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Conversion of Conservation Tillage to Rotational Tillage to Reduce Phosphorus Losses during Snowmelt Runoff in the Canadian Prairies

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Abstract

In a preceding study, converting conventional tillage (ConvT) to conservation tillage (ConsT) was reported to decrease nitrogen (N) but to increase phosphorus (P) losses during snowmelt runoff. A field-scale study was conducted from 2004 to 2012 to determine if conversion of ConsT to rotational tillage (RotaT), where conservation tillage was interrupted by a fall tillage pass every other year, could effectively reduce P losses compared with ConsT. The RotaT study was conducted on long-term paired watersheds established in 1993. The ConvT field in the pair has remained under ConvT practice since 1993, whereas tillage was minimized on the ConsT field from 1997 until 2007. In fall 2007, RotaT was introduced to the ConsT field, and heavy-duty cultivator passes were conducted in the late fall of years 2007, 2009, and 2011. Runoff volume and nutrient content were monitored at the edge of the two fields, and soil and crop residue samples were taken in each field. Greater soil Olsen P and more P released from crop residue are likely the reasons for the increased P losses in the ConsT treatment (2004–2007) relative to the ConvT treatment (2004–2007). Analysis of covariance indicated that, compared with ConsT (2004–2007), RotaT (2008–2012) increased the concentrations of dissolved organic carbon (DOC) by 62%, total dissolved N (TDN) by 190%, and total N (TN) by 272% and increased the loads of DOC by 34%, TDN by 34%, and TN by 60%. However, RotaT (2008–2012) decreased soil test P in surface soil, P released from crop residue, and duration of runoff compared with ConsT (2004–2007) and thus decreased the concentrations of total dissolved P (TDP) by 46% and total P (TP) by 38% and decreased the loads of TDP by 56% and TP by 42%. In the Canadian Prairies, where P is a major environmental concern compared with N, RotaT was demonstrated to be an effective practice to reduce P losses compared with ConsT.

Lake Winnipeg, the world's 10th largest freshwater lake, was named the Threatened Lake of the Year 2013 by the Global Nature Fund (Global Nature Fund, 2013), bringing attention to the severity of pollution in this lake. Nutrient exports from agricultural land through runoff are one of the main reasons for the enrichment of nitrogen (N) and phosphorus (P) and the degradation of water quality in Lake Winnipeg (Bourne et al., 2002). Multiple beneficial management practices (BMPs) are being implemented in many parts of the Lake Winnipeg watershed with the goal of reducing nutrient exports from agricultural land by runoff. Conservation tillage is a BMP designed to reduce soil erosion and nutrient exports. Assessment of this BMP in a paired watershed study in Manitoba demonstrated that conservation tillage was effective in reducing N export but exacerbated P export in runoff (Tiessen et al., 2010). Therefore, in this region where snowmelt dominates annual runoff and P enrichment is the major cause of algal blooms and related deterioration of water quality in Lake Winnipeg (McCullough et al., 2012; Schindler et al., 2012), conservation tillage needs to be modified to reduce P export.

Conservation tillage provides several benefits, including increased soil organic matter (SOM) and reduced soil erosion by covering soil with crop residue. The risk of soil erosion is relatively small in the Canadian Prairies, where the landscape is relatively flat and where major runoff (i.e., snowmelt) occurs on frozen soils; however, large amounts of crop residue left on the soil surface through conservation tillage practices can be a source for nutrient losses in runoff (Messiga et al., 2010). In cold regions such as the Canadian Prairies, crop residue on the soil surface is subjected to multiple freeze–thaw cycles from late fall to early spring. Phosphorus released from crop residue after freezing is a potential source of P in runoff from cropland (Roberson et al., 2007; Elliott, 2013). The proportion of total plant P released

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Abbreviations: ANCOVA, analysis of covariance; BMP, beneficial management practice; ConsT, conservation tillage; ConvT, conventional tillage; DOC, dissolved organic carbon; DurR, duration of runoff; FWMC, flow-weighted mean concentration; PkFlow, peak flow rate; PN, particulate nitrogen; PP, particulate phosphorus; RotaT, rotational tillage; SOM, soil organic matter; SSP, the sum of the snow water equivalent and precipitation during runoff; SWE, snow water equivalent; TDN, total dissolved nitrogen; TDP, total dissolved phosphorus; TN, total nitrogen; TP, total phosphorus; VolR, volume of runoff.

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by the first freeze–thaw cycle varies from 14 to 50% of total P (TP) (Bechmann et al., 2005; Roberson et al., 2007), and a greater portion of TP is released under multiple freeze–thaw cycles (Messiga et al., 2010). Nutrient contributions from crop residue are especially critical for nutrient export in runoff in the Canadian Prairies because freeze–thaw cycles occur several times per year (van Vliet and Hall, 1991) and crop residue has a relatively long opportunity to interact with snow and snowmelt water. On the basis of results of a simulated snowmelt study, Elliott (2013) concluded that nutrients released from crop residue could have a significant impact on receiving waters in the Canadian Prairies. Therefore, the benefits of leaving soil covered by crop residue under conservation tillage practice might be offset by crop residue–derived P losses during snowmelt runoff (Ranaivoson et al., 2005; Tiessen et al., 2010).

Under conservation tillage practices, SOM, P, and other low-mobility nutrients are often stratified in surface soil. Because soil organic anions and P compete for the sorption sites, increased SOM in surface soil under conservation tillage might increase soil labile P (Muukkonen et al., 2007). In addition, long-term conservation tillage practices can lead to P stratification and labile P accumulation in surface soil (Selles et al., 1999; Saavedra et al., 2007; Cade-Menun et al., 2010). High levels of labile P in surface soil is an environmental concern because excess labile P is susceptible to loss in runoff (Sharpley, 2003). To reduce P loss due to nutrient stratification, long-term conservation practices need to be altered to decrease soil P stratification. One approach for destratification of P is to introduce occasional tillage to conservation tillage and mix high-P soil at the surface with low-P soil in deeper soil layers.

The conversion of conservation tillage to rotational tillage by introducing a biannual fall tillage pass would redistribute crop residue and soil nutrients and potentially affect N and P losses in runoff. For example, tillage can accelerate mineralization of SOM and can affect carbon (C), N, and P export in runoff. Ranaivoson et al. (2005) reported that infrequent tillage in the fall reduced snowmelt nutrient losses compared with conservation tillage. However, the benefits gained during the conservation tillage period could be partially lost when rotating conservation tillage with conventional tillage (Pierce et al., 1994; Reicosky et al., 1995). Therefore, more studies on the effects of rotational tillage on nutrient losses, particularly on P, are needed (Daloğlu et al., 2012).

In large-scale (e.g., watershed) studies, replication at multiple sites is not practical, and treatments are often arranged one after another, making data analysis a challenge. Under such situations, a paired watershed approach is often used to evaluate effects before and after management practices (Clausen et al., 1996; Tiessen et al., 2010). Nutrient export by runoff is heavily affected by weather variables such as precipitation, but precipitation can vary greatly in a long-term study, and this variation likely confounds the treatment effects on nutrient export. To mitigate the effects of climatic and other types of year-to-year variation on response variables, analysis of covariance (ANCOVA) has often been performed in paired watershed studies (Jokela and Casler, 2011; Li et al., 2011).

The objective of this study was to determine if the introduction of a biannual fall tillage pass to a conservation tillage system would reduce P export in surface runoff and to evaluate the impacts of the tillage treatment on sediment, C, and N losses in snowmelt runoff. We hypothesized that conversion of conservation tillage to rotational tillage will increase sediment, C, and N losses but decrease P losses.

