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Fall Tillage Reduced Nutrient Loads from Liquid Manure Application during the Freezing Season

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Abstract

Reducing agricultural runoff is important year round, particularly on landscapes that receive wintertime applications of manure. No-tillage systems are typically associated with reduced runoff loads during the growing season, but surface roughness from fall tillage may aid infiltration on frozen soils by providing surface depressional storage. The timing of winter manure applications may also affect runoff, depending on snow and soil frost conditions. Therefore, the objective of this study was to evaluate runoff and nutrient loads during the freezing season from combinations of tillage and manure application timings. Six management treatments were tested in south-central Wisconsin during the winters of 2015–2016 and 2016–2017 with a complete factorial design: two tillage treatments (fall chisel plow vs. no-tillage) and three manure application timings (early December, late January, and unmanured). Nutrient loads from winter manure application were lower on chisel-plowed versus untilled soils during both monitoring years. Loads were also lower from manure applied to soils with less frost development. Wintertime manure applications pose a risk of surface nutrient losses, but fall tillage and timing applications to thawed soils can help reduce loads.

Core Ideas

- Fall tillage reduced winter runoff and manure nutrient losses compared with no-tillage.
- Nutrient loads were greatest on no-tillage soil with winter-applied liquid manure.
- Timing liquid manure application to unfrozen or partially thawed soil reduced loss.

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Balancing production with environmental sustainability is a critical challenge for manure management in animal production systems. Land application of manure is a longstanding practice for recycling farm nutrients back to cropland, but research has demonstrated that surface manure application to fields without incorporation can be a significant source of N and P losses in surface runoff (Daniel et al., 1998; Kleinman and Sharpley, 2003; Vadas et al., 2007). For many northern US states, as well as Canadian provinces and northern European countries, manure is applied year round and must be left unincorporated during winter because of the presence of frozen soils and snow. Winter application can help reduce manure storage expenses, provide more time for field operations in other seasons, and avoid soil compaction, but it can lead to elevated runoff risks from frozen soils, snowmelt, and rain-on-snow events (Srinivasan et al., 2006; Liu et al., 2017).

Over half of annual runoff can occur during the winter season in temperate regions with snow and frozen soils present (Stuntebeck et al., 2011; Good et al., 2012), and consequently there are regulations and recommendations restricting winter manure spreading to protect water quality (Srinivasan et al., 2006; Liu et al., 2018). Limited data exist, however, that quantify manure nutrient loads in runoff after winter application. Most research has been observational with little replication, has taken place prior to 1980, and has focused on solid manure (13.8–55.5% dry matter [DM]), which was most common at that time (Hensler et al., 1970; Converse et al., 1976; Klausner et al., 1976; Phillips et al., 1981; Steenhuis et al., 1981; Young and Mutchler, 1976; Young and Holt, 1977). Generally, nutrient loads in runoff were greater from manure applied early in the winter to frozen ground without snowpack, compared with late-winter applications on top of frozen ground with snowpack (Hensler et al.,

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Abbreviations: CT, fall tillage with a chisel plow and spring finisher; CT-C, fall tillage and unmanured control treatment; CT-D, fall tillage treatment with December manure application timing; CT-J, fall tillage treatment with January manure application timing; DM, dry matter; DRP, dissolved reactive phosphorus; NT, no-tillage; NT-C, no-tillage and unmanured control treatment; NT-D, no-tillage treatment with December manure application timing; NT-J, no-tillage with January manure application timing treatment; SWE, snow-water equivalent; TKP, total Kjeldahl phosphorus; TN, total nitrogen; TP, total phosphorus; TS, total solids; VS, volatile solids.

1970; Converse et al., 1976; Young and Mutchler, 1976). The mulching effect of solid-bedded manure explained this trend. When applied onto snow, solid manure reduced runoff by slowing melt and providing more time for snowmelt and manure nutrients to infiltrate into soil (Kongoli and Bland, 2002).

The plot-scale research of the 1970s focused on solid manure and may not directly relate to runoff from more liquid forms (<11% DM). Since the 1990s, the number of larger dairy farms increased by 70%, smaller farms (<500 heads) decreased by 49%, and 90% of farms with >200 heads now produce liquid manure (USDA-NASS, 2010). This manure is expected to interact differently with snowpack than solid manure. For example, liquid manure applied onto snow infiltrates and remains in the snowpack instead of maintaining a thick, insulative layer (Kongoli and Bland, 2002; Vadas et al., 2017, 2018) and may be prone to runoff because of its high water content. In a comparison of winter-applied liquid swine manure (4% DM) with turkey litter (57% DM), nutrient runoff loads were greater from the liquid manure, despite greater nutrient amounts applied with the litter (Owens et al., 2011). Liquid manure applications may pose greater risk to nutrient loss because the infiltrated manure liquid has greater physical contact with snowmelt water for nutrient release, as opposed to solid manure that remains on the snow in a discrete layer (Vadas et al., 2017). Other field research investigated liquid dairy manure applications at the basin scale (7–16 ha) and found that the greatest nutrient loads from liquid manure occurred when applied within 1 wk of a runoff event (Komiskey et al., 2011). However, runoff loads could not be attributed to specific practices because of multiple manure timings, application rates, manure types, and lack of replication. Research is still needed to understand the impact of specific management practices and runoff hydrology processes to reliably quantify the risk for nutrient loads from winter manure application.

