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Nutrient and Sediment Losses in Snowmelt Runoff from Perennial Forage and Annual Cropland in the Canadian Prairies

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Abstract

An 8-yr field-scale study, 2005 to 2012, investigated effects of agricultural land use on nutrient and sediment losses during snowmelt runoff from four treatment fields in southern Manitoba. In 2005, two fields with a long-term history of annual crop (AC) production were planted to perennial forage (PF), while two other fields were left in AC production. In 2009, the AC fields were converted to PF, while the PF fields were returned to AC. Runoff flow rates were monitored at the lower edge of the fields, and nutrient concentrations of runoff water were determined. The effects of AC and PF on selected variables were similar for the spatial (between-fields) and temporal (within-field) comparisons. The flow-weighted mean concentrations (FWMCs) and loads of particulate N, P, and sediment were not affected by treatment. Soil test N and the FWMC and load of NO_x (NO_3^- + NO_2^-) were significantly greater in the AC treatment, but the FWMC and load of NH_3 were greater in the PF treatment. Loads of total dissolved N (TDN) and total N (TN) were not affected by treatment, although the concentrations of TDN and TN were greater in the AC treatment. The PF treatment significantly increased FWMCs and loads of total dissolved P (TDP) and total P (TP). On an annual snowmelt runoff basis, the PF treatment increased the FWMC of TDP by 53% and TP by 52% and increased the load of TDP by 221% and TP by 160% compared with the AC treatment. The greater P and NH_3 losses in the PF treatment were attributed mainly to nutrient release from forage residue due to freezing.

Lake Winnipeg, the world's 10th largest freshwater lake, is situated on the Canadian Prairies and has recently received increasing attention due to the deteriorated water quality. One important contributor to the degraded water quality in the lake was the inputs of N and P from nonpoint sources such as agricultural land during snowmelt runoff (Bourne et al., 2002). Consequently, reducing nutrient losses from agricultural land is one of many solutions to mitigate water contamination. Numerous studies have demonstrated that changes in agricultural land use can effectively influence nutrient export from agricultural land to surface water (Randall and Mulla, 2001; Schilling and Spooner, 2006; Zhou et al., 2010). Nielsen et al. (2012) reported that an increase in the proportion of agricultural land area in a watershed often led to higher total N and total P exports to receiving waters. Zampella et al. (2007) reported that a 10% change in land cover in a basin can result in a significant change in surface water quality. In an extensive literature review on N export to streams worldwide, Alvarez-Cobelas et al. (2008) concluded that two times more total N and 30 times more NO_3–N were exported from watersheds dominated by annual crops than from watersheds dominated by perennial pasture.

Incorporation of perennial forage into annual crop systems may reduce the use of synthetic N fertilizers, increase soil organic matter content, prevent soil erosion, and reduce water contamination by N (Kelner et al., 1997; Schilling and Spooner, 2006; Miller et al., 2013; Xu et al., 2013). For example, conversion of an annual-crop-dominated cropping system to a mixed perennial and annual cropping system in the U.S. Corn Belt showed environmental benefits of reduced N concentrations in streams (Schilling et al., 2008; Zhou et al., 2010). This is supported by the findings by Alexander et al. (2008), who predicted that N losses to the Gulf of Mexico were mainly from cultivated croplands in a study assessing N and P losses in the Mississippi River Basin. However, Alexander et al. (2008) also suggested that pasture and rangeland were the greatest source of

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Abbreviations: AC, annual crop; FWMC, flow-weighted mean concentration; PF, perennial forage; PN, particulate nitrogen; PP, particulate phosphorus; TDN, total dissolved nitrogen; TDP, total dissolved phosphorus; TN, total nitrogen; TP, total phosphorus; VolR, volume of runoff.

P delivered to the Gulf. Therefore, it is possible that perennial crops might increase P losses under certain circumstances.

In a cold region, crop residue remaining on the soil surface after harvest is subjected to freeze and thaw cycles and may release nutrients during snowmelt. Studies have shown that P release from vegetation increased dramatically after it was frozen and thawed, compared with the control that was not frozen and thawed (Roberson et al., 2007; Liu et al., 2013a). In addition, potential P release from plant vegetation increased with increasing freeze–thaw cycles (Bechmann et al., 2005; Liu et al., 2013a). Recently, Henry (2008) predicted an increasing frequency of freeze–thaw cycles in Canada. Consequently, plant residue associated with crop land use potentially plays an important role in nutrient losses, particularly in P losses, to surface waters during snowmelt runoff.

On the Canadian Prairies, snowmelt runoff accounts for the majority of annual runoff and represented approximately 70% of annual runoff and nutrient losses in a study of South Tobacco Creek (STC) watershed in Manitoba (Glozier et al., 2006). Under snowmelt runoff circumstances, Cade-Menun et al. (2013) compared nutrient exports between an annual crop and a perennial pasture that was dominated by smooth bromegrass (*Bromus inermis* L.) and concluded that total N was significantly higher in the annual crop than the pasture but total P was not different between the two systems. Cropping systems in the Lake Winnipeg watershed are dominated by a cereal (e.g., wheat [*Triticum aestivum* L.], barley [*Hordeum vulgare* L.], and oat [*Avena sativa* L.]) and oilseed (e.g., canola [*Brassica napus* L.] and flax [*Linum usitatissimum* L.]) rotation. In Manitoba, where Lake Winnipeg is situated, annual crops including cereal and oilseed crops accounted for approximately 68% of the agricultural land use in 2006 and 70% in 2011 (Manitoba Agriculture, Food and Rural Initiatives, 2011). Perennial alfalfa (*Medicago sativa* L.) and alfalfa mixtures comprise the third largest crop group, accounting for 15% of the agricultural land use in 2006 and 13% in 2011. However, there is little information comparing nutrient export in snowmelt runoff between annual cropland and perennial forage hay land not impacted by manure. Conservation initiatives on the Canadian Prairies are attempting to reverse the decline in acreage of forage land by promoting conversion of annual cropland to perennial forages. Therefore, it becomes important to determine how this initiative will impact nutrient exports during snowmelt runoff.

A previous assessment at the Steppler subwatershed in the STC watershed in Manitoba demonstrated reduced N and P exports as a result of the collective effects of five beneficial management practices (BMPs), including conversion of annual cropland to perennial forages receiving no manure, but the impact of the individual BMPs was not reported (Li et al., 2011). The objective of this study was to evaluate the effectiveness of the conversion of annual cropland to perennial forage as a BMP to reduce the exports of nutrients and sediment in snowmelt runoff.

Materials and Methods

Watershed Description

The study was performed at the Steppler subwatershed in the STC basin, southern Manitoba, Canada (49°20′ N, 98°22′ W). Soils in the watershed are classified as Dark Gray Chernozems (Boralfic Borols). The climate is subhumid continental and characterized by long, cold winters (Environment Canada, 2014). 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 Li et al. (2011).