Materials and Methods

Watershed Description

The study site is a paired watershed located in the South Tobacco Creek Watershed, southern Manitoba, Canada (49°20′ N, 98°22′ W) (Fig. 1). One watershed has remained under conventional tillage (ConvT) practices since monitoring began in 1993 and was used as the control field. The second field (treatment field) has experienced three types of tillage operations since its establishment: ConvT from 1993 to 1996, conservation tillage (ConsT) from 1997 to 2007, and rotational tillage (RotaT) from 2008 to 2012. The data reported in this manuscript were collected from 2004 to 2012. During this period, the ConvT treatment was characterized by one or two primary fall tillage operations to a depth of approximately 13 cm with a heavy-duty cultivator. The ConsT treatment minimized tillage operations and had no fall tillage except for a light harrowing in the fall of 2005 to reduce and redistribute the large amount of crop residue. The detailed tillage operations in this study were reported by Tiessen et al. (2010). The RotaT treatment introduced fall tillage every second year to the ConsT with tillage passes made in the fall of 2007, 2009, and 2011 with a heavy duty cultivator. Both fields were cropped in a cereal–oilseed rotation. Cropping sequence, tillage operations, and fertilizer application rates are given in Table 1.

Soils in the watershed are classified as Dark Gray Chernozems (Mollisols). The climate is subhumid continental and is characterized by long, cold winters. The long-term mean annual precipitation is approximately 550 mm, with 25 to 30% of precipitation occurring as snowfall (Environment Canada, 2014). A detailed site description was given by Tiessen et al. (2010).

Soil Sampling and Laboratory Analyses

Each fall, after crop harvest, soil samples were collected at depths of 0 to 5 cm and 0 to 15 cm. Soil samples were collected at three slope positions (lower, middle, and upper slope). At each slope position, four permanent soil sampling sites were randomly selected and marked with GPS coordinates for future sampling reference. Each fall, one composite soil sample was taken at each sampling site, resulting in 12 soil samples per depth per watershed. Soil samples were sent to AgVise Laboratories for soil nitrate N (NO_3–N) and Olsen-P analyses using standard methods. Soil nitrate N was analyzed for samples collected in the 0- to 15-cm soil layer, and Olsen-P was determined for samples collected in the 0- to 5-cm and the 0- to 15-cm soil layers. Soil organic matter in the 0- to 5-cm soil layer was determined using weight loss on ignition method from 2004 to 2007.

Crop Residue Sampling and Laboratory Analyses

Crop residue samples were taken in late fall at the same sampling sites where soil samples were taken. Two subsamples of crop residue (0.25 m^2 area; 0.5 m × 0.5 m) were collected per sampling site before snowfall. Soil was excluded from the residue as far as was practically possible. Each year a composite sample was formed for each sampling site, and a representative subsample of the residue (25% of the subsample weight, equivalent to 0.0625 m^2) was cut

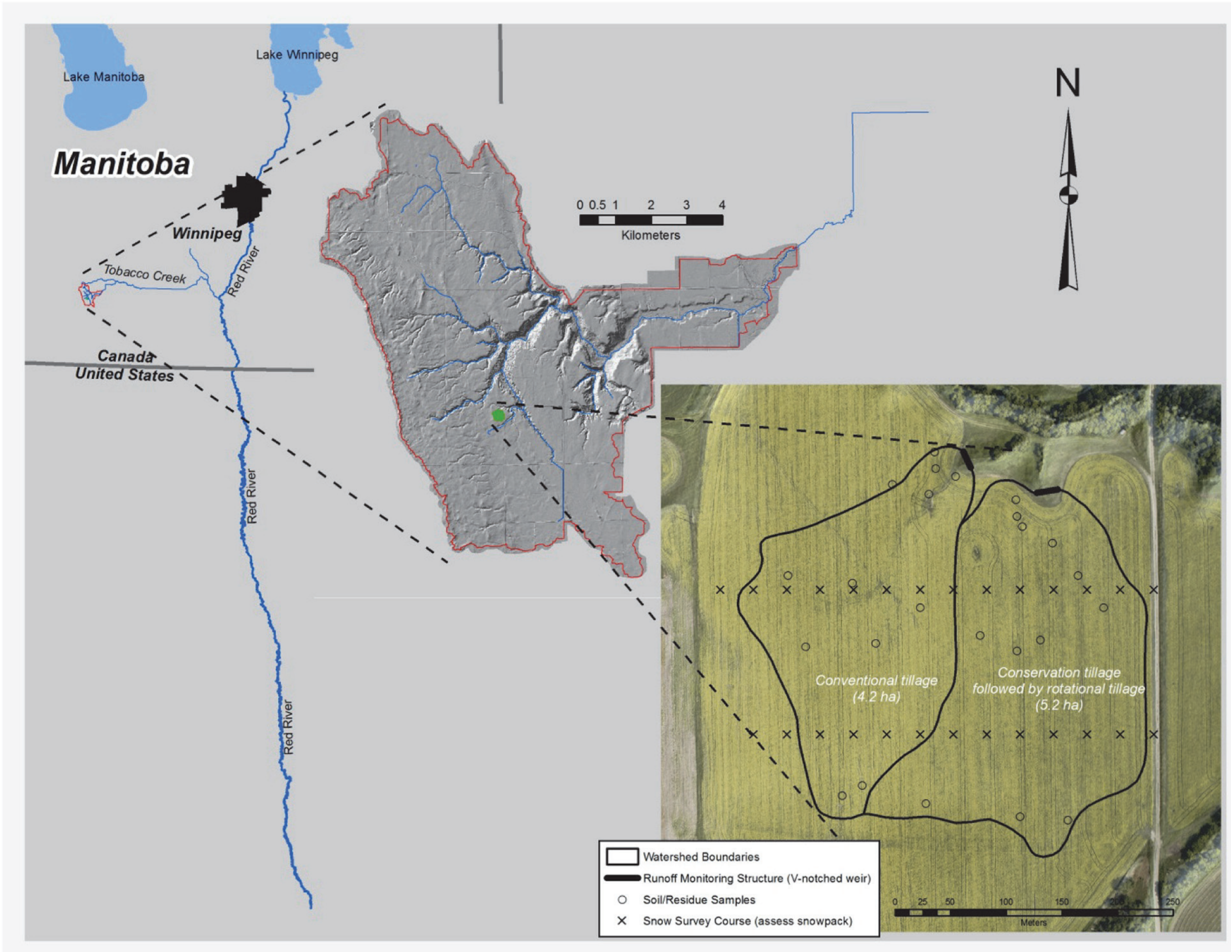

Fig. 1. Map of the study paired watersheds.

Table 1. Summary of crops, tillage implement in the previous fall, number of tillage passes, fertilizer application rate, snow water equivalent, and precipitation during snowmelt runoff in the paired watersheds.

Tillage type†	Year	Crop	Tillage implement‡	No. of tillage passes	N rate	P rate	Snow water equivalent	Precipitation
					kg N ha^{-1}	kg P_2O_5 ha^{-1}	mm	mm
ConvT	2004	canola (*Brassica napus* L.)	HDC	1	90	17	74.9	46.6
ConvT	2005	barley (*Hordeum vulgare* L.)	HDC	1	67	0	58.7	0.2
ConvT	2006	canola	HDC	1	78	5	93.9	28.4
ConvT	2007	spring wheat (*Triticum aestivum* L.)	HDC	1	185	5	93.3	2.8
ConvT	2008	canola	HDC	2	13	5	28.1	2.2
ConvT	2009	spring wheat	HDC	1	90	5	86.6	69.0
ConvT	2010	canola	HDC	1	112	10	88.2	1.0
ConvT	2011	spring wheat	HDC	1	90	15	48.0	41.1
ConvT	2012	canola	HDC	1	103	15	66.2	0.2
ConsT	2004	canola	no tillage	0	90	17	71.0	46.6
ConsT	2005	barley	no tillage	0	67	0	76.0	0.2
ConsT	2006	canola	harrow	1	78	5	90.9	28.4
ConsT	2007	spring wheat	no tillage	0	185	5	91.9	2.8
RotaT	2008	canola	HDC	2	13	5	33.9	2.2
RotaT	2009	spring wheat	no tillage	0	101	5	69.5	69.0
RotaT	2010	canola	HDC	1	112	10	79.5	1.0
RotaT	2011	spring wheat	no tillage	0	90	15	71.7	41.1
RotaT	2012	canola	HDC	1	103	15	60.8	0.2

† ConsT, Conservation tillage; ConvT, conventional tillage; RotaT, rotational tillage.