The effect of tillage on winter runoff and nutrient loads is also unclear, particularly for frozen soils (Komiskey et al., 2011). During the growing season, no-tillage (NT) is generally considered to increase infiltration and maintain soil aggregate stability, thereby reducing nutrient transport via erosion and runoff (Zhang et al., 2007). However, as soils freeze and infiltration decreases, the smooth surface of NT may increase runoff (Ranaivoson et al., 2005). Nutrient accumulation near the soil surface from lack of tillage may increase dissolved nutrient loads compared with conventional tillage (Tiessen et al., 2010). Moreover, wintertime nutrient release from vegetation in NT, perennial forage systems can elevate losses (Liu et al., 2014). Young and Mutchler (1976) compared runoff for continuous corn (*Zea mays* L.) with fall tillage and harrowing versus NT alfalfa (*Medicago sativa* L.), both with winter-applied, solid dairy manure. Despite tilling parallel to the slope, significantly greater runoff occurred from alfalfa, with winter nutrient loads over five times greater on soils with NT. Depending on study year, 9 to 42 kg ha^{-1} more total N (TN) and 3 to 6 kg ha^{-1} more total P (TP) were lost from manure applied to frozen soils with NT versus tillage (nutrient release from alfalfa accounted for up to 0.5 kg P ha^{-1} of losses based on the unmanured controls). Similarly, Hansen et al. (2000) observed that springtime nutrient loads decreased with increasing surface roughness across three tillage systems (ridge-tillage, chisel plow with spring disking, and fall moldboard), despite tillage parallel to the slope.

Ultimately, the impact of management to reduce nutrient runoff from winter-applied liquid manure has been difficult to assess from literature data due to differences in study designs, wide-ranging weather within and between years, and a lack of data to analyze the hydrologic and manure property controls on nutrient loss (Klausner et al., 1976; Komiskey et al., 2011; Owens et al., 2011). Our main goal is to improve the understanding and modeling of biochemical and physical processes controlling frozen-soil and snowmelt infiltration, runoff, and nutrient loads from soil and winter-applied dairy manure through a series of laboratory and plot-scale experiments (Vadas et al., 2017, 2018). The objective of this study was to investigate winter surface runoff and nutrient loads for variations in tillage and timing of winter manure application that are common management practices in temperate states. Specifically, we tested tillage with a fall chisel plow versus NT, and manure applications timed (i) early in the freezing season (early December), (ii) later in the freezing season (late January), and (iii) with unmanured controls. Here, we report plot-scale observations on the effect of tillage and winter manure application timing on overall winter runoff amounts and nutrient loads across the freezing season. Vadas et al. (2019) describes runoff hydrology and nutrient concentrations on an event-by-event basis. We hypothesized that fall tillage will reduce runoff through surface roughness, and manure applications later in the freezing season will result in greater losses because of greater frost development and snow accumulation.

Materials and Methods

Site Description and Treatments

We conducted the study at the University of Wisconsin Arlington Agricultural Research Station (AARS; 43°17′ N, 89°21′ W) using 18 plots (5 × 15 m each) established on a 5.8% slope with south-facing aspect and a silt-loam texture (Saybrook [fine-silty, mixed, superactive, mesic Oxyaquic Argiudolls]–Ringwood [fine-loamy, mixed, superactive, mesic Typic Argiudolls]–Griswold [fine-loamy, mixed, superactive, mesic Typic Argiudolls] series association). For 4 yr prior to the study (2011–2014), the field was under NT alfalfa. During the study (2015–2017), the field was in continuous corn for silage with a 76-cm row spacing. All field operations were performed along the contour.

We evaluated two tillage and three manure timing treatments in a complete factorial design during two winters (2015–2016 and 2016–2017). Tillage treatments were tillage with a fall chisel and spring soil finisher (CT) and NT, to result in rough and smooth surfaces, respectively, during the winter. The soils were tilled on 2 Oct. 2015 and 5 Oct. 2016. In fall 2015, Bray-1 soil test P was 32 and 51 mg kg^{-1} for CT and NT, respectively, at a 0- to 2.5-cm depth. In fall 2016, Bray-1 soil test P was 31 and 39 mg kg^{-1} for CT and NT at a 0- to 2.5-cm depth. Timing of manure applications included early December at the typical onset of the soil freezing (D), late January (J), and an unmanured control (C). The manure application dates were 10 Dec. 2015, 26 Jan. 2016, 9 Dec. 2016, and 27 Jan. 2017. All treatment combinations were replicated in triplicate. The experimental design was a paired-plot design in which there were 10 pairs (Supplemental Fig. S1). Five of the pairs were assigned to NT, and five pairs were assigned to CT, arranged in a completely

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randomized design. Two of the three manure treatments were assigned within each pair, completely at random, but balanced between NT and CT treatments. There were two "empty" plots, assigned at random within the field area.

We manually applied liquid dairy manure at a rate of 37.4 kL ha^{-1}. Six to twelve samples collected during each application were analyzed by the University of Wisconsin Soil and Forage Analysis Laboratory (Marshfield, WI) (Table 1). Total N was measured by using methods of Peters et al. (2003, Section 3.2). After dry ashing, P and K concentrations were measured with colorimetric spectrophotometry (Peters et al., 2003, Section 5.2). Total solids (TS) and volatile solids (VS) were measured as percentages according to Standards Methods 2540 B and 2540 E (APHA, 1995).

Field Measurements

An onsite weather station was used to measure air temperature (VP-3, Decagon Devices) and precipitation as rainfall (RG3, Onset Computer Corporation) or liquid equivalent of snowfall (adaptor: CS705, Campbell Scientific). Soil frost depth was manually measured with one frost tube per plot (Rickard and Brown, 1972; Mackay, 1973), and snow depth with three snow sticks installed equidistantly along the slope of each plot. Snow-water equivalent (SWE, depth of water stored as snow in mm) was calculated by measuring snow density with a snow corer in each plot (US Army Corps of Engineers, 2015). Manual measurements of frost and snow were collected at least once per week, and up to daily during precipitation and thaw events.

