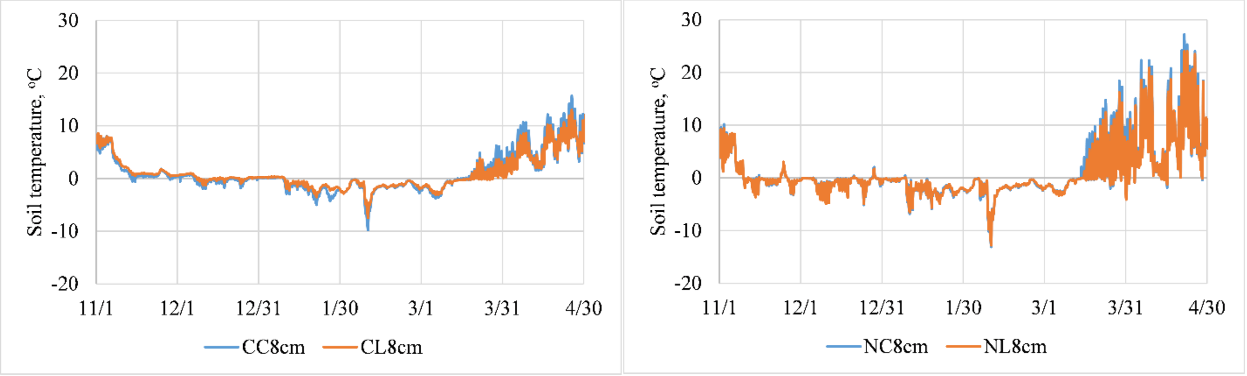

Figure 3: Soil temperature at 8 cm depths for the 2018-19 experimental season (CC-chisel tillage-control; CL-chisel tillage liquid manure; NC-no-tillage-control; NL- no-tillage-liquid manure)

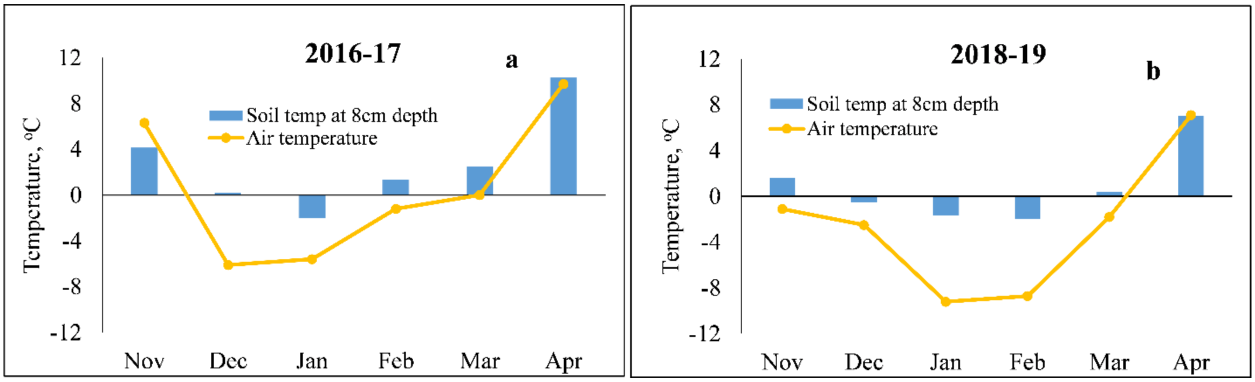

Figure 4: Mean monthly air temperature and soil temperatures at 8 cm depth for the monitoring seasons 2016-17 (a) and 2018-19 (b)