‡ HDC, heavy duty cultivator. Tillage depths were 12.7 and 7.6 cm for HDC and harrow, respectively. The tillage speed was 8.0 km h^{-1} for HDC and 6.4 km h^{-1} for harrow.

into lengths of approximately 10 cm and placed into polyethylene bags. Deionized water (1.875 L, equivalent to 30 mm of runoff on an area basis) was added to each bag. The bags were secured with plastic zip-ties, excluding as much air as possible, and carefully shaken by hand for 30 s to ensure all residues were in contact with water. After storage for 24 h at room temperature, the bags were placed in a freezer at −20°C for at least 24 h.

To extract the residue, the frozen samples were taken out of the freezer and left to thaw overnight. After each bag was gently rolled, the bag's contents were quickly poured into a plastic colander placed over a plastic bucket. The samples were left to drain by gravity for 1 min, and the bucket contents were left to settle for 5 min before a sample of the water extract (500 mL) was gently decanted into a plastic storage bottle for analyses. Residue extracts were analyzed for total dissolved N (TDN) and total dissolved P (TDP) at Fisheries and Oceans Canada's Freshwater Institute Laboratory. Release of TDN and TDP by crop residue after the freeze–thaw cycle was calculated and reported on a kg ha^{-1} basis.

Water Sampling and Laboratory Analyses

The surface runoff generated by snowmelt occurred in March and/or April of each year on soil that was usually frozen. Snowmelt runoff was typically characterized by diurnal hydrograph, with less flow at night. Snowmelt runoff is often separated into smaller events for evaluation of concentration and load affected by treatments (Ranaivoson et al., 2005; Tiessen et al., 2010). Because the hydrographs for the paired watersheds were similar, yearly snowmelt runoff in the watersheds was divided into identical runoff events (two or three events per year), with each event separated by a period with a flow rate of approximately 0. As a result, both watersheds had a total of nine runoff events for the first study period (2004–2007) and 12 for the second study period (2008–2012).

The procedures for the measurement of hydrologic variables of runoff and water sampling and laboratory analyses were described in detail by Tiessen et al. (2010) and Liu et al. (2013). Briefly, runoff was monitored at 5-min intervals at both watershed outlets using v-notched weirs and ultrasonic depth instruments (SR50, Campbell Scientific) connected to data loggers (CR10X0, Campbell Scientific). The volume of runoff was expressed as runoff yield (volume per unit of watershed area). Average flow rate was calculated as the flow volume per unit of flow time. Peak flow rate (PkFlow) was the maximum flow rate during runoff. The cumulative duration of flow was expressed as duration of runoff (DurR).

An auto-sampler (800SL, Sigma) controlled by the data logger sampled water at the v-notched weirs during runoff, and occasional supplementary grab samples were taken. Increases or decreases in flow rate were used to trigger sample collection so that the runoff hydrograph was well represented by the samples. The concentrations of TDN, TDP, total N (TN), TP, and sediment were determined using standard methods as described by Tiessen et al. (2010). The concentration of dissolved organic carbon (DOC) was determined by removing inorganic C using 10% phosphoric acid and digesting the remaining C with sodium persulfate/phosphoric acid reagent. The carbon dioxide released was quantified with an infrared detector (Phoenix 8000, Tekmar-Dohrmann). Loads of nutrient and sediment were calculated as the product of flow volumes (m^3) and concentrations (mg L^{-1}) and summed for the given time period of runoff. The flow-weighted mean concentrations (FWMCs) of nutrients and sediment were calculated by dividing load by the corresponding volume of runoff.

A snow survey was conducted in anticipation of snowmelt runoff. During each snow survey, 12 snow depths in each watershed were measured, and snow density was determined. Snow water equivalent (SWE) was calculated as the product of snow depth and density. Data for precipitation (including snowfall and rainfall) during snowmelt runoff were obtained from a nearby Environment Canada weather station (Miami Thiessen [49°22′ N, 98°17′ W]).

Statistical Analyses

For data collected at ConvT and ConsT treatments during the first study period (2004–2007), a paired-t comparison was conducted to determine the difference between the ConvT and ConsT treatments using the TTEST procedure of SAS (SAS Institute, 2008). The difference drawn from the paired-t comparison reflected the difference caused by the tillage practice because these two paired watersheds had no difference during the pretreatment period (1993–1996) (Tiessen et al., 2010). The normality assumption was verified by checking the distribution of the difference of pairs of variables using Shapiro-Wilk test. Data were transformed to pass the normality test, and the back-transformed means were reported. The same analysis was conducted for the RotaT and ConvT comparison during the second study period (2008–2012). Due to a small sample size and a large degree of variability associated with field-scale studies, the significance level was set as $P = 0.1$ unless otherwise stated.

Analysis of covariance is commonly used when determining before and after BMP effects in paired watershed studies (Clausen et al., 1996; Bishop et al., 2005; McBroom et al., 2008; Tiessen et al., 2010; Li et al., 2011), using variables in the control watershed as covariates. Analysis of covariance assumes linear relationships between covariates and variables of interest and no difference in slopes (homogeneity of slopes) between the compared regression lines. In addition, covariates are more effective to equalize background differences if covariates are not significantly different between before and after study periods (McBroom et al., 2008).

A preliminary analysis indicated that there were weak linear relationships for FWMC variables between the paired fields during each of the two study periods (2004–2007 and 2008–2012), making ANCOVA invalid to compare FWMC variables between the ConsT (2004–2007) and RotaT (2008–2012) treatments. No difference in FWMC variables between the two study periods in the control field demonstrated that background differences (mainly caused by weather) during the two study periods had no effect on FWMC variables. Consequently, a group comparison of FWMC variables between the ConsT (corresponding to the first study period) and RotaT (corresponding to the second study period) treatments was made using Proc GLM (SAS Institute, 2008).

Preliminary analyses also indicated that hydrologic and load variables were significantly different between the two study periods in the control field (probably due to weather variations), suggesting that ANCOVA, using variables in the control field as covariates, was not appropriate for comparing hydrologic and load variables between the ConsT and RotaT treatments (corresponding to the two study periods). A previous study at this site demonstrated that flow-related variables, such as volume of runoff (VolR), flow rate, and DurR, are the critical factors for nutrient exports during snowmelt runoff (Liu et al., 2013). Therefore, accounting for precipitation that would contribute to snowmelt runoff during the two study periods is critical to provide an accurate assessment of the difference between the ConsT and RotaT treatments on hydrologic and load variables. The sum of SWE before snowmelt and precipitation during snowmelt (SSP) was the closest estimate of precipitation contributing to runoff and was chosen as a candidate covariate for ANCOVA to adjust the treatment effects when comparing the hydrologic and load variables between ConsT and RotaT.