Runoff volumes were monitored from each plot with a storm-integrated, discharge-weighted collection system (Bonilla et al., 2006; Vadas and Powell, 2013). Earthen berms hydrologically isolated each plot. Runoff was directed into a passive, divider collection system that consisted of three, sequential 19-L buckets for each plot. The first two buckets each had a steel crown with 24 precision-cut, V-slot weirs that directed 1/24th of the runoff water to the subsequent bucket, allowing a runoff event of up to 152 mm (11.4 kL) to be measured. After each runoff event, we measured the height of the water in the buckets with a meter stick to the nearest millimeter. To determine nutrient loads for each plot, we collected a water sample from each bucket as the water was agitated. The total runoff volume and nutrient loads for each plot were then calculated from the dilution ratio of the weirs. "Runoff ratios" (the proportion of runoff to the total water that interacted with manure through rain and snowmelt) were also calculated and are described in more detail by Vadas et al. (2019).

Runoff samples were stored at 4°C. Unfiltered samples were analyzed for TS and VS (APHA, 1995). Acid-preserved (2 mL L^{-1} H_2SO_4) samples were analyzed for total Kjeldahl N (USEPA, 1993) and total Kjeldahl P (TKP; SEAL Analytical, 2015) with an automated colorimetric analyzer after digestion (AQ2 Discrete Analyzer, SEAL Analytical Brand). Filtered samples (0.45 μm) were analyzed for dissolved reactive P (DRP; Murphy and Riley, 1962), NH_4–N with QuickChem Methods 12-107-06-2-A, and NO_3–N with QuickChem Methods 12-107-04-1-B on a Lachat automated analyzer. Total N was calculated as the sum of total Kjeldahl N and NO_3–N. Nutrient loads were calculated by multiplying the nutrient concentrations by the runoff volume for each plot.

Statistical Analysis

We tested total runoff volume and cumulative nutrient loads (kg ha^{-1}) across three monitoring periods each year by summing all events for each plot for each period. Periods included "pre-freezing," "frozen ground," and "post-freezing," which accounted for changes in hydrology from soil frost dynamics. Pre-freezing was from the start of monitoring on 24 November until the soil froze (we considered the soil to be frozen when 0.5 cm of soil frost persisted for at least 24 h). "Frozen ground" was when frost was present in all or part of the soil profile, and "post-freezing" was when the soil profile fully thawed until the end of monitoring on 30 April each year. Corresponding dates for all periods are in Table 2. Frozen ground and post-freezing periods of 2016–2017 were discontinuous because the soil thawed between 23 Feb. and 2 Mar. 2017 and refroze on 3 Mar. 2017. The number of runoff events for all periods is in Table 2.

We analyzed data with the GLIMMIX procedure of SAS software version 9.4 (SAS Institute, 2013). Slope position, pair, and pair × tillage were treated as random effects, and Akaike information criterion (AIC) was used to determine which random effects belonged in the model. Tillage, manure treatments, and their interactions were the only fixed effects. Data were modeled using the lognormal distribution, which resulted in residual plots that generally demonstrated randomly distributed errors and homogenous variances. Fixed effects of tillage, manure timing, and their interaction were assessed by differences of least squares means with the Bonferroni adjustment for multiple comparisons ($\alpha = 0.05$). The interaction of manure timing with tillage was evaluated by computing and testing simple effects of manure timings within each of the tillage treatments. All significance tests were conducted on lognormal data with the log transformation, and least squares means were all back-transformed prior to presentation in tables and figures. Standard errors of back-transformed means were computed according to the Taylor expansion (Stroup, 2013).

Table 1. The dates and nutrient additions for each manure application with the corresponding field conditions during the application dates.

Application date	Manure analysis†					Field conditions	
	TN	TP	TK	TS	VS	Frost depth	SWE‡
	kg ha^{-1}			%		cm	mm
10 Dec. 2015	65.9	8.7	68.2	2.0	1.3	0.0	0
26 Jan. 2016	80.6	11.3	56.3	2.9	2.0	0.0–50.1	24
9 Dec. 2016	102.9	17.8	53.1	5.8	4.4	0.0–10.4	10
27 Jan. 2017	99.2	14.4	57.5	5.5	4.1	6.2–43.9	31

† TN, total N; TP, total P; TK, total K; TS, total solids; VS, volatile solids. Values are from manure on each of the four application dates.

‡ SWE, snow-water equivalent.

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Results and Discussion

Hydrology

Weather and soil freezing conditions are drivers of runoff hydrology during the winter, and conditions of the two monitoring seasons caused significant differences in runoff hydrology. In 2015–2016, the soil froze on 30 December, 41 d later than the 10-yr average (University of Wisconsin, 2010), which resulted in the December manure application occurring during the pre-freezing period and the January application during the frozen ground period. Most precipitation fell as rain (Fig. 1a, Table 2) during the pre- and post-freezing periods (12 wk, 84% of precipitation) compared with the frozen ground period (11 wk, 16%). In December 2015, total precipitation was over two times greater than normal, whereas air temperature was 7°C greater and above freezing (1981–2010; NOAA, 2017). Weather during January 2016 was near normal, but February 2016 had about one-third less precipitation and greater air temperature than normal (see the supplemental table for more comparisons with normals). These conditions generated more frequent runoff events and statistically greater runoff volumes from NT soils (9 events, 39 mm) than CT (1 event, 1 mm) (Tables 2 and 3, Fig. 2). Runoff events from NT soils were fairly evenly distributed across unfrozen and frozen ground periods (four and five events, respectively), and the single event from CT soils was during the frozen ground period. The cumulative runoff volume from NT was 10 times greater than from CT, which was statistically significant (Table 3). Moreover, the seasonal average of runoff ratios calculated for each event (November 2015–March 2016) were eight times greater across NT than across CT, indicating that NT was consistently more prone to runoff across rain and snowmelt events. The depressional storage created by the fall chisel plow operation caused these runoff differences, which corroborates the findings of Young and Mutchler (1976) and Hansen et al. (2000) on tillage. Soils with CT had a network of ridges and furrows oriented along the contour, which provided areas for rainfall and snowmelt to pond, allowing more time for infiltration. From field observation, the smooth surface of NT soils was unable to slow runoff.