Experimental Design

The study site consists of five fields: Field 3 (F3), Field 4 (F4), Field 7 (F7), Field 9 (F9), and Field 10 (F10) (Fig. 1). In F3 and F9, annual crops were planted in 2005 for the first 5 yr (2005–2009); those fields were converted to perennial forages (a mixture of alfalfa and timothy [*Phleum pratense* L.] grass) in the last 3 yr (2010–2012) (Table 1). In contrast, F4 and F7 were planted to and remained as perennial forages from 2005 to 2009 and were converted to annual crops from 2010 to 2012. In 2009, forages were underseeded to cereals in F3 and F9 in the spring, while forage crops in F4 and F7 were tilled after they were sprayed with a nonselective herbicide in the fall. Field 10 was a control field planted with annual crops from 2005 to 2012. Anhydrous NH_3 fertilizer was applied to the annual crop fields using an anhydrous rig with knives before seeding in May, with the exception of 2006 and 2007 when anhydrous NH_3 was applied in late October of the previous year. Diammonium phosphate was side-banded during the seeding operation. Fertilizer application rates were based on soil test recommendations. Detailed information about crops and fertilizer application rates is given in Table 1.

Soil Sampling and Analyses

Each fall after crop harvest, soil samples were collected in F3 and F4 at two depths, 0 to 5 cm and 0 to 15 cm. In each field, soil samples were collected from four transects. Along each transect, three sampling sites corresponding to lower, middle, and upper slopes were randomly selected and GPS coordinates were recorded for future sampling reference. Each fall, one composite soil sample was taken at each sampling site, resulting in 12 soil samples per depth per field. Soil samples were sent to AgVise Laboratories (Northwood, ND) to determine water-extractable soil NO_3–N in the 0- to 15-cm soil layer (1:2.5 soil/water) using a modified Technicon auto analyzer and $NaHCO_3$–extractable (Olsen) P in the 0- to 5-cm soil layer (1:10 soil/Olsen extracting solution) using a FiaLab 2500 (Missouri Agricultural Experiment Station, 2012).

Runoff Water Sampling and 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 a diurnal hydrograph, with less or no flow at night. A v-notched weir or circular flume was installed at the lower edge of the field to monitor runoff. The edge-of-field runoff monitoring started in 2005 for F7, F9, and F10 and in 2010 for F3 and F4. An autosampler (Sigma 800SL) controlled by a datalogger sampled water at the outlet of the weirs or flumes during runoff, and occasional supplementary grab samples were taken. The procedures for the measurement of hydrologic variables of runoff, and water sampling and laboratory analyses were detailed by Tiessen et al. (2010) and Liu et al. (2013b). Briefly, runoff was monitored at 5-min intervals

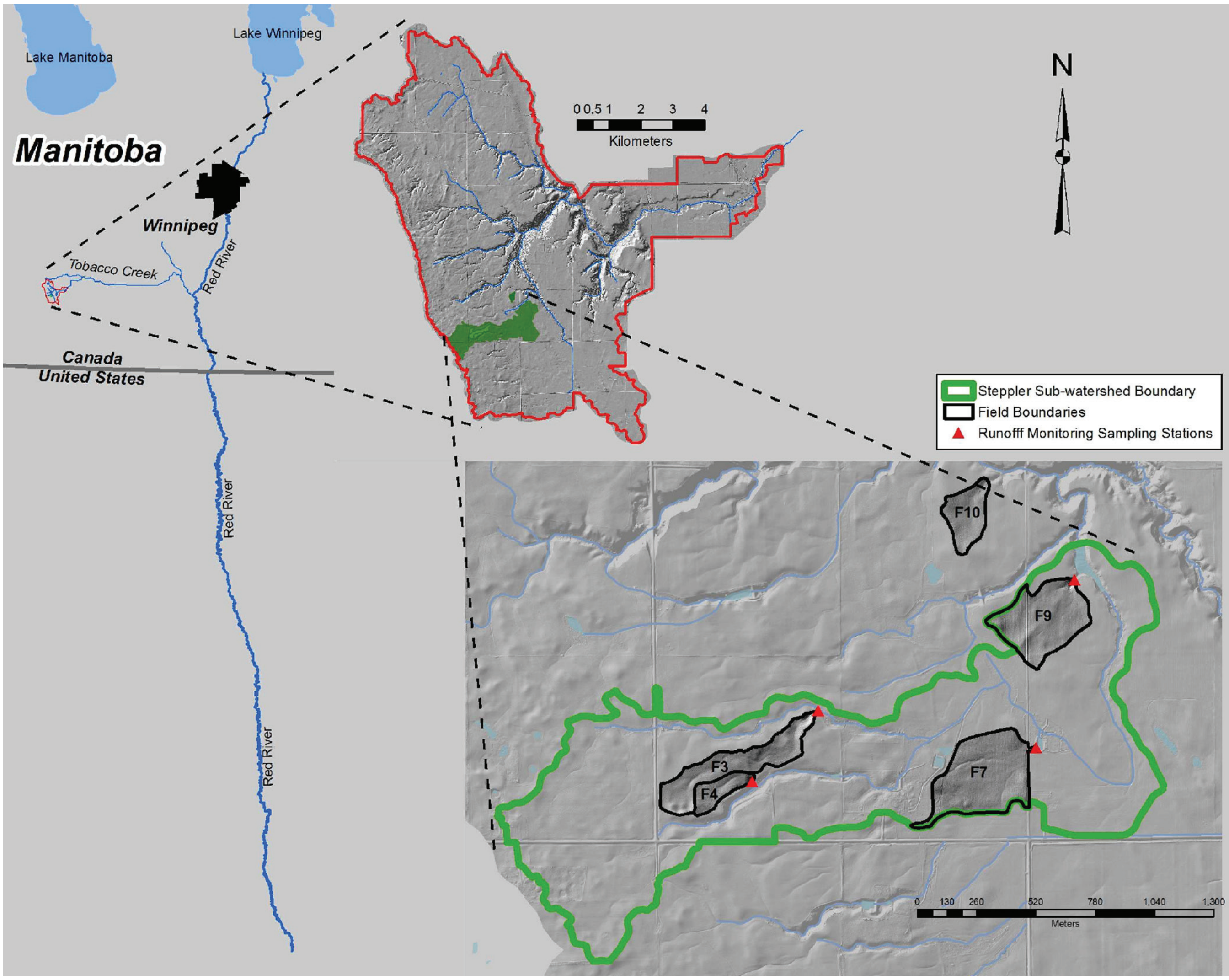

Fig. 1. Map of the study South Tobacco Creek watershed showing locations of treatment fields (F3, F4, F7, and F9) and a control field (F10).

at the lower edge of fields using v-notched weirs or circular flumes in conjunction with a datalogger (CR10X0, Campbell Scientific) and an ultrasonic depth instrument (SR50, Campbell Scientific). The volume of runoff was expressed as runoff yield (volume per unit of watershed area). The concentrations of total ammonia including ionized and un-ionized ammonia N (NH_3), NO_3^-–N + NO_2^-–N (NO_x), total N (TN), total dissolved N (TDN), total P (TP), total dissolved P (TDP), and sediment were determined using standard methods as described by Tiessen et al. (2010). Loads of nutrient and sediment were calculated as the product of flow volumes (m^3) and nutrient concentrations (mg L^{-1}) and summed for a given time period of runoff. The flow-weighted mean concentrations (FWMCs) of nutrients and sediment were calculated by dividing the nutrient load by the corresponding volume of runoff.