A full ANCOVA model, including the interaction term (covariate × tillage treatment), was conducted using Proc GLM of SAS (SAS Institute, 2008). When the interaction effect was significant, signaling a significant difference between the ConsT and RotaT treatments, no further ANCOVA was conducted. In this case, the amount of the difference between the ConsT and RotaT treatments was expressed as a percentage change (Li et al., 2011) and was calculated as the following:

$$\%\text{change} = \frac{\overline{Y}_{\text{RT}} - \overline{Y}_{\text{ConsT}}}{\overline{Y}_{\text{ConsT}}} \times 100$$

where $\overline{Y}_{\text{RT}}$ is the average of predicted values in RotaT, and $\overline{Y}_{\text{ConsT}}$ is the average of predicted values in ConsT.

When the interaction effect of a full ANCOVA model was not significant, suggesting parallel slopes between the paired regression lines, a reduced ANCOVA model without the interaction term was conducted to detect differences. The adjusted means were computed using LSMEANS statement and were reported.

Normality of the distribution and constant variance of the error terms were verified by examining the residuals for group comparison and ANCOVA. Data were either log or square root transformed to meet the assumption, and the back-transformed data are reported.

Results

Fall Soil Test Nitrogen and Phosphorus

Soil test N (i.e., NO_3^-–N) in the 0- to 15-cm soil layer was not significantly different between the ConvT and ConsT fields during the first study period (2004–2007) ($P = 0.16$) and between the ConvT and RotaT fields during the second study period (2008–2012) ($P = 0.24$) (Fig. 2A). In the control ConvT field, soil test N averaged 9.8 mg kg^{-1} during the first study period and 10.2 mg kg^{-1} during the second study period. In the treatment field, soil test N averaged 8.7 mg kg^{-1} in the ConsT treatment, corresponding to the first study period, and 8.2 mg kg^{-1} in the RotaT treatment, corresponding to the second study period.

In the 0- to 5-cm soil layer, soil Olsen P was significantly ($P < 0.01$) greater in the treatment field than in the control field for each of the two study periods (Fig. 2B). On average, soil Olsen P was 58% greater in the ConsT treatment than in the ConvT treatment (26.4 vs. 16.7 mg kg^{-1}) and 47% greater in the RotaT treatment than in the ConvT treatment (24.3 vs. 16.5 mg kg^{-1}).

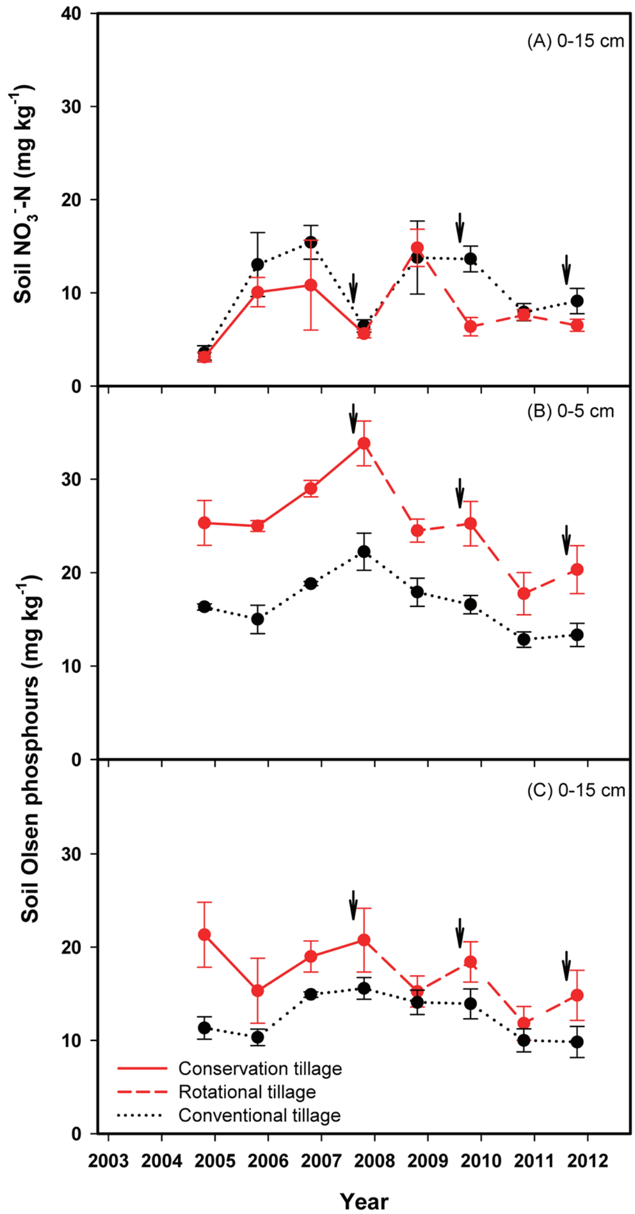

Fig. 2. Changes in fall soil NO_3–N in the 0- to 15-cm soil layer (A) and soil Olsen P in the 0- to 5-cm soil layer (B) and the 0- to 15-cm soil layer (C) in the paired watersheds, 2004 to 2012. Arrows indicate when fall tillage occurred.

Soil Olsen P in the treatment field slightly ($P = 0.12$) decreased by 8% from 26.4 mg kg^{-1} in the first study period (ConsT treatment) to 24.3 mg kg^{-1} in the second study period (RotaT treatment), whereas soil Olsen P remained stable during the two study periods in the control field (16.7 vs. 16.5 mg kg^{-1}).

Similar to soil Olsen P in the 0- to 5-cm soil layer, soil Olsen P in the 0- to 15-cm soil layer was significantly ($P < 0.01$) greater in the treatment field than in the control field (Fig. 2C). On average, soil Olsen P was 52% greater in the ConsT treatment than in the ConvT treatment in the first study period (18.6 vs. 12.2 mg kg^{-1}) and 28% greater in the RotaT treatment than in the ConvT treatment in the second study period (16.2 vs. 12.7 mg kg^{-1}).

In both control and treatment fields, soil Olsen P was consistently greater in the 0- to 5-cm soil layer than in the 0- to 15-cm soil layer. Compared with soil Olsen P in the 0- to 15-cm soil layer, soil Olsen P in the 0- to 5-cm soil layer was 33% greater ($P < 0.01$) in the control treatment (16.6 vs. 12.5 mg kg^{-1}), 42% greater ($P < 0.01$) in the ConsT treatment (26.4 vs. 18.6 mg kg^{-1}), and 50% greater ($P < 0.01$) in the RotaT treatment (24.3 vs. 16.2 mg kg^{-1}).

Water-Soluble Nitrogen and Phosphorus Extracted from Crop Residue

During the first study period (2004–2007), TDN extracted from crop residue under laboratory conditions was significantly ($P = 0.04$) greater in the ConsT than in the ConvT treatment (13.3 vs. 1.9 kg N ha^{-1}) (Fig. 3A). Similarly, TDP released from crop residue under laboratory conditions was significantly ($P = 0.05$) greater in the ConsT than in the ConvT treatment (3.4 vs. 0.4 kg P ha^{-1}) (Fig. 3B).

During the second study period (2008–2012), TDN extracted from crop residue was significantly ($P = 0.04$) greater in the RotaT than in the ConvT treatment (4.9 vs. 1.9 kg N ha^{-1}) (Fig. 3A). Similarly, TDP extracted from crop residue in the RotaT treatment was significantly ($P = 0.04$) greater than in the ConvT treatment (1.1 vs. 0.3 kg P ha^{-1}) (Fig. 3B). Unlike the first study period, the difference(s) of TDN and TDP extracted from crop residue between treatments during the second study period varied depending on tillage operation. There was no difference in plant-extracted TDN or TDP between the ConvT and RotaT treatments during the tillage phase (i.e., 2008, 2010, and 2012) of the RotaT treatment, but the differences were pronounced in years when there was no tillage in the RotaT field (Fig. 3).