In 2016–2017, runoff was also more frequent and of greater magnitude from NT soils (10 events, 44 mm) than CT soils (6 events, 31 mm), but not as much as in 2015–2016 (Tables 2 and 4, Fig. 3). In fact, the 30% more runoff from NT soils was not statistically significant for tillage as a main effect (Table 4), and the runoff ratios of NT were only two times greater than CT in this second year. The greater runoff from CT in the second winter compared with the first winter is likely a function of contrasting soil freezing and weather conditions. Compared with 2015–2016, soil froze 23 d earlier in 2016–2017 (but still 18 d later than the 10-yr average; University of Wisconsin, 2010), there was 44% more precipitation across the entire winter, and the frozen ground period had nearly four times as much rain and snow (Fig. 1d–1f, Table 2). Therefore, the pre- and post-freezing periods (8.5 wk) were shorter, the frozen ground period (13.5 wk) was longer and included both the December and January manure applications, and precipitation was more evenly distributed across the frozen ground and nonfrozen periods (42 and 58%, respectively) (Fig. 1, Table 2), which increased runoff ratios across tillages. December 2016 to February 2017 had two to three times more monthly precipitation than normal, and air temperature was most notably greater than normal in February (NOAA, 2017). These conditions caused greater runoff on CT soils in this second winter season, as all six events were during the frozen ground period (Table 2). The weather conditions of 2016–2017, particularly greater amounts of rain and more frequent melt events, increased runoff by both compromising and overflowing some ridges that structured the surface depressional storage on CT soil.

Year-to-year weather introduced variability in the effectiveness of depressional storage, but surface roughness from tillage on the contour reduced overall runoff during both years. Tillage may be important during the freezing season when the risk of runoff is high in corn silage fields. These systems are particularly vulnerable because the bare soils—without residue or cover crops—are less able to slow the velocity of runoff (Starkloff et al., 2017) without surface roughness (Ramos et al., 2016). The surface hydraulic conductivity may also be lower in NT compared with freshly tilled soils that have a lower bulk density (Ranaivoson et al., 2005; Lampurlanés and Cantero-Martínez, 2006). This difference may reduce the infiltration potential of NT during field-saturated conditions that are common from fall rain and spring melt in pre- and post-freezing seasons, respectively. The importance of ponding meltwater and rainfall may be emphasized for frozen soils, which have a reduced infiltration potential from pore ice (Iwata et al., 2010; Starkloff et al., 2017) and explain the lower runoff losses from Young and Mutchler's (1976) plowed fields.

Nutrient Loads

Differences in nutrient loads in runoff (g ha^{-1}) between CT and NT soils were a function of runoff hydrology and the

Table 2. Pre-freezing, frozen ground, and post-freezing periods during the 2015–2016 and 2016–2017 monitoring seasons according to soil frost dates. Precipitation for each period is given as rainfall and snowfall, with snowfall expressed in liquid equivalents (snow-water equivalent [SWE]). Corresponding runoff events are given for soils with no-tillage (NT) and fall tillage with a chisel plow (CT).

Year	Period	Days frozen	Precipitation		Runoff events	
			Rain	SWE	NT	CT
		d	mm		no.	
2015–2016	Pre-freezing (24 Nov.–29 Dec.)	74	132	7	2	0
	Frozen ground (30 Dec.–11 Mar.)		24	24	5	1
	Post-freezing (12 Mar.–30 Apr.)		105	17	2	0
2016–2017	Pre-freezing (24 Nov.–6 Dec.)	94†	75	12	1	0
	Frozen ground (7 Dec–22 Feb., 3–20 Mar.)		102	87	8	6
	Post-freezing (23 Feb–2 Mar., 21 Mar.–30 Apr.)		163	7	1	0

† The frozen ground and post-freezing periods of 2016–2017 are discontinuous because the soil thawed between 23 Feb. and 2 Mar. 2017 and refroze by 3 Mar. 2017.