Crop Residue Sampling and Analyses

Crop residue in F3 and F4 was collected at the same sites where soil samples were collected. At each slope position, two subsamples of crop residue (0.25 m^2 area: 0.5 by 0.5 m) were collected in November before snowfall and formed one composite sample. A representative sample of the residue at each slope position (25% of the subsample weight corresponding to 0.0625 m^2) was cut into lengths of approximately 10 cm and placed into a polyethylene bag. Assuming 30 mm of runoff on an area basis, 1.875 L of deionized water 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 that all residues were in contact with water. After 24-h storage at room temperature, the bags were placed in a freezer at −20°C for a period of 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 leachate (500 mL) was gently decanted into a plastic storage bottle for analyses. Residue extracts were analyzed for TDN and TDP at Fisheries and Oceans Canada's Freshwater Institute Laboratory, using the same methods as those described above for the runoff water samples. Release of TDN and TDP by crop residue after the freeze–thaw cycle was calculated and reported on a kilogram per hectare basis (Liu et al., 2014).

Table 1. Summary of crop and N and P application rates on study fields in the South Tobacco Creek watershed, 2005 to 2012.

Field	Year	Crop	Application rate	
			N	P
			kg N ha^{-1}	kg P ha^{-1}
F3	2005	flax	54	0
	2006	spring wheat	73	5
	2007	canola	123	10
	2008	spring wheat	95	5
	2009	oat + forage	56	0
	2010	forage (mixture of alfalfa and grass)	0	0
	2011	forage	0	0
	2012	forage	0	0
F4	2005	forage	54	0
	2006	forage	0	0
	2007	forage	0	0
	2008	forage	0	0
	2009	forage	0	0
	2010	canola	112	10
	2011	spring wheat	85	15
	2012	canola	103	15
F7	2005	forage	54	0
	2006	forage	0	0
	2007	forage	0	0
	2008	forage	0	0
	2009	forage	0	0
	2010	spring wheat	95	5
	2011	canola	105	15
	2012	spring wheat	91	10
F9	2005	oat	56	0
	2006	flax	56	0
	2007	barley	90	5
	2008	canola	109	5
	2009	oat + forage	56	0
	2010	forage	0	0
	2011	forage	0	0
	2012	forage	0	0
F10	2005	barley	67	0
	2006	canola	78	5
	2007	spring wheat	185	5
	2008	canola	13	5
	2009	spring wheat	90	5
	2010	canola	112	10
	2011	spring wheat	90	15
	2012	canola	103	15

Statistical Analyses

Analysis of Variance

Fields located physically together show more similarity than fields located farther apart; therefore, F3 and F4 were grouped into one block and F7 and F9 into another spatial block. The entire study was divided into two periods: the first study period was from 2005 to 2009 and the second study period was from 2010 to 2012, resulting in a total of four spatial × temporal blocks. Because runoff data at F3 and F4 were collected only in the second period, only three blocks of runoff data were analyzed using the PROC MIXED procedure of SAS (SAS Institute, 2008), with random blocks and fixed treatments (i.e., AC and PF). Runoff data collected in the early spring of 2005 at F7 and F9 were excluded from the analysis because these data were collected before forage seeding in 2005. A paired *t* comparison was conducted for the soil nutrient data and water-extractable nutrients from the frozen and thawed crop residue collected from F3 and F4.

Analysis of Covariance

Analysis of covariance (ANCOVA) can be used to determine sequential management practice 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). An ANCOVA was used in this study using variables in the control watershed as covariates. Because there were no runoff data collected at F3 and F4 during the first study period, no ANCOVA was conducted for data collected at F3 and F4. To perform ANCOVA analysis, F7 and F10 were considered one pair, regarding F7 as a treatment field and F10 as a control field. Similarly, F9 and F10 were another pair, with F9 being a treatment field and F10 being a control. For ANCOVA, snowmelt runoff was separated into smaller events according to matched hydrographs for each set of paired fields (Tiessen et al., 2010). Because separate ANCOVA for each paired field generated similar results, the results of ANCOVA using the combined two pairs is reported. An ANCOVA assumes linear relationships between the covariates and the variables of interest and parallel slopes (homogeneity of regression) between the compared regression lines. For variables that met these assumptions, ANCOVA was conducted.

A full ANCOVA model, including the interaction term (covariate × crop conversion), was used with PROC GLM of SAS (SAS Institute, 2008). When the interaction effect was significant, signaling a significant difference between the AC and PF treatments, no further ANCOVA was conducted. In this case, the amount of the difference between the AC and PF treatments was expressed as a percentage change (Li et al., 2011) and was calculated as

$$\%\text{change} = \frac{\overline{Y}_{\mathrm{PF}} - \overline{Y}_{\mathrm{AC}}}{\overline{Y}_{\mathrm{AC}}} 100$$

where $\overline{Y}_{\mathrm{PF}}$ is the average of the predicted values in the perennial forage treatment and $\overline{Y}_{\mathrm{AC}}$ is the average of the predicted values in the annual crop treatment.

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 used to test for differences in *Y* intercept values. The adjusted means were computed using the LSMEANS statement and are reported when there was a significant difference between the AC and PF treatments.

For each response variable, the validity of model assumptions (normal distribution and constant variance of the error term) was verified by examining the residuals. Data transformations (e.g., square root or logarithmic transformation) were applied to the response variables with violated assumptions, and back-transformed data are reported. Due to the large degree of variability associated with field-scale studies, the significance threshold for *P* values was set as 0.1 unless otherwise stated.