In the control ConvT field, TDN and TDP extracted from crop residue were similar between the two study periods (1.9 vs. 1.9 kg ha^{-1} for TDN and 0.4 vs. 0.3 kg ha^{-1} for TDP). In the treatment field, however, TDN extracted from crop residue decreased by 63% from 13.3 kg ha^{-1} in the ConsT treatment (corresponding to the first study period) to 4.9 kg ha^{-1} in the RotaT treatment (corresponding to the second study period). Similarly, TDP extracted from crop residue in the treatment field decreased by 68% from 3.4 kg ha^{-1} in the ConsT treatment to 1.1 kg ha^{-1} in the RotaT treatment.

Hydrologic Variables

During the first study period (2004–2007), VolR was not different between the ConsT and ConvT treatments (Table 2). Similarly, there was no difference in VolR between RotaT and ConvT during the second study period (2008–2012).

In the ConvT field, none of the yearly-based but most of the event-based hydrologic variables were significantly different between the two study periods. The yearly-based hydrologic variables had smaller sample size ($n = 4$) and had less power to distinguish treatment differences.

The SSP was strongly correlated with the hydrologic variables and was not significantly different ($P = 0.80$) between the two study periods in the ConvT treatment; therefore, SSP was selected as a covariate in the ANCOVA. The full model of ANCOVA indicated that, for each hydrologic variable, the slopes of the paired regression lines were parallel, as indicated by the nonsignificant interaction (SSP × TC) effects. The reduced ANCOVA model indicated that conversion of ConsT to RotaT had no effect on average flow rate and VolR but significantly

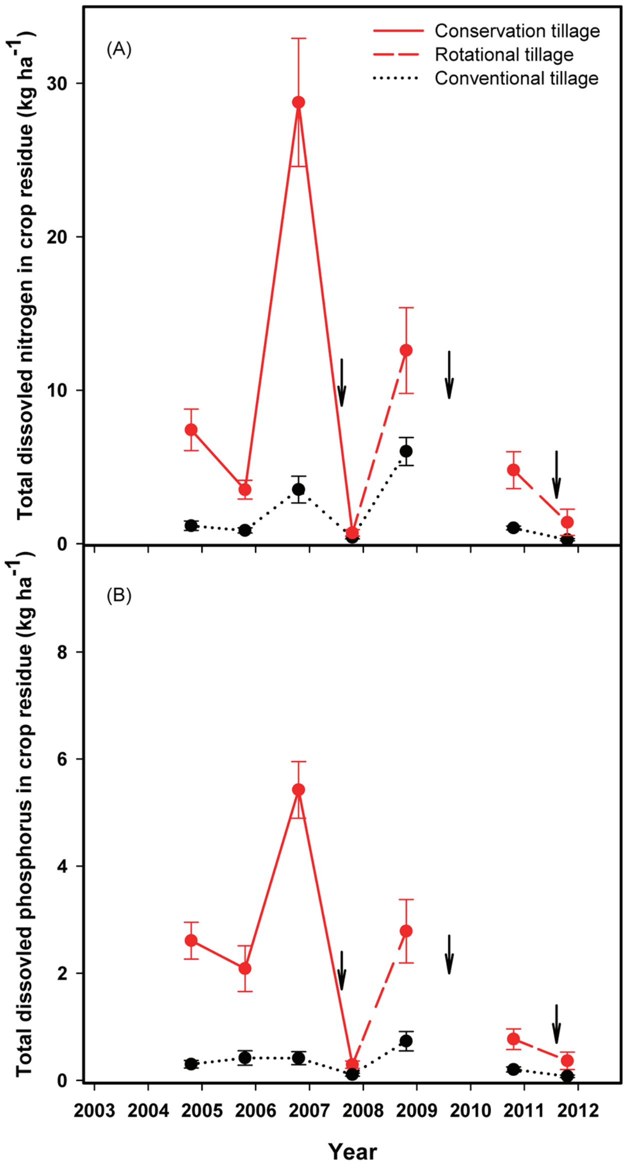

Fig. 3. Effects of tillage systems on total dissolved nitrogen (A) and phosphorus (B) extracted from frozen–thawed crop residue in the paired watershed, 2004 to 2012. Arrows indicate when fall tillage occurred in rotational tillage. Data in 2009 were not reported because of sample losses. Nutrients extracted from frozen–thawed residue collected in the late fall reflect the nutrient losses during snowmelt runoff in the following spring.

affected PkFlow and DurR. According to the means adjusted by ANCOVA, adopting RotaT reduced PkFlow by 49% from 33.0 L s^{-1} in the ConsT treatment to 16.8 L s^{-1} in the RotaT treatment. Similarly, DurR was reduced by 21% from 202.1 h in the ConsT treatment to 158.9 h in the RotaT treatment.

Flow-weighted Mean Concentrations of Nutrients and Sediment

During the first study period (2004–2007), the flow-weighted mean concentrations (FWMCs) of DOC, particulate N (PN), particulate P (PP), and sediment were not different between the ConvT and ConsT fields, but the ConsT practice significantly reduced the FWMC of TDN and TN and increased the FWMC of TDP and TP compared with the ConvT treatment (Table 3; Fig. 4A). During the second study (2008–2012),

Table 2. Summary of paired-t comparison, group comparison, correlation analysis, and full and reduced analysis of covariance on hydrologic variables of average flow rate, peak flow rate, duration of runoff, and volume of runoff.

		Hydrologic variables†			
		AvFlow	PkFlow	DurR	VolR
		P values of paired comparison between the paired watersheds‡			
2004–2007	ConvT vs. ConsT§	–	–	–	0.99
2008–2012	RotaT vs. ConvT	–	–	–	0.87
		P values of group comparison between two study periods in the control watershed			
Yearly	2004–2007 vs. 2008–2012	0.20	0.11	0.57	0.43
Event based	2004–2007 vs. 2008–2012	0.04	0.02	0.37	0.04
		Correlation coefficient between SSP and hydrologic variables			
ConsT period	SSP	0.94*	0.94*	0.91*	0.98*
RotaT period	SSP	0.68*	0.72*	0.85*	0.83*
		P values of full model of ANCOVA¶ for the tillage comparison between ConsT and RotaT			
Tillage		0.10	0.03	0.02	0.41
SSP		<0.01	<0.01	<0.01	<0.01
SSP × tillage		0.31	0.69	0.30	0.67
		P values of reduced model of ANCOVA for the tillage comparison between ConsT and RotaT			
Tillage		0.16	<0.01	0.02	0.43
SSP		<0.01	<0.01	<0.01	<0.01

* Significant at the 0.05 probability level.

† AvFlow, average flow rate; DurR, duration of runoff; PkFlow, peak flow rate; VolR, volume of runoff.

‡ No paired t comparison was made for AvFlow, PkFlow, and DurR because the sizes of the paired watersheds were not identical.

§ ConsT, conservation tillage; ConvT, conventional tillage; RotaT, rotational tillage; SSP, the sum of SWE (snow water equivalent) before snowmelt runoff and precipitation during snowmelt runoff.

¶ Analysis of covariance.

among all examined FWMC variables, only FWMC of DOC was significantly different between RotaT and ConvT treatments (Table 3), being 27% higher in the RotaT treatment (20.0 mg L^{-1}) than in the ConvT treatment (15.8 mg L^{-1}).