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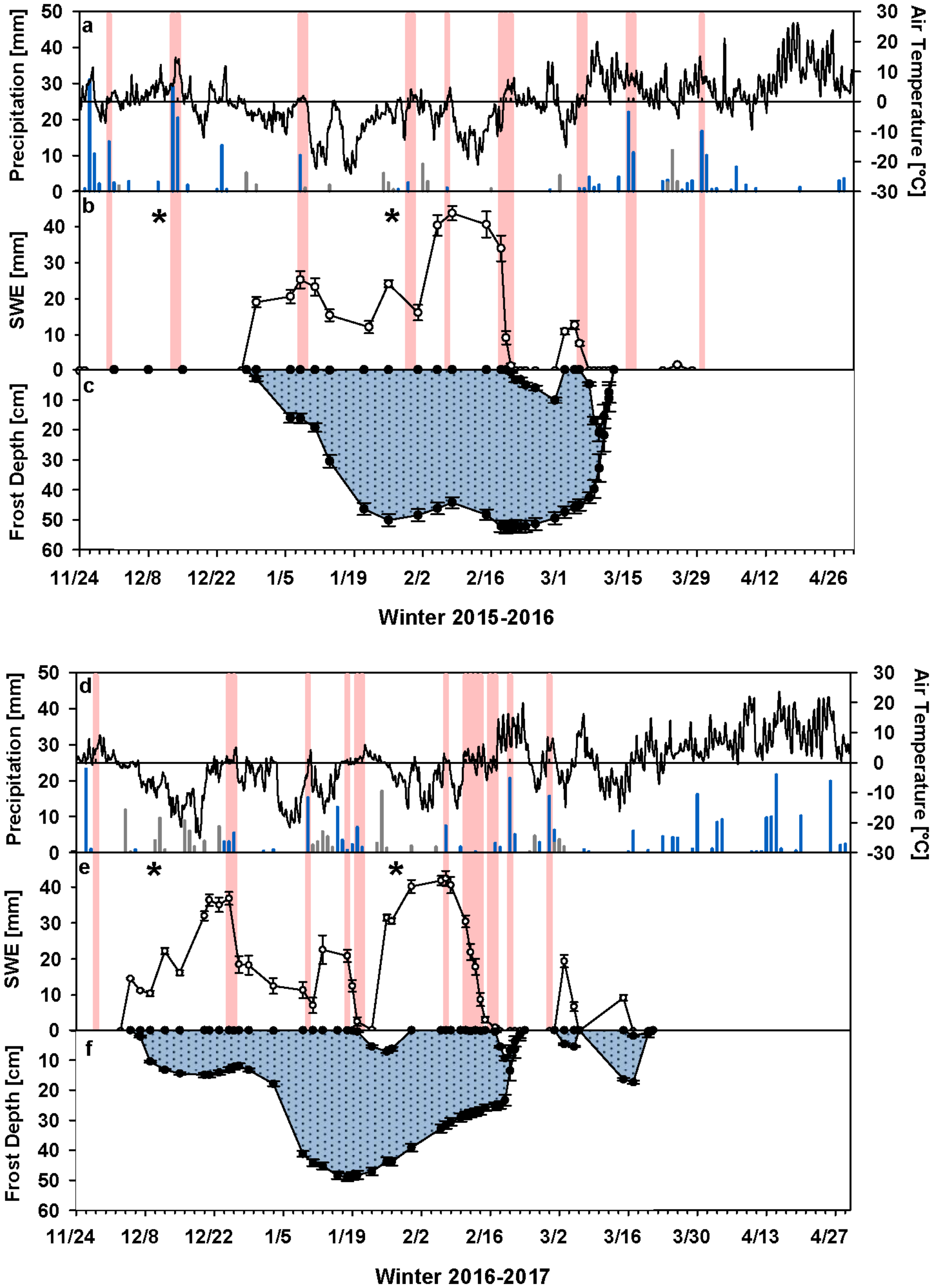

Fig. 1. Average hourly air temperature and total daily precipitation as rainfall or the liquid equivalent of snowfall during (a) 2015–2016 and (d) 2016–2017; the snow-water equivalent (SWE) of snowpack during (b) 2015–2016 and (e) 2016–2017; and the average frost depth during (c) 2015–2016 and (f) 2016–2017. Runoff event dates are designated in Panels a, b, d, and e with pink, vertical lines; and manure application dates are denoted with an asterisks in Panels b and e.

presence and condition of manure when runoff occurred. In 2015–2016, the December manure application occurred on soil that was field saturated, but not frozen or snow covered, and the January application was on top of snow overlying soil frozen from the surface to a 50-cm depth (Fig. 1a–1c, Table 1). During this winter season, greater nutrient losses from NT soils were driven by greater runoff: as the runoff volume increased, the concentration of runoff nutrients also increased, as detailed by Vadas et al. (2019). Subsequently, loads of TKP, DRP, TN, NH_4^+, TS, and VS were 44 to 276 times greater on NT than on CT, which were all statistically significant as a main effect (Table 3). Most nutrient loss occurred during the frozen ground and post-freezing periods with NT, and solely the frozen ground period with CT (Fig. 2).

During 2016–2017, the December application was on top of snow overlying soil frozen from the surface to a 10-cm depth, and the January application was on top of snow overlying soil that was thawed at the surface and frozen at depths of 6 to 44 cm (Fig. 1, Table 1). The nutrient (TKP, DRP, TN, and NH_4^+) and sediment (TS and VS) loads were only 1.5 to 3.4 times greater

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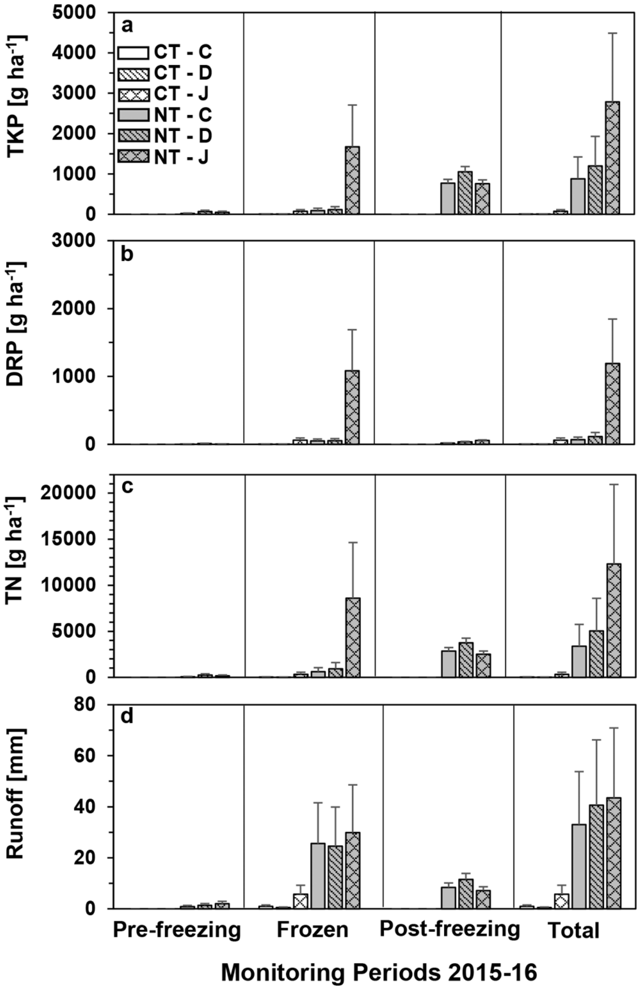