Results and Discussion

Soil Test Nitrogen and Phosphorus

During the first study period (2005–2009), soil NO_3–N in the top 15 cm of soil was significantly (P = 0.03) greater for AC than for PF treatments, with 119% more N in the AC field (5.9 mg kg^{-1}) than in the PF field (2.7 mg kg^{-1}) (Fig. 2A). Similarly, during the second study period (2010–2012) soil NO_3–N was also significantly (P = 0.07) greater in the AC field (9.5 mg kg^{-1}) than in the PF field (4.6 mg kg^{-1}). Greater soil NO_3–N in the AC treatment was probably due to a combination of factors, including N fertilizer inputs and enhanced soil N mineralization in response to tillage in the AC treatment, as well as late-season N uptake by perennial forage. First, following the usual practices for the study area, annual cereal and oilseed crops relied heavily on adequate synthetic N fertilizer to achieve high yields, while no N fertilizer was applied to perennial forage. The yearly average N application rate in the AC treatment was 88 kg N ha^{-1}. The external N fertilizer input in the AC treatment probably contributed to the greater soil test N in the AC treatment. Second, annual crop fields in the second study period were converted from perennial forage (i.e., a mixture of alfalfa and grass) fields and inherited mineralizable N from the perennial forages. The N benefits of perennial forages to the succeeding crops are well documented (Kelner et al., 1997; Mohr et al., 1999). The preceding alfalfa forage in the current study led to a significant increase in soil NO_3–N from 2.7 to 9.5 mg kg^{-1} and resulted in a greater soil test N in the AC treatment. Due to N benefits from the preceding perennial forage, the difference in soil NO_3–N between the two treatments was larger in the second study period than in the first study period. Third, in the fall after the annual crop was harvested, the regrowth of perennial alfalfa probably decreased soil N because perennial alfalfa can effectively utilize excessive soil N (Entz et al., 2001). Effective N uptake by perennial forage plants in part decreased soil NO_3–N in the PF treatment. Finally, tillage promotes mineralization of organic N by increasing aeration and creating contact between soil organisms and soil organic matter, potentially increasing the mineralization of N (Tiessen et al., 2010). Enhanced soil N mineralization in response to fall tillage might partially explain higher N in the AC treatment.

In contrast to soil NO_3–N, soil test P in the 0- to 5-cm soil depth was not different between the AC and PF treatments (P = 0.66 for the first period and 0.19 for the second period) (Fig. 2B). The average yearly P fertilizer input was 7.1 kg P ha^{-1} in the AC treatment during the entire study period (2005–2012). In comparison, no P fertilizer was applied in the PF treatment; however, the lack of any tillage operation in the PF treatment may have resulted in more stratification of surface soil P in the PF fields than in the AC fields. Both P fertilizer inputs in the AC treatment and no tillage in the PF treatment might explain the lack of a difference in soil test P between the AC and PF treatments. Across the entire study period in the study fields, the average agronomic soil Olsen P in the 0- to 15-cm soil depth was 19.8 mg kg^{-1}, which is rated as a very high soil P level according to the provincial soil fertility guide (Manitoba Agriculture, Food and Rural Initiatives, 2013). The high soil P level was another reason for the lack of difference in soil test P between the two treatments in the 0- to 5-cm soil. Although there was no significant difference in soil P between the AC and PF treatments, there was relatively less soil P in the PF treatment at the end of the study. In western Canada, forage hay was reported to remove up to 39 kg P^{-1} ha for the first cut and 24 kg P ha^{-1} for the second cut (Canadian Fertilizer Institute, 2001). In addition to no P fertilizer application in the PF treatment, the cumulative P removal by forage harvest as cut hay might be the main reason for decreased soil P in the PF fields at the end of the study. The decreased soil P in the PF treatment is consistent with the findings of Welsh et al. (2009), who reported a declining trend in soil P in forage haying production systems because of P removals as cut hay.

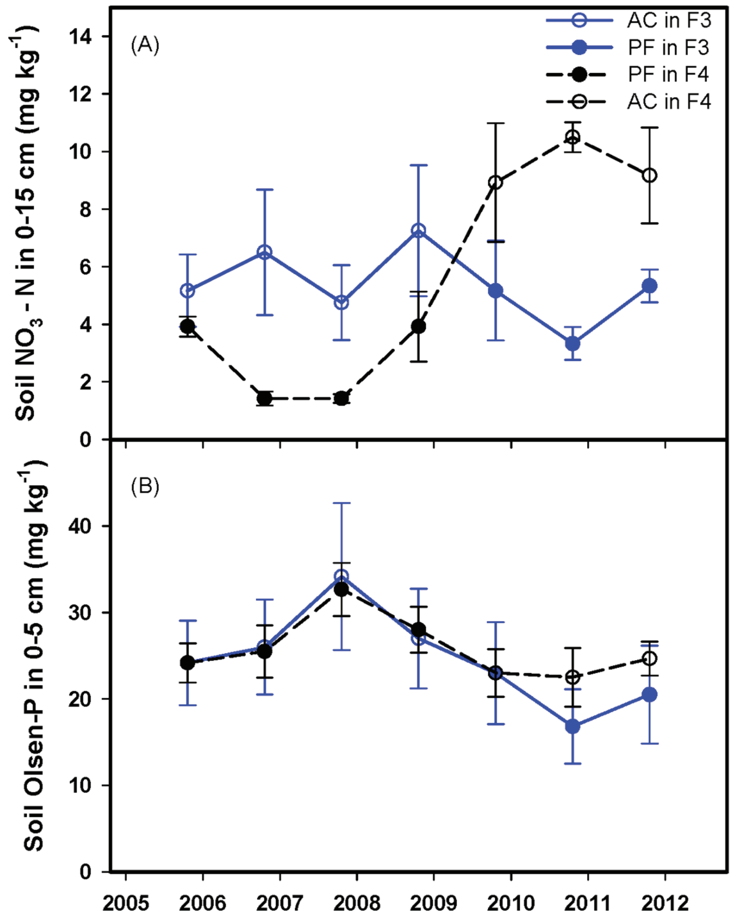

Fig. 2. Soil test (A) NO_3–N and (B) Olsen-extractable P as affected by the annual crop (AC) and perennial forage (PF) treatments in Field 3 (F3) and Field 4 (F4). Error bars are standard errors of the mean.