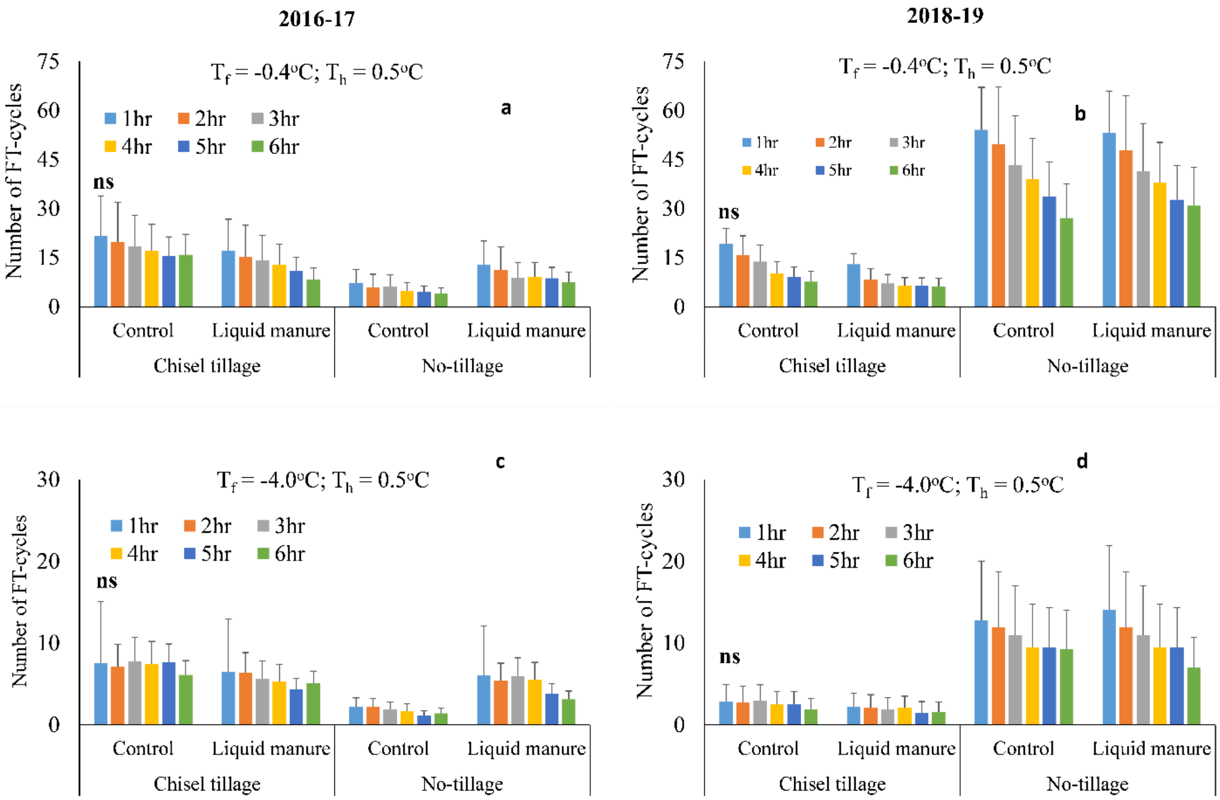

Figure 5: Freeze-thaw cycles calculated at 8cm depth for the 2016-17 (5a and 5c) and 2018-19 (5b and 5d) experimental seasons

ns- FT-cycles are not significantly different (α=0.05) within and across the treatments; T_f- freezing temperature; T_h- thawing temperature

Conclusion and Implications

This study evaluated tillage, residue, and winter manure application practices to better understand their impact on surface runoff and nutrient losses. Field experiments were conducted in south-central Wisconsin on soils with chisel tillage (fall chisel plow and spring finisher) and no-tillage receiving three manure types (liquid, solid, and un-manured controls) as a late winter application on snow-covered frozen soils. Chisel tillage resulted in the greatest reduction of nutrient loads by significantly reducing runoff volumes compared to no-tillage. Solid manure, irrespective of tillage or no-tillage, had higher nutrient losses than liquid manure. Chisel tillage with liquid manure application demonstrated the greatest reduction of runoff and nutrient losses compared to other tillage and manure type combinations studied.