Fig. 2. Treatment means (± SE) of (a) total Kjeldahl P (TKP), (b) dissolved reactive P (DRP), (c) total N (TN), and (d) runoff by tillage × manure timing treatments during the 2015–2016 monitoring season. Nutrients and runoff are shown within the pre-freezing, frozen ground, and post-freezing periods, as well as the cumulative of the three periods (total). CT, fall tillage with a chisel plow; NT, no-tillage; control, no manure; Dec, December manure timing; Jan, January manure timing.

on NT than CT, in part because there was more runoff from CT soil this second winter than during the first winter, which led to greater concentrations, hence loads, of runoff nutrients. Only TKP was significantly greater with NT as a main effect (Table 4), indicating that nutrient losses in winter runoff are a function of hydrology that tillage may not fully control. It may also indicate that the increase in infiltration from fall tillage is greatest in the first year of tillage. At the same time, TN and TKP losses in NT controls, as well as the background nutrient levels of NT soils, were lower by the second year. Reducing some surface nutrient enrichment in NT may have also decreased differences between tillages. A need exists for longer term studies that evaluate the effect of tillage on infiltration and soil fertility effects during the freezing season.

Nutrient loads in runoff were also driven by the presence of manure and availability of nutrients for transport when the runoff occurred, which was based on the application timing within each tillage. In 2015–2016, the greatest nutrient loads occurred during the frozen ground period, when most runoff was produced and nutrients from the January manure application were lost (Fig. 2). Cumulative loads of the dissolved nutrients were significantly greater for NT-J compared with NT-C or NT-D (Table 3). There were no significant differences between NT-C and NT-D, although most nutrients were elevated numerically after both manure application timings. Volatile S losses in runoff, indicative of manure, were elevated from both manure timings compared with the unmanured control (Table 3). Greater losses from the January manure application timing over the December timing may be partly due to greater nutrients applied in January (Table 1) but are largely driven by the field conditions during manure application. We applied 1.2 and 1.3 times as much TN and TP, respectively, in January 2016 than in December 2015, but NT soils with the January application lost two times as much TN and TKP compared to NT soils with the December application (Table 3). This was due to manure application to unfrozen, snow-free soil in December 2015 and onto snow-covered soil with extensive frost development in January 2016. The liquid in the December-applied manure had a greater chance to infiltrate into the soil and be removed from risk of runoff loss compared with that in January because of the greater infiltration potential and hydraulic conductivity of unfrozen soils (Azmatch et al., 2012), which likely caused the lower runoff ratios. Some January-applied manure also stayed suspended in the snowpack, which further increased the chance of loss in runoff by accelerating snowmelt (Stock et al., 2019) and the availability of nutrients for surface transport. For event-by-event dynamics related to surface transport, see Vadas et al. (2019). Overall, the presence of frozen soils and manure application onto snow restricted on manure liquid infiltration and contributed to greater nutrient loads from the January manure application in 2015–2016.

There were also significant differences between manure application timings within CT that followed trends from NT during 2015–2016, although little runoff occurred from any of the CT treatments. All nutrient and sediment loads were significantly lower in CT-C and CT-D than CT-J, and CT-C and CT-D were not significantly different (Table 3). Nutrients had greater and sediment loads had lower numerical values in CT manure timings because the low runoff volumes likely had slow flow rates, and thus an inability to carry significant sediment. Moreover, the only runoff event for CT was during the frozen ground period, when soil frost limited sediment losses (Vadas et al., 2019). Overall, the January manure timing resulted in the greatest loads on both tillages, but nutrient losses were 20 to 40 times lower when the manure was applied to CT soils. Nutrient concentrations in manure runoff are generally greatest during the first runoff events post application (Komiskey et al., 2011; Vadas et al., 2019). Therefore, manure nutrient loads in runoff were also likely reduced because the sole CT runoff event did not occur until 18 to 20 February 2016, weeks after either manure application took place. This delayed runoff timing—combined with ~10 times less runoff volume in CT than NT during the event—resulted in nutrient concentrations that were significantly lower in CT than in NT. CT effectively reduced runoff at key times and was especially important during the frozen ground period when the potential for surface nutrient transport was greatest and could account for most annual runoff losses (Good et al., 2012). The surface depressional storage thereby provided more time for nutrients in liquid manure, along with rain and snowmelt, to infiltrate.

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Table 3. Treatment means and *p* values for comparisons of tillage, manure timing, and tillage × manure timing effects on total loads in the 2015–2016 monitoring season.