Water-Extractable Nitrogen and Phosphorus from Frozen and Thawed Crop Residue

Water-extractable N from frozen and thawed crop residue was significantly (P < 0.01) greater in the PF treatment (16.5 kg ha^{-1}) than in the AC treatment (0.7 kg ha^{-1}) (Fig. 3A). Similar to water-extractable N, there was significantly (P < 0.01) more water-extractable P in the residue from the PF treatment (3.8 kg ha^{-1}) than from the AC treatment (0.2 kg ha^{-1}) (Fig. 3B). Previous studies measured increased N and P releases from crop

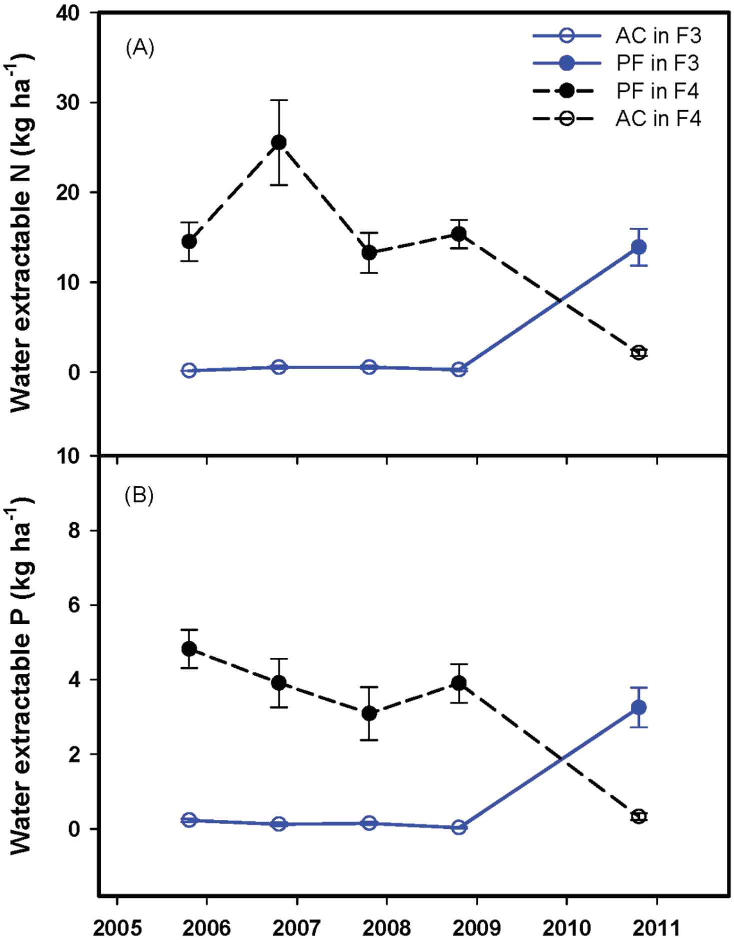

Fig. 3. Water-extractable (A) N and (B) P from frozen and thawed plant residue for the annual crop (AC) and perennial forage (PF) treatments in Field 3 (F3) and Field 4 (F4). Error bars are standard errors of the mean.

residue as a result of the rupture of plant cells caused by multiple freeze–thaw cycles (Miller et al., 1994; Bechmann et al., 2005; Roberson et al., 2007). The greater water-extractable N and P from the frozen and thawed residue in the PF treatment than the AC treatment was attributed to the difference in residue biomass and plant species. The forage regrowth after hay cutting in the PF treatment and the fall tillage operation in the AC treatment together probably resulted in greater residue biomass left on the soil surface in the PF treatment. In addition, the amounts of N and P release from plant vegetation have been shown to be different among vegetation species and were highly correlated with nutrient concentration in plant vegetation (Elliott, 2013; Liu et al., 2013a). In a simulated snowmelt study, P released from established perennial alfalfa was significantly higher than from annual crop residues left after growing wheat, barley, and canola (Elliott, 2013). Actively growing vegetation generally has a higher moisture content that contributes to greater nutrient release on freezing than senesced annual crop residue (Elliott, 2013). Post-harvest growth of annual crops is negligible when compared with perennial alfalfa that would still be actively growing in the fall of the year, explaining the higher water-extractable N and P in the PF treatment. Because water-extractable N and P in plant vegetation are important N and P sources in runoff, greater quantities of water-extractable nutrients in the PF treatments increase the potential for export of N and P during subsequent runoff during snowmelt.

Volume of Runoff

The results of ANOVA using data collected from replicated treatment fields (F3, F4, F7, and F9) indicated that the annual volume of runoff (VolR) during snowmelt was not significantly different between the AC and PF treatments (Table 2), although the VolR in the PF treatment was slightly greater than in the AC treatment. The event-based VolR in the control field was highly correlated with the event-based VolR in the treatment field during each of the AC and PF study periods when converting AC to PF or converting PF to AC in the same treatment field (Table 3). The ANCOVA also indicated that there was no significant difference in event-based VolR between the AC and PF treatments when converting crops from one to the other (Table 4).

Although the numerical value for the mean VolR from AC (399 m^3 ha^{-1}) appeared to be less than from PF (591 m^3 ha^{-1}), the means were not statistically different, probably due to the large variation in VolR (SE = 138 and 158 m^3 $ha^{-1}$for the AC and PF treatments, respectively). Schilling et al. (2008) predicted that perennial grassland in central Iowa decreased VolR during rainfall runoff due to an increase in evapotranspiration compared with corn (*Zea mays* L.)-dominated fields. Under snowmelt runoff conditions, van der Kamp et al. (2003) reported that grassland reduced VolR compared with agricultural fields dominated by a rotation of cereal and summer fallow in the semiarid Canadian Prairies, and they attributed the decreased VolR in the grassland to an increase in water infiltration into the soil. The drier climate at their study site compared with our study site (i.e., 500 vs. 550 mm in precipitation) might amplify infiltration effects on reducing VolR. In addition, the current experimental fields were established on long-term cereal–oilseed fields and the newly introduced perennial forage had a shorter duration compared with the van der Kamp et al. (2003) study (maximum of 5 vs. >15 yr). Therefore, the soil macropores in PF fields might not have been well formed, and infiltration might not have played an important role in determining VolR during snowmelt runoff. Fall tillage implementation in the AC treatment probably not only reduced the soil moisture content before snowfall but also increased surface roughness and then water retention and infiltration, subsequently reducing VolR during spring snowmelt runoff. The VolR under snowmelt runoff conditions is also closely related to the capacity of crop residue to trap snow. Fang et al. (2010) reported that taller residue normally trapped more snow. In the current study, tillage operations each fall in the AC treatment buried most residues of cereal and oilseed crops; in contrast, tall alfalfa residue as a result of fall regrowth after the last cut of hay probably trapped more snow and explained the numerically higher VolR in the PF treatments. Similarly, Tiessen et al. (2010) reported no difference in VolR between conservation tillage and conventional tillage at the same study site.

Table 2. Analysis of variance *P* values and means of flow (volume of runoff), flow-weighted mean concentrations (FWMCs) and loads of total NH_3, $NO_3 + NO_2$ (NO_x), particulate N (PN), total dissolved N (TDN), total N (TN), particulate P (PP), total dissolved P (TDP), total P (TP), and sediment as affected by annual crop and perennial forage. The FWMCs of NO_x, PP, and sediment were double square root transformed; FWMCs of PN and loads of TDP and TP were logarithmically transformed; and FWMCs of TP and loads of PN, PP, and sediment were square root transformed. Back-transformed means are reported.