In the ConvT field, there was no difference in FWMC variables between the two study periods (2004–2007 vs. 2008–2012) (Table 3). In the treatment field, conversion of ConsT (2004–2007) to RotaT (2008–2012) had no effect on the FWMC of PN, PP, or sediment but significantly affected the FWMC of DOC, TDN, TN, TDP, and TP (Table 3). Compared with ConsT, RotaT increased FWMC of DOC by 62%, TDN by 190%, and TN by 272%. In contrast, conversion of ConsT to RotaT decreased FWMC of TDP by 46% and TP by 38% (Fig. 5A).

Loads of Nutrients and Sediment

During the first study period (2004–2007), the loads of DOC, PN, PP, and sediment were not significantly different between the ConvT and ConsT treatments, but the loads of total (TN and TP) and dissolved (TDN and TDP) nutrients were significantly different (Table 4). The loads of TDN and TN decreased, but the loads of TDP and TP increased in the ConsT treatment compared with the ConvT treatment (Fig. 4B). During the second study period (2008–2012), among all examined load variables, only the load of DOC was significantly different between RotaT and ConvT treatments (Table 4), being 44% higher in the RotaT treatment (7.9 kg ha^{-1}) than in the ConvT treatment (5.5 kg ha^{-1}).

Table 3. *P* values of paired-t comparison and group comparison on flow-weighted mean concentrations of dissolved organic carbon, particulate nitrogen, total dissolved nitrogen, total nitrogen, particulate phosphorus, total dissolved phosphorus, total phosphorus, and sediment.

		Flow-weighted mean concentrations†							
		DOC	PN	TDN	TN	PP	TDP	TP	Sediment
		P values of paired t comparison between the paired watersheds							
2004–2007	ConvT vs. ConsT‡	0.99	0.22	<0.01	<0.01	0.82	0.02	0.03	0.11
2008–2012	RotaT vs. ConvT	0.07	0.79	0.29	0.29	0.82	0.43	0.56	0.21
		P values of group comparison between two study periods in the control watershed							
Yearly based	2004–2007 vs. 2008–2012	0.28	0.47	0.44	0.51	0.37	0.95	0.98	0.31
Event based	2004–2007 vs. 2008–2012	0.15	0.24	0.16	0.19	0.18	0.95	0.72	0.37
		P values of group comparison between ConsT (2004–2007) and RotaT (2008–2012) in the treatment watershed							
Yearly based	ConsT vs. RotaT	0.10	0.39	0.04	0.03	0.90	0.02	0.02	0.18
Event based	ConsT vs. RotaT	<0.01	0.18	<0.01	<0.01	0.78	<0.01	<0.01	0.26

† DOC, dissolved organic carbon; PN, particulate nitrogen; PP, particulate phosphorus; TDN, total dissolved nitrogen; TDP, total dissolved phosphorus; TN, total nitrogen; TP, total phosphorus.

‡ ConsT, conservation tillage; ConvT, conventional tillage; RotaT, rotational tillage.

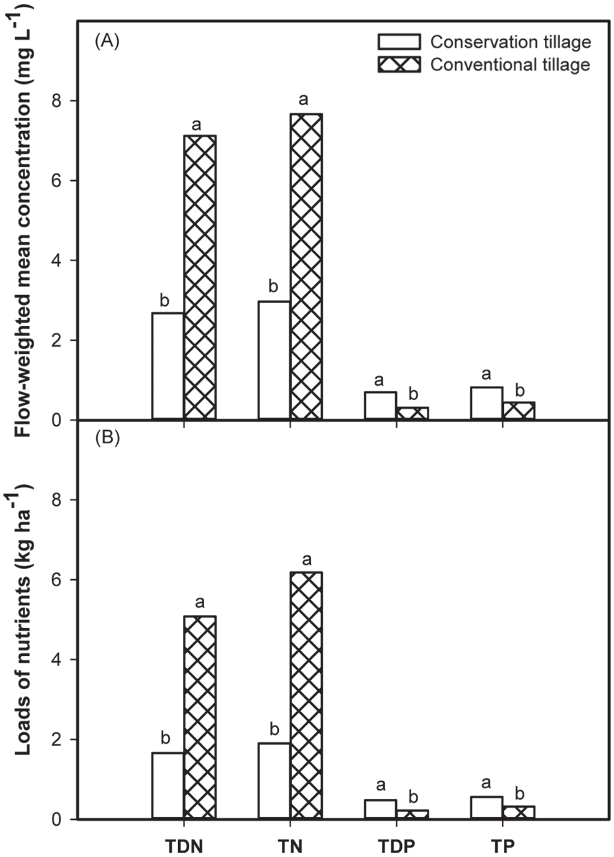

Fig. 4. Flow-weighted mean concentration (A) and load (B) of total dissolved nitrogen (TDN), total nitrogen (TN), total dissolved phosphorus (TDP), and total phosphorus (TP) as affected by conservation tillage and conventional tillage, 2004 to 2007. For each variable, means sharing the same letters are not significantly different at the 0.1 level.

In the control field where the management remained the same during the two study periods, the loads of TDN, TN, TDP, and TN between the two study periods were significantly different (Table 4), with greater loads in the first study period.

The SSP value was linearly related to and had a medium to strong correlation with load of nutrients and sediment (Table 4); therefore, an ANCOVA, using SSP as a covariate, was conducted to adjust treatment effects when comparing response variables between the ConsT and RotaT treatments. The significant interaction effects in the full ANCOVA model indicated that conversion of ConsT to RotaT significantly increased loads of DOC by 34%, TDN by 34%, and TN by 60%, as estimated by the percentage change (Table 4; Fig. 6). The reduced ANCOVA model indicated that converting ConsT to RotaT had no effect on loads of PN, PP, or sediment but significantly reduced loads of TDP by 56% and TP by 42% (Table 4; Fig. 5B).

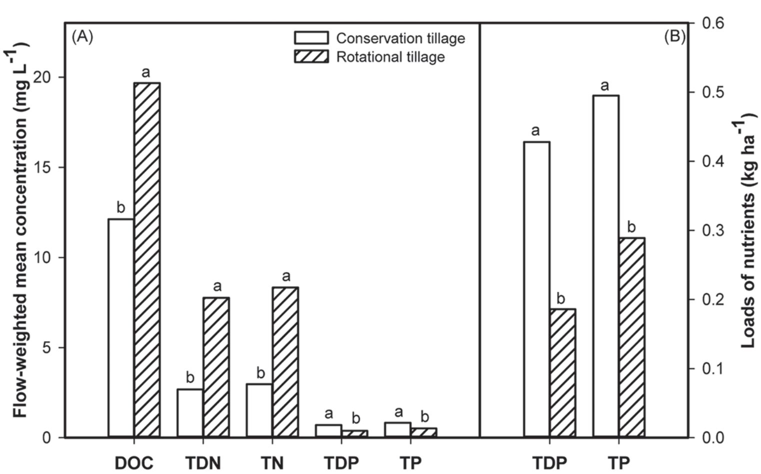

Fig. 5. Flow-weighted mean concentration (A) of total dissolved nitrogen (TDN), total nitrogen (TN), total dissolved phosphorus (TDP), and total phosphorus (TP) and load (B) of TDP and TP as affected by conservation tillage and rotational tillage, 2008 to 2012. For each variable, means sharing the same letters are not significantly different at the 0.1 level.