It has been well-established and promoted that no-tillage reduces nutrient losses, especially on landscapes with >6% slope (Angle et al., 1984; Maetens et al., 2012). However, the field observations/results of this study challenge these previous findings and perceptions, specifically chisel tillage reduced runoff volumes through surface roughness and depressional storage of snowmelt and rain, thus providing additional time for infiltration. This result suggests that no-tillage might not be the solution in all situations, and depressional storage mechanism could also reduce runoff and nutrient losses during non-winter conditions. Therefore, published research on tillage and residue management across the US (21 states) and Canada (4 provinces) was analyzed (meta-analysis) to more broadly understand the tillage effects. The meta-analysis included 1,571 site-years of data categorized into tillage, no-tillage, tillage with residue cover (>30%), and no-tillage with residue cover (>30%). Nutrient stratification, poor drainage characteristics (in clay-rich soils), and surface sealing in no-tillage management (with and without residue cover) resulted in higher dissolved nitrogen and phosphorus losses than tillage management (with and without residue cover). Depending upon the soil antecedent moisture, precipitation intensity and duration, benefits of depressional storage observed in field experiments were valid for the large geographical area studied, especially tillage management (<30% cover) resulted in 41% less annual runoff than no-tillage management (<30% cover).

Field experiments and the meta-analysis combined highlight the long-term challenges of no-tillage, which resulted in greater wintertime and annual runoff and dissolved nutrient losses. Perhaps factors such as nutrient stratification and soil compaction are bigger drivers for runoff losses than previously anticipated across North America. Also, depressional storage created by tillage can reduce runoff, but higher precipitation intensities might erode and breach the ridges negating its benefits. Therefore, for regulating runoff and nutrient losses from agricultural landscapes, it is important to evaluate the seasonal tradeoffs of tillage and residue management for field management decisions throughout the growing and non-growing seasons. Specifically, in cold agricultural regions, surface and subsurface hydrology of frozen soils must be taken into account when considering appropriate tillage management. In continuous no-tillage systems, occasionally disturbing the soil needs to be considered and investigated to limit the effect of compaction and stratification and aid in achieving the targets of reducing the nutrient loads into water bodies from agricultural landscapes. A recent literature review (Blanco-Canqui and Wortman 2021) on occasional tillage indicated that disturbing the soil once in 5 to 10 years did not negate the other benefits (soil carbon, microbial population, and greenhouse gas fluxes) of no-tillage. However, occasional tillage reduced compaction, nutrient stratification and aided weed control.

The findings from the field experiments also highlight the importance of winter manure type (liquid vs solid) application on snow-covered frozen landscapes with different tillage management. Liquid manure applied on tilled surfaces can infiltrate into the soil depending on surface (depressions) and sub-surface storage capacities. Solid manure, irrespective of tillage or no-tillage, can be physically present on the surface for a longer period and release nutrients every time it interacts with runoff. Therefore, depending upon field conditions, manure type needs to be considered in winter manure applications, especially applications on frozen, snow-covered landscapes. Further, freeze-thaw cycles in cold regions were identified as a factor affecting runoff and nitrogen losses, with tillage management affecting freeze-thaw characteristics. Factors affecting freezing and thawing, linkages to runoff losses, and their potential to improve wintertime modeling efforts should be further studied. One of the limitations of the field experiments was that manure application rates were 49% less than the recommended maximum because of runoff concerns when applying liquid manure on no-tillage treatments. It is suggested that different application rates be assessed to identify optimal rates for different manure types and tillage surfaces. Also, it is recommended to investigate the effect of residue or cover crops on runoff losses from snow-covered frozen landscapes receiving winter manure applications.