Treatment	Flow	FWMC									Load								
		NH_3	NO_x	PN	TDN	TN	PP	TDP	TP	Sediment	NH_3	NO_x	PN	TDN	TN	PP	TDP	TP	Sediment
	$m^3\ ha^{-1}$	mg L^{-1}									kg ha^{-1}								
Annual crop	387.7	0.36 b†	9.08 a	0.62	9.73 a	10.35 a	0.11	0.53 b	0.64 b	21.77	0.12 b	2.08 a	0.33	2.56	2.89	0.06	0.14 b	0.20 b	8.70
Perennial forage	590.6	1.25 a	1.46 b	0.87	4.86 b	5.73 b	0.16	0.81 a	0.97 a	11.97	0.75 a	0.96 b	0.38	2.73	3.11	0.07	0.45 a	0.52 a	4.71
										P value									
	0.15	<0.01	<0.01	0.40	0.01	0.02	0.28	0.06	0.04	0.18	0.01	0.07	0.56	0.86	0.84	0.49	0.06	0.08	0.40

† Means within a column followed by a different letter are significantly different at the 0.1 significance level.

Concentrations and Loads of Mineral Nitrogen in Runoff

The ANOVAs were performed using the annual-based data during the entire snowmelt runoff and compared the two treatments replicated twice at four fields across 8 yr, while the ANCOVAs were performed using the event-based data and compared the two treatments as a result of crop conversion at a single treatment field. The ANOVA showed that the annual FWMC of NH_3 during the entire snowmelt was 247% greater for the PF treatments than for the AC treatment ($P < 0.01$; Table 2). Similarly, the ANOVA indicated that the annual load of NH_3 during snowmelt was significantly greater in the PF treatment than in the AC treatment (Table 2). Compared with the AC treatment, the PF treatment had an increased annual load of NH_3 in the snowmelt by 525% (from 0.12 to 0.75 kg ha^{-1} yr^{-1}). The event-based loads of NH_3 were highly correlated between the control and treatment fields during each of two study periods corresponding to the two treatments in the same treatment field during the crop conversion (Table 3). Like the ANOVA, the ANCOVA also indicated that the load of NH_3 was significantly greater for the PF treatment than for the AC treatment (Table 4; Fig. 4). According to the average of predicted values obtained from ANCOVA, the event-based load of NH_3 increased from 0.04 kg ha^{-1} $event^{-1}$ in the AC treatment to 0.16 kg ha^{-1} $event^{-1}$ in the PF treatment. The significantly greater FWMC of NH_3 in the PF treatment, together with the numerically greater VolR, explained the greater load of NH_3.The statistical results from these two analyses support each other, indicating that similar effects of treatments can be determined by either annual-based or event-based data or determined by either spatial (e.g., multiple sites) or temporal (e.g., two study periods at one field) data.

The significantly greater FWMC and load of NH_3 in the PF treatment was mainly attributed to significantly greater N release from forage residue. Summaries across multiple watersheds worldwide suggested that NH_3 export in runoff was highly related to organic N export (Alvarez-Cobelas et al., 2008). In a simulated snowmelt freeze–thaw study, Elliott (2013) also reported that N released by crop residue was mainly as dissolved organic N and NH_3. With respect to NH_3 release among different crop species, perennial alfalfa residue released significantly more NH_3 than residues of harvested cereal and oilseed crops (Elliott, 2013). In addition, Su et al. (2010) reported that the freeze–thaw process increased the concentration of NH_4^+–N considerably compared with the unfrozen control for soils amended with legume residue, suggesting that the freeze–thaw process accelerated legume NH_4^+ release.

The ANOVA showed that the AC treatment resulted in a 5.2-fold increase in the annual FWMC of NO_x during the entire snowmelt compared with the PF treatment ($P < 0.01$; Table 2). With respect to the load of NO_x, both ANOVA and ANCOVA showed that loads were significantly smaller in the PF treatment than in the AC treatment. The ANOVA showed that the AC treatment increased the annual load of NO_x by 117% relative to the PF treatment ($P = 0.07$), and the ANCOVA indicated that the PF treatment significantly decreased the event-based load of NO_x by 64% compared with the AC treatment. Nitrogen fertilizer inputs and enhanced mineralization of soil N resulting from tillage were probably the main reasons for the significantly greater FWMC and load of NO_x in the AC treatment. Soil

Table 3. Correlation coefficients between the control and treatment fields for flow (volume of runoff) and flow-weighted mean concentrations (FWMCs) and loads of total NH_3, NO_3 + NO_2 (NO_x), particulate N (PN), total dissolved N (TDN), total N (TN), particulate P (PP), total dissolved P (TDP), total P (TP), and sediment during the annual crop and perennial forage periods.

Treatment	Flow	FWMC									Load								
		NH_3	NO_x	PN	TDN	TN	PP	TDP	TP	Sediment	NH_3	NO_x	PN	TDN	TN	PP	TDP	TP	Sediment
Annual crop phase	0.66*	0.72*	0.51*	0.21	0.25	0.23	0.06	0.47†	0.55*	0.56*	0.59*	0.57*	0.38†	0.60*	0.53*	0.45†	0.51*	0.42†	0.74*
Perennial forage phase	0.41†	0.05	0.08	0.13	−0.01	−0.01	0.27	0.83*	0.74*	−0.15	0.75*	0.41†	0.37†	0.40†	0.41†	0.54*	0.86*	0.81*	−0.01

* Significant at a *P* level of 0.05.

† Significant at the *P* level of 0.1.

Table 4. Full and reduced analysis of covariance (ANCOVA) *P* values that show the effects of treatment (annual crop vs. perennial crop) on flow (volume of runoff) and flow-weighted mean concentrations (FWMCs) and loads of total NH_3, NO_3 + NO_2 (NO_x), particulate N (PN), total dissolved N (TDN), total N (TN), particulate P (PP), total dissolved P (TDP), and total P (TP) using variables collected in the control field as covariates.

Parameter	Flow	FWMC		Load							
		TDP	TP	NH_3	NO_x	PN	TDN	TN	PP	TDP	TP
						Full model of ANCOVA					
Treatment (Trt)	0.89	<0.01	0.06	0.17	0.25	0.38	0.48	0.41	0.36	0.22	0.23
Covariate	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Trt × Covariate	0.67	<0.01	<0.01	0.03	0.01	0.50	0.53	0.45	0.47	0.01	0.02
						Reduced model of ANCOVA					
Treatment	0.17	NA†	NA	NA	NA	0.33	0.65	0.63	0.31	NA	NA
Covariate	<0.01	NA	NA	NA	NA	<0.01	<0.01	<0.01	<0.01	NA	NA

† NA, not applicable.