Discussion

Previous studies have reported tillage effects on hydrologic variables. Conservation tillage was reported to increase VolR during snowmelt runoff compared with conventional tillage (Elliott et al., 2001; Ranaivoson et al., 2005). In the current study, the difference in VolR between the ConsT, RotaT, and ConvT treatments was not sufficiently large to be statistically significant, possibly due to the small sample size ($n = 4$). Tillage practice has been shown to determine the degree to which the soil surface was covered by crop residue, which affects snow distribution (Elliott et al., 2001). Qiu et al. (2011) reported that standing crop residue under ConsT practice retained more snow than under ConvT practice. Crop residues in the ConsT treatment likely captured more snow by standing stubble than in the RotaT treatment, leading to greater DurR. Duration of runoff was reported to be one critical factor affecting N and P export in snowmelt runoff (Liu et al., 2013). Compared with ConsT, RotaT decreased the interaction time among soil, crop residue, and runoff water and therefore reduced the potential for nutrient loading.

Changes in tillage practice had no effect on concentrations and loads of particulate nutrients and sediment. Conservation tillage can effectively control erosion and related particulate nutrient losses under hilly conditions (Shipitalo and Edwards, 1998). In the gently sloping study region, the risk of water erosion is relatively small during snowmelt runoff on frozen soils. Consequently, dissolved nutrients account for the majority of total nutrient export in snowmelt runoff (Hansen et al., 2000; Tiessen et al., 2010), and the absence of an effect of tillage on particulate nutrients and sediment concentrations was expected.

Conservation tillage can enrich organic matter in surface soil by minimizing soil disturbance and maintaining residue cover compared with conventional tillage (Saavedra et al., 2007). During the first study period, SOM in the 0- to 5-cm soil layer was significantly greater ($P < 0.01$) in the ConsT treatment than in the ConvT treatment (4.6 vs. 4.0%). Fall tillage operations every other year in the second study period would have enhanced the mineralization of SOM accumulated during the ConsT period and released DOC. The accumulation of SOM in the ConsT treatment during the first study period explained the increased concentration and load of DOC on RotaT compared with either ConsT or ConvT.

Tillage also normally enhances soil N mineralization (Campbell et al., 2008) and releases soluble N. The relatively high soil test N in the ConvT and

RotaT treatments might be the main contributor to the high concentrations and loads of TDN and TN compared with the ConsT treatment. Ortega et al. (2002) reported a pronounced stratification of soil organic N in the top 10-cm soil layer 8 yr after adopting ConsT. In the current study, no evidence of stratification of soil NO_3^-–N under the ConsT practice was found due to the depth of soil sampling (15 cm) and the high mobility of NO_3^-–N.

Like ConvT, RotaT increased the concentrations and loads of TDN and TN in runoff compared with ConsT. Loads of TDN and TN also tended to be greater under the RotaT than under the ConvT practice, but the differences were not statistically significant. The high loads of TDN and TN in the RotaT treatment compared with ConsT or ConvT treatment were attributed mainly to the mineralization of SOM accumulated during the first study period under the ConsT practice. Under similar soil fertility conditions, the flexibility of altering the frequency of tillage in RotaT would likely provide an opportunity to reduce N loss compared with ConvT through reducing the frequency of tillage in RotaT. One of the benefits of RotaT over ConvT is that RotaT retains some capacity to store soil C compared with ConvT (Venterea et al., 2006; Hou et al., 2012), thus improving soil quality.

Phosphorus concentration in runoff has been reported to be related to P concentration in surface soil (Daverede et al., 2003), particularly when soil test P had a wide range (i.e., 3–512 mg kg^{-1}) (Little et al., 2007). Phosphorus is low in mobility, and applied P tends to remain in the surface soil without soil mixing by tillage. Such P stratification under ConsT (Selles et al., 1999; Saavedra et al., 2007) might in part explain the high soil Olsen P in the ConsT treatment compared with ConvT and RotaT treatments, thus resulting in greater P losses in the ConsT treatment. In addition, soil organic anions and P compete for the same absorption site on soil particles; therefore, high SOM increases the availability of labile P, such as Olsen P (Muukkonen et al., 2007; Saavedra et al., 2007). In the current study, high SOM in the ConsT treatment could contribute the greater soil Olsen P we observed compared with the ConvT and RotaT treatments. Saavedra et al. (2007) also observed greater Olsen P in conservation tillage (e.g., no till) than in ConvT in the top 5 cm of soil in a long-term (21-yr) study. During runoff, the interaction between soil and water mainly occurs in the surface soil, and elevated soil P in the soil–water interaction zone under the ConsT treatment would be a factor increasing P losses in runoff.

High concentrations of P in surface soil under ConsT have been reduced through tillage operations (Sharpley, 2003; Garcia et al., 2007). Tillage in ConvT and RotaT not only dilutes high soil P by redistributing relatively immobile P; it also increases P sorption at the soil surface (Sharpley, 2003; Watkins et al., 2012), thus reducing the concentration of Olsen P in the surface soil. In the current study, for example, tillage operations in the RotaT treatment decreased soil Olsen P by 8% in the 0- to 5-cm soil layers compared with the preceding ConsT treatment. The decreased surface soil Olsen P in the RotaT would have partially contributed to the reduced concentrations and loads of TDP and TP compared with the ConsT treatment. Similarly, Quincke et al. (2007) reported that occasional one-time tillage of no-till systems effectively reduced dissolved P loss in runoff, particularly when concentrations of P in surface soil were high.

Crop residue is an important source for nutrient losses in snowmelt runoff (Roberson et al., 2007; Messiga et al., 2010; Elliott, 2013). For example, Jokela and Casler (2011) reported

Table 4. Summary of paired t comparison, group comparison, correlation analysis, and full and reduced analysis of covariance on loads of dissolved organic carbon, particulate nitrogen, total dissolved nitrogen, total nitrogen, particulate phosphorus, total dissolved phosphorus, total phosphorus, and sediment.

		Loads†							
		DOC	PN	TDN	TN	PP	TDP	TP	Sediment
		***P* values of paired comparison between the paired watersheds**							
2004–2007	ConvT vs. ConsT‡	0.81	0.27	0.07	0.08	0.61	<0.01	<0.01	0.14
2008–2012	RotaT vs. ConvT	0.09	0.91	0.16	0.19	0.68	0.52	0.59	0.46
		***P* values of group comparison between the two study periods in the control watershed**							
Yearly	2004–2007 vs. 2008–2012	0.36	0.15	0.04	0.03	0.30	0.05	0.06	0.22
Event based	2004–2007 vs. 2008–2012	0.11	0.13	0.02	0.05	0.12	0.04	0.06	0.10
		Correlation coefficient between SSP and loads							
ConsT period	SSP	0.94*	0.83*	0.85*	0.99*	0.84*	0.97*	0.98*	0.88*
RotaT period	SSP	0.91*	0.59*	0.96*	0.96*	0.57§	0.75*	0.68*	0.53§
		***P* values of full model of ANCOVA for the tillage comparison between ConsT and RotaT**							
Tillage		0.07	0.50	0.13	0.15	0.60	<0.01	0.47	0.38
SSP		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
SSP × tillage		<0.01	0.12	<0.01	<0.01	0.97	0.17	0.30	0.33
		***P* values of reduced model of ANCOVA for the tillage comparison between ConsT and RotaT in the treatment field**							
Tillage		NA¶	0.72	NA	NA	0.40	<0.01	0.03	0.82
SSP		NA	<0.01	NA	NA	<0.01	<0.01	<0.01	<0.01

* Significant at the 0.05 probability level.

† DOC, dissolved organic carbon; PN, particulate nitrogen; PP, particulate phosphorus; TDN, total dissolved nitrogen; TDP, total dissolved phosphorus; TN, total nitrogen; TP, total phosphorus.

‡ ConsT, conservation tillage; ConvT, conventional tillage; RotaT, rotational tillage; SSP, the sum of snow water equivalent before snowmelt runoff and precipitation during snowmelt runoff.

§ Significant at the 0.1 probability level.