Effect	Tillage/timing†	Runoff	Total load‡					
			TKP	DRP	TN	NH_4^+	TS	VS
		mm	g ha^{-1}				kg ha^{-1}	
Tillage	Tillage with chisel (CT)	1.3	7.2	3.8	56.7	11.9	2.7	1.1
	No-tillage (NT)	38.8	1432	209	5943	525	746	126
	CT vs. NT (*p* value)	0.01	<0.01	<0.01	0.01	0.01	<0.01	0.01
Manure timing	Control (C)	5.5	55.2	8.8	336	38.3	33.8	9.0
	December (D)	4.2	42.5	9.3	291	27.2	26.2	6.5
	January (J)	15.7	443	269	2005	476	99.8	29.5
	C vs. D (*p* value)	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	C vs. J (*p* value)	0.11	0.01	<0.01	0.02	0.01	0.11	0.12
	D vs. J (*p* value)	0.03	<0.01	<0.01	0.01	<0.01	0.03	0.03
Tillage × manure timing	CT-C	0.9	3.5	1.1	33	5.3	1.6	0.9
	CT-D	0.4	1.5	0.8	17	3.1	0.9	0.4
	CT-J	5.7	70	61	326	104	13	5.0
	NT-C	33.0	881	68	3379	275	720	94
	NT-D	40.6	1197	113	5045	241	769	122
	NT-J	43.5	2784	1192	12313	2191	750	174
	CT-C vs. CT-D (*p* value)	0.60	0.34	1.00	0.66	1.00	0.93	0.56
	CT-C vs. CT-J (*p* value)	0.06	0.01	<0.01	0.03	0.01	0.04	0.10
	CT-D vs. CT-J (*p* value)	0.05	0.01	0.02	0.03	0.05	0.01	0.03
	NT-C vs. NT-D (*p* value)	1.00	1.00	0.94	1.00	1.00	1.00	1.00
	NT-C vs. NT-J (*p* value)	1.00	0.15	0.01	0.16	0.05	1.00	1.00
	NT-D vs. NT-J (*p* value)	1.00	0.21	0.01	0.26	0.02	1.00	1.00

† Tillage × manure timing treatments are: CT-C, chisel control; CT-D, chisel with December manure; CT-J, chisel with January manure; NT-C, no-tillage control; NT-D, no-tillage with December manure; NT-J, no-tillage with January manure.

‡ TKP, total Kjeldahl P; DRP, dissolved reactive P; TN, total N; TS, total solids; VS, volatile solids.

Table 4. Treatment means and *p* values for comparisons of tillage, manure timing, and tillage × manure timing effects on total loads in the 2016–2017 monitoring season.

Effect	Tillage/timing†	Runoff	Total load‡					
			TKP	DRP	TN	NH_4^+	TS	VS
		mm	g ha^{-1}				kg ha^{-1}	
Tillage	Tillage with chisel (CT)	30.9	181	105	1464	146	56	23
	No-tillage (NT)	43.5	608	319	2216	248	120	39
	CT vs. NT (*p* value)	0.19	0.05	0.07	0.32	0.31	0.07	0.21
Manure timing	Control (C)	35.5	88	34	755	46	57	19
	December (D)	41.5	919	719	3400	778	101	38
	January (J)	33.4	452	253	2276	192	96	37
	C vs. D (*p* value)	0.49	<0.01	<0.01	0.01	<0.01	<0.01	0.01
	C vs. J (*p* value)	1.00	0.01	0.01	0.02	0.02	<0.01	0.01
	D vs. J (*p* value)	0.14	0.12	0.05	0.24	0.01	1.00	1.00
Tillage × manure timing	CT-C	35.1	61	25	896	48	45	21
	CT-D	26.3	369	291	2122	475	63	26
	CT-J	31.9	265	160	1648	137	62	23
	NT-C	36.0	127	46	636	45	73	18
	NT-D	65.4	2289	1778	5445	1274	161	55
	NT-J	35.1	770	399	3143	268	148	59
	CT-C vs. CT-D (*p* value)	0.26	0.03	0.01	0.12	0.01	0.07	0.45
	CT-C vs. CT-J (*p* value)	1.00	0.06	0.04	0.30	0.14	0.08	1.00
	CT-D vs. CT-J (*p* value)	1.00	0.68	1.00	1.00	1.00	0.58	1.00
	NT-C vs. NT-D (*p* value)	0.03	0.01	<0.01	0.01	<0.01	<0.01	<0.01
	NT-C vs. NT-J (*p* value)	1.00	0.03	0.02	0.02	0.02	0.01	<0.01
	NT-D vs. NT-J (*p* value)	0.01	0.10	0.05	0.26	0.02	0.97	1.00

† Tillage × manure timing treatments are: CT-C, chisel control; CT-D, chisel with December manure; CT-J, chisel with January manure; NT-C, no-tillage control; NT-D, no-tillage with December manure; NT-J, no-tillage with January manure.

‡ TKP, total Kjeldahl P; DRP, dissolved reactive P; TN, total N; TS, total solids; VS, volatile solids.

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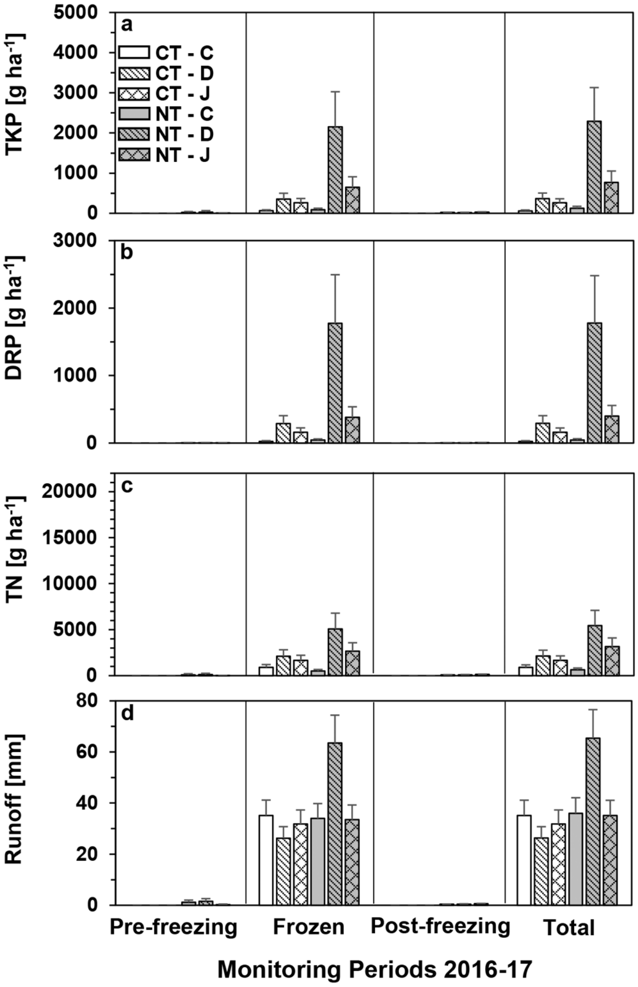

Fig. 3. Treatment means (± SE) of (a) total Kjeldahl P (TKP), (b) dissolved reactive P (DRP), (c) total N (TN), and (d) runoff by tillage × manure timing treatments during the 2016–2017 monitoring season. Nutrients and runoff are shown within the pre-freezing, frozen ground, and post-freezing periods, as well as the cumulative of the three periods (total). CT, fall tillage with a chisel plow; NT, no-tillage; control, no manure; Dec, December manure timing; Jan, January manure timing.