NO_3–N concentrations (discussed above) were significantly greater in the AC than PF treatment and were probably the main contributors to the greater NO_x in the AC treatment. Although there was a large amount of forage residue in the PF treatment, NO_3–N released from crop residue has been shown to be relatively small compared with NH_4^+ and organic N (Elliott, 2013). Therefore, NO_x released from forage residue would not make a substantial contribution to NO_x in runoff. In addition, perennial forages increase soil C sequestration compared with annual row crops (Olmstead and Brummer, 2008). In a simulated snowmelt freeze–thaw study, dissolved C released from alfalfa residue was significantly greater than from the residues of harvested wheat or canola (Elliott, 2013). Another factor is the greater water-extractable C concentration in a perennial forage crop system than in an annual crop system, as reported by Xu et al. (2013). Tatti et al. (2014) reported substantial N_2O emissions during the winter period in snow-covered agricultural soils. Therefore, greater a water-soluble C supply in the PF treatment probably accelerated denitrification under wet conditions during the runoff period and contributed to lowering the NO_x concentration in the PF treatment.

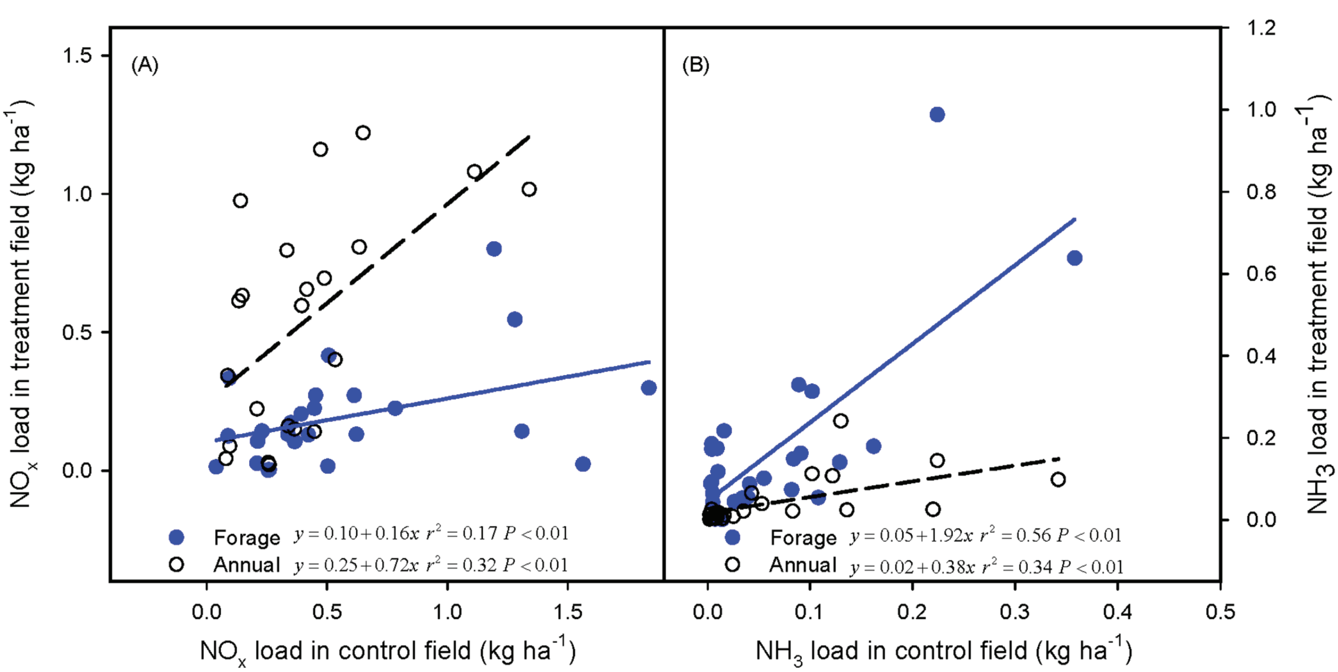

Fig. 4. Relationships between control and treatments for N load of (A) NO_x and (B) NH_3 during the perennial forage and annual crop phases in the same field.

Concentrations and Loads of Total Dissolved Nitrogen and Total Nitrogen

The annual FWMCs of TDN and TN during the entire snowmelt were 50 and 45% smaller, respectively, in the PF treatments than in the AC treatments (P = 0.01 and 0.02, respectively; Table 2). However, the annual loads of TDN and TN during the entire snowmelt were not significantly affected by the AC and PF treatments (P = 0.86 and 0.84, respectively). The lower FWMCs of TDN and TN in the PF treatment were due in large part to less soil test NO_3–N and to the dilution effects by the numerically greater VolR.

Mineral N (NO_x and NH_3) losses represented 86% of TDN and 76% of TN losses in the AC treatment and 63% of TDN and 56% of TN in the PF treatment, demonstrating that mineral N was the major N lost during snowmelt runoff. The relatively lower percentage of mineral N losses in the PF treatment suggested that a larger proportion of dissolved organic N was lost from the perennial forage, which was consistent with the findings of Elliott (2013). Alvarez-Cobelas et al. (2008) gathered N export data from 946 rivers worldwide and concluded that organic N export comprised the main fraction of N export to streams. The difference between our study and that of Alvarez-Cobelas et al. (2008) can be explained by the fact that our study was conducted during snowmelt while the majority of data gathered by Alvarez-Cobelas et al. (2008) were from rainfall runoff. Two previous studies conducted at the current study watershed also reported that >50% of TN losses were in an inorganic form (NO_x and NH_3) during snowmelt runoff (Tiessen et al., 2010; Li et al., 2011). As discussed above, NO_x loss was greater in the AC than in the PF treatment, while NH_3 loss was greater in the PF than in the AC treatment. The counteracting treatment effects on NO_x and NH_3, which are the majority components of TDN and TN during snowmelt runoff, contributed to the lack of difference in TDN or TN losses between the AC and PF treatments. In addition, the numerically greater VolR in the PF treatment compensated for the lower FWMCs of TDN and TN and partially explained the lack of difference in the loads between treatments.

Studies in the U.S. Corn Belt (Schilling and Spooner, 2006; Olmstead and Brummer, 2008; Zhou et al., 2010) demonstrated that water quality impairment caused by intensive annual crop production could be ameliorated through conversion of annual crops to perennial forage. For example, studies in the U.S. Corn Belt showed that the NO_3–N concentration ranged from six to 14 times higher in a corn–soybean [*Glycine max* (L.) Merr.] cropping system than in a perennial alfalfa cropping system (Randall and Mulla, 2001). Total NO_3–N losses during a 4-yr period from a continuous corn field were 30 times higher than from a perennial alfalfa field (Randall et al., 1997). In addition to no or reduced synthetic fertilizer N input to perennials, fully developed perennial vegetation in the warmer region of the U.S. Corn Belt reduces soil and nutrient losses from erosion, reduces the volume of flow by increasing evapotranspiration (Schilling et al., 2008), and acts as a sink for uptake of N, thus effectively reducing N leaching losses (Schilling and Spooner, 2006; Zhou et al., 2010). However, there are significant differences in the environmental conditions between the U.S. Corn Belt and the current study region. For example, a large portion of N loading to surface water in the Corn Belt occurs through subsurface movement into tile drains and groundwater, mainly during rainfall runoff. In the study region, however, approximately 70% of annual runoff and nutrient losses occurred in the spring as snowmelt runoff (Glozier et al., 2006). The benefits of perennials on reducing N loss through tile drains were not observed in this study, which measured only surface runoff during snowmelt, and therefore the absence of an impact of conversion to PF on N load is not surprising.