¶ Not applicable because the interaction effects for SSP × tillage are significant.

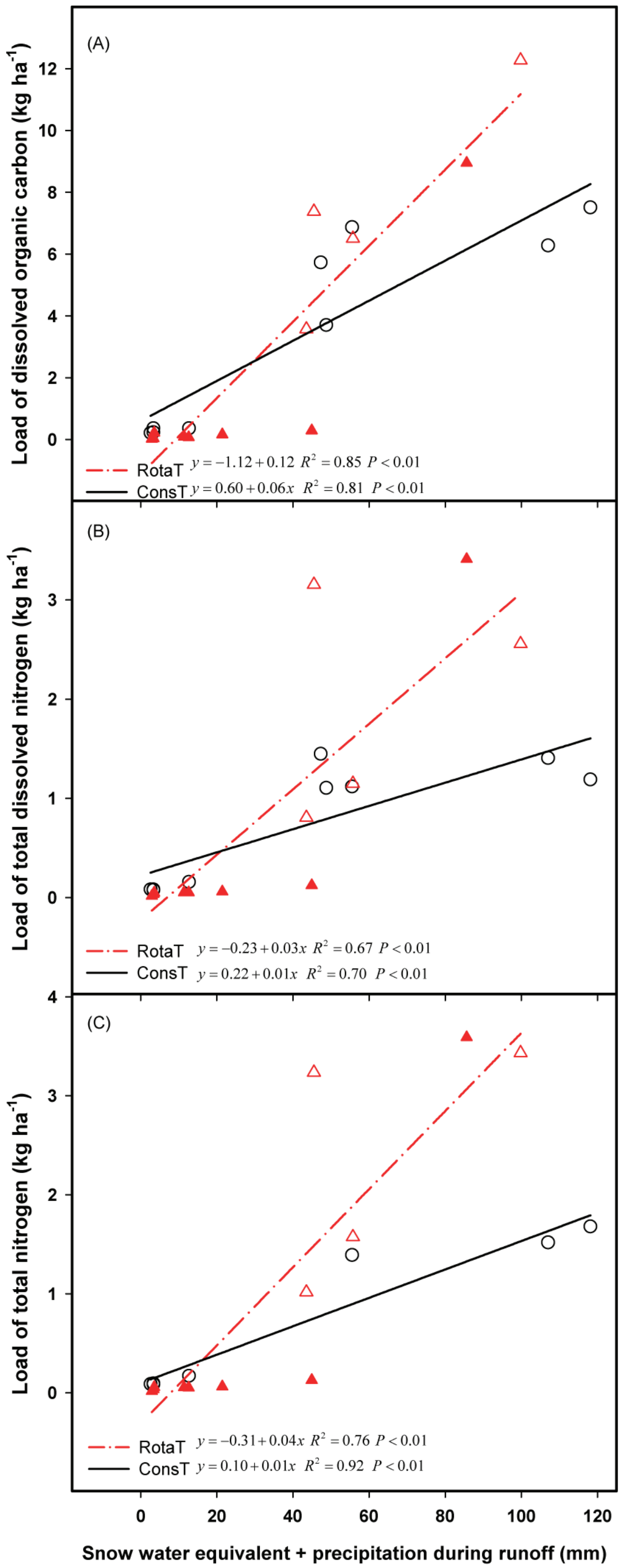

Fig. 6. Relationships between the sum of snow water equivalent and precipitation during runoff and loads of dissolved organic C (A), total dissolved N (B) and total N (C) in snowmelt runoff in the rotational tillage (RotaT) and conservation tillage (ConsT). The open triangle represents no tillage phase in RotaT; the solid triangle represents tillage phase in RotaT; the circle represents ConsT. The snow water equivalent and precipitation corresponding to each runoff event was calculated based on total snow water equivalent plus precipitation, volume of individual runoff event, and total volume of runoff.

that large losses of TDP were partially attributed to P released from vegetation after freeze–thaw cycles. Our data show that the quantity of residue on the soil surface and its potential to release nutrients were decreased by tillage operations. The dry biomass of crop residue in the ConvT treatment was 54% less than in the ConsT treatment (8.9 vs. 4.1 Mg ha^{-1}), and RotaT reduced the nutrients extracted from crop residue by more than 60% relative to ConsT. The potential for the residues to release P might also reflect a greater plant uptake under the high soil P conditions in ConsT. Roberson et al. (2007) reported that P release from plants after freezing increased as the level of soil test P increased. Under the RotaT treatment, surface soil Olsen P was reduced, possibly reducing plant uptake and potential to release P.

The nutrient release from residues in our study may also have been affected by the reduction in DurR in RotaT relative to ConsT that would have shortened the contact time between crop residue and snowmelt water. In addition, tillage operations in the RotaT treatment increased the chances of the contact between soil and crop residue remaining on soil surface. Elliott (2013) reported that P released from crop residue was reduced by 60% due to the contact and interaction between soil and crop residue. Therefore, tillage in the RotaT treatment reduced the TDN and TDP released from crop residue and contributed to the reduction in the concentrations and loads of TDP and TP in snowmelt runoff. Although both N and P were released by residues, the reduction in N release from the residues under RotaT was masked by the increase in N mineralization and soil N contribution.

Weather, particularly precipitation, played an important role in nutrient exports. Loads of nutrients were more sensitive to precipitation than concentrations, as demonstrated by no difference in FWMC variables but significant differences in most load variables between the two study periods in the control field. At the same site, Tiessen et al. (2010) concluded that ConsT increased P export in snowmelt runoff compared with ConvT, using ANCOVA to adjust weather and other year-to year variations throughout the experimental period. Similarly, our results demonstrated that tillage reduced P export, using a side-by-side paired-t comparison between the control and treatment fields. Also, during the RotaT period of 2008 to 2012, the loads of P were much greater in the year of absence of tillage than in the year with tillage (0.28 vs. 0.06 kg ha^{-1} for TDP and 0.50 vs. 0.07 kg ha^{-1} for TP). In addition to the greater precipitation, the no-tillage operation contributed to the greater P loss in the year of absence of tillage.

Conversion of ConsT to RotaT reduced P losses during runoff by altering soil Olsen P, crop residue, and duration of runoff. Although conversion of ConsT to RotaT exacerbated N losses in runoff, reducing the frequency of tillage in RotaT might provide a solution to reduce N losses. The optimal frequency and intensity of tillage needs to be further studied to reduce N and P losses in runoff. In the study region, P rather than N was considered to be the major cause of deterioration of water quality. Therefore, RotaT can be used as a beneficial management practice to reduce P losses in runoff occurring mainly on frozen soil.

Conclusions

Changes in tillage practices in the Canadian Prairies had no effect on the particulate fractions of N and P primarily because of insignificant erosion during snowmelt runoff. Rotational tillage had similar effects on runoff variables to the conventional tillage but had the potential to improve soil quality by reducing tillage frequency. Conversion of ConsT to RotaT enhanced the breakdown of SOM accumulated in surface soil during the ConsT period, increasing the concentrations and loads of DOC, TDN, and TN in snowmelt runoff. However, the conversion also reduced the amounts of crop residue and associated P release during runoff, shortened the duration of runoff, and destratified soil P in the 0- to 5-cm soil layer, decreasing the concentrations of TDP by 46% and TP by 38% and the loads of TDP by 56% and TP by 42%. In the Canadian Prairies, where the majority of snowmelt runoff occurs on frozen soils, adopting RotaT is an effective management practice to reduce P loss from ConsT, but the beneficial effects of ConsT on N transport are lost when RotaT is adopted. The frequency and intensity of tillage operations in RotaT might affect soil properties and nutrient export and need to be further studied.

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