Overall, tillage, residue, winter manure applications, and soil FT-dynamics will affect runoff, sediment and nutrient losses differently across different seasons (growing and non-growing) and regions [Temperate (cold) to Tropical (hot and humid)]. For water quality protection, multiple managements combined or management practices that can adapt to different seasons of a region need to be implemented. Tillage, residue, and other field management practices (cover crops, grassed waterways, and drainage) at large only affects water volume (runoff and percolation) and their transportation pathways and nutrient carrying capacities by affecting soil physicochemical properties. Managements that reduce runoff losses might risk percolation, nutrient stratification and volatile losses. Similarly, managements that reduce percolation losses might risk runoff losses. Therefore, an integrative biological systems approach that considers conservation of mass and energy needs to be investigated for the future of water quality.

Appendix A

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Appendix B

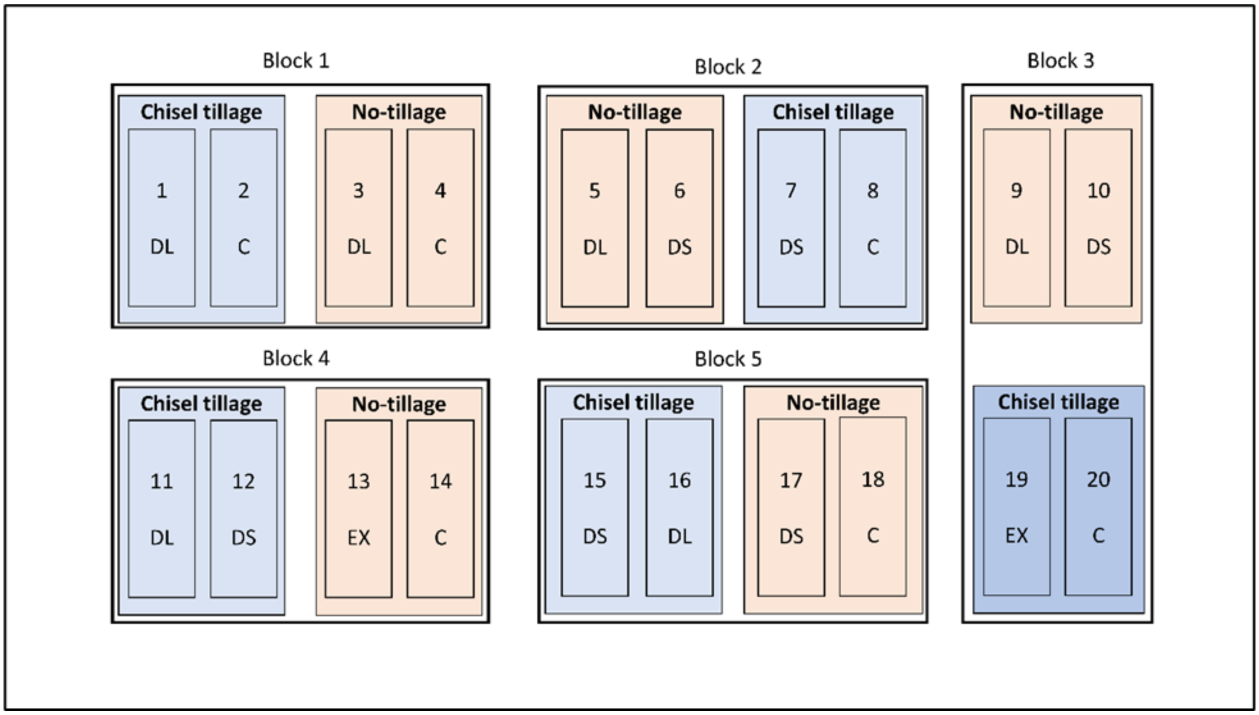

Figure S1: Field experimental layout at the University of Wisconsin- Arlington Agricultural Research Station (DL: Liquid manure plot; DS: Solid manure plot; C- Un-manured plot; EX: Extra plot not used for experiments; Individual plot size: 15 m x 4.5 m)

Figure S2: Arial view of field experimental setup at the University of Wisconsin- Arlington Agricultural Research Station during Sep 2019 (top) and after winter manure application during Jan 2019