Manure timings within tillages also had a significant effect on nutrient loads during 2016–2017, but patterns were nearly opposite from 2015–2016. Within both NT and CT, December and January manure timings significantly increased nutrient and sediment loads compared with their unmanured controls, but the greatest loads occurred from the December timing (Table 4). Greater losses from the December manure application timing over the January timing may be partly due to greater nutrients applied in December (Table 1), but also the field conditions during and after manure application. We applied 1.0 and 1.2 times more TN and TP, respectively, in December 2016 than in January 2017, but soils with the December application had up to two times more TN and TKP than those with the January application (regardless of tillage) (Table 4). Both manure applications this winter were on top of snow and frozen soils, which restricted manure liquid infiltration into soil. However, the presence of surface thaw during application in January 2017, as opposed to soil frozen from the surface downward in December 2016, likely allowed some manure liquid and nutrients to immediately infiltrate into the soil, reducing manure nutrient loss potential in subsequent runoff events. Moreover, December and January were wet months. Prior to the January manure application, the December manure interacted with 134 mm precipitation and four runoff events on frozen soil, creating additional opportunities for surface nutrient transport. During this time prior to the January application, the runoff ratios of CT peaked, leading to greater runoff nutrient concentrations and, ultimately, nutrient loads.

Overall, the elevated loads from December and January manure timings, but especially during January 2016 and December 2016, was a function of the environmental conditions after application. Frozen soils increased the likelihood of runoff by lowering thresholds of available water (precipitation or snowmelt) needed to induce runoff (Vadas et al., 2017) by reducing infiltration. According to a laboratory investigation, the process of infiltration into a frozen soil follows three steps: (i) delayed or no initial infiltration, (ii) slow infiltration as the wetting front advances through the soil frost layer, and (iii) more rapid infiltration as the wetting front reaches the unfrozen soil beneath the frozen soil layer (Watanabe et al., 2013). During 2015–2016, the presence of unfrozen soil in December versus substantial soil frost and snow in January (frost thickness = 50.1 cm, SWE = 24 mm) resulted in significantly greater runoff and nutrient loss from the January application. During 2016–2017, both manure timings encountered soil frost, which elevated runoff, nutrient, and sediment losses from manure. There was a thinner soil frost layer and less snow accumulation during the December 2016 application (frost thickness = 10 cm, SWE = 10 mm) than in January 2017 (frost thickness = 38 cm, SWE = 31 mm). Losses were likely lower in January 2017 because the surface layer of soil was thawed, allowing some manure liquid to immediately infiltrate the soil, thereby reducing the runoff ratio. Moreover, the December manure interacted with more precipitation and runoff events on frozen soil, and therefore had more opportunity for surface losses—higher runoff ratios—before the January manure was even applied. From field observation, as manure was applied, the liquids rapidly infiltrated snow, leaving coarser solids suspended on the snow surface. Some manure remained trapped throughout the snow profile after percolation, whereas the rest of the liquid accumulated in the snow at the soil surface. When surface thaw of soil frost was present (i.e., January 2017), some liquid infiltrated the soil. When the soil surface was frozen (i.e., January 2016 and December 2016), the manure liquid that accumulated in the snow at the soil surface became an icy layer. Based on these processes, initial infiltration was delayed or did not occur for manure applications on soils with a frozen surface layer (i.e., January 2016 and December 2016), which led to more nutrient losses during subsequent runoff events, particularly when greater precipitation fell on frozen soils.

Conclusion

Wintertime manure applications pose a significant challenge to on-farm nutrient retention because of the limited infiltration potential of frozen soils, presence of snow, and likelihood of runoff during snowmelt and rain-on-snow events. Corn silage systems lack residue, and thus surface roughness from tillage is important in reducing runoff and nutrient transport. In this study, fall tillage reduced nutrient and sediment loads by reducing runoff volume but was less effectiveness in the season with greater precipitation. Although fall tillage reduced winter runoff relative to NT, erosion may be greater during the growing season,

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and these seasonal tradeoffs must be quantified for year-round management decisions. Liquid manure application to unfrozen soil significantly reduced losses, and partially thawed soil helped to a lesser degree. Application atop snow increased runoff risk by increasing the availability of nutrients for transport and accelerating snowmelt. Overall, however, timing manure applications was a less predictable control because runoff hydrology was strongly driven by seasonal weather, and that led to an inherently greater risk of nutrient losses during winter. Additional research that investigates long-term field conditions, different soil textures, and infiltration rates on variably saturated frozen soils would help establish physical processes that drive nutrient transport in winter. Tillage, frozen soil, snow cover, and weather should be considered with manure application during the freezing season to reduce the risk of nutrient loss to the environment.

Supplemental Material

Supplemental materials are available to download and include: (i) a diagram of the plot experimental design, and (ii) a table of historic air temperature, precipitation, and frost depths versus study years (2015–2017).

Conflict of Interest

The authors declare no conflict of interest.

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