Concentrations and Loads of Total Dissolved Phosphorus and Total Phosphorus in Runoff

The ANOVA showed that the annual FWMCs and loads of TDP and TP during the entire snowmelt were significantly greater for the PF treatments than for the AC treatments (Table 2). On an annual snowmelt runoff basis, the PF treatment increased the annual FWMCs of TDP by 53% (0.81 vs. 0.53 mg L^{-1}) and TP by 52% (0.97 vs. 0.64 mg L^{-1}) and increased the annual loads of TDP by 221% (0.45 vs. 0.14 kg ha yr^{-1}) and TP by 160% (0.52 vs. 0.20 kg ha yr^{-1}) relative to the AC treatment. On an event basis, both FWMCs and loads of TDP and TP were significantly correlated between the control and treatment fields during each of two crop conversion periods in the same treatment field (Table 3). Similar to the annual-based results evaluated by ANOVA, the ANCOVA indicated that event-based FWMC of TDP, FWMC of TP, load of TDP, and load of TP were significantly different between the AC and PF treatments represented by the two study periods in the same treatment field during crop conversion (Table 4; Fig. 5 and 6). According to the average of predicted values obtained from ANCOVA, the event-based FWMC of TDP increased by 60%, from 0.45 mg L^{-1} in the AC treatment to 0.72 mg L^{-1} in the PF treatment, the FWMC of TP increased by 41%, from 0.59 mg L^{-1} in the AC treatment to 0.83 mg L^{-1} in the PF treatment, the load of TDP increased by 100%, from 0.04 kg ha^{-1} $event^{-1}$ in the AC treatment to 0.08 kg ha^{-1} $event^{-1}$ in the PF treatment, and the load of TP increased by 100%, from 0.05 kg ha^{-1} $event^{-1}$ in the AC treatment to 0.10 kg ha^{-1} $event^{-1}$ in the PF treatment.

In the absence of differences in soil test P between the AC and PF treatments, the significantly greater losses of TDP and TP in the PF treatment were attributed to the numerically greater VolR and the significantly greater P release from the PF residue. Liu et al. (2013a) found that four freeze–thaw cycles led to up to a 40-fold increase in P release from young vegetation compared with a no-freeze–thaw control. In the same watershed, Tiessen et al. (2010) observed significantly greater P losses under conservation tillage than under conventional tillage during snowmelt runoff. They partially attributed the greater P losses to the greater biomass of crop residue under conservation tillage. Previous studies have shown that pasture land use often results in a large amount of P loss to streams (Alexander et al., 2008; Little et al., 2007; Lin et al., 2009), and such increased P losses are closely linked with manure deposition by grazing livestock. In the current study, the PF treatment received no manure or fertilizer and was not grazed; however, the large amount of alfalfa residue, particularly from actively regrowing alfalfa, was considered to be one of the main reasons for significantly greater P losses in the PF treatment. Compared with the AC treatment,

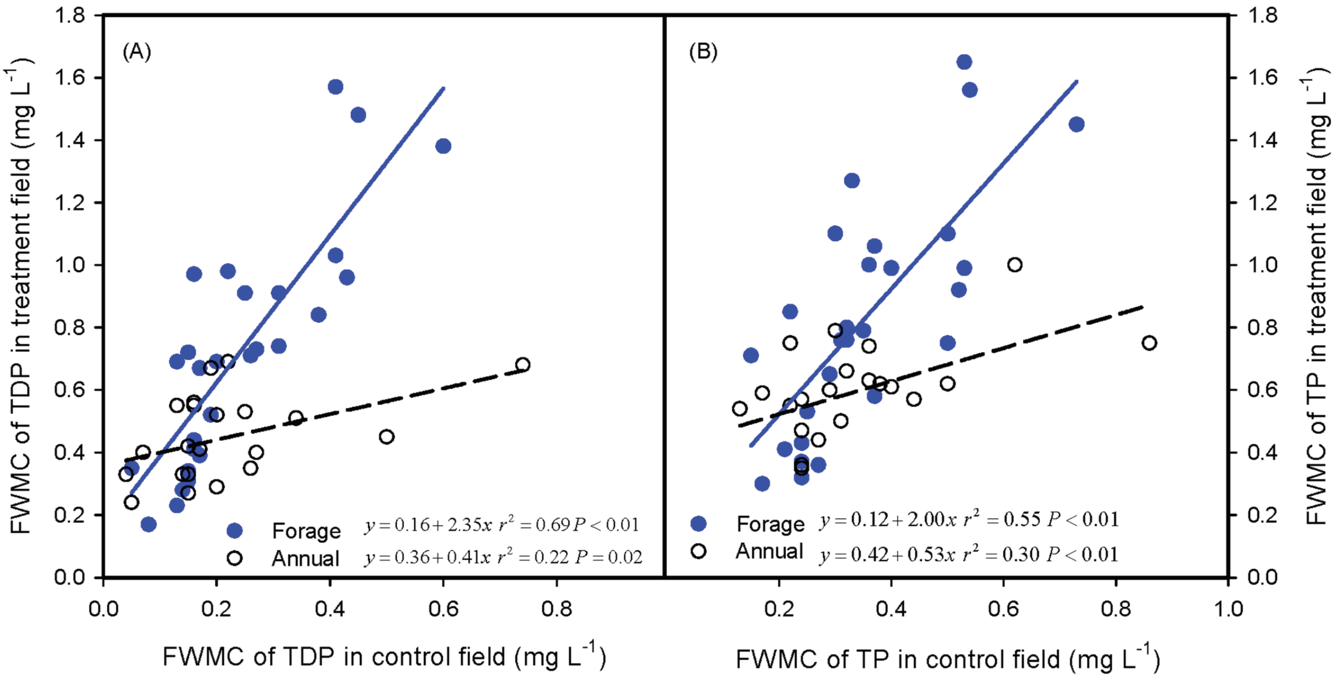

Fig. 5. Relationships between the control and treatments for flow-weighted mean concentration (FWMC) of P as (A) total dissolved P and (B) total P during the perennial forage and annual crop phases in the same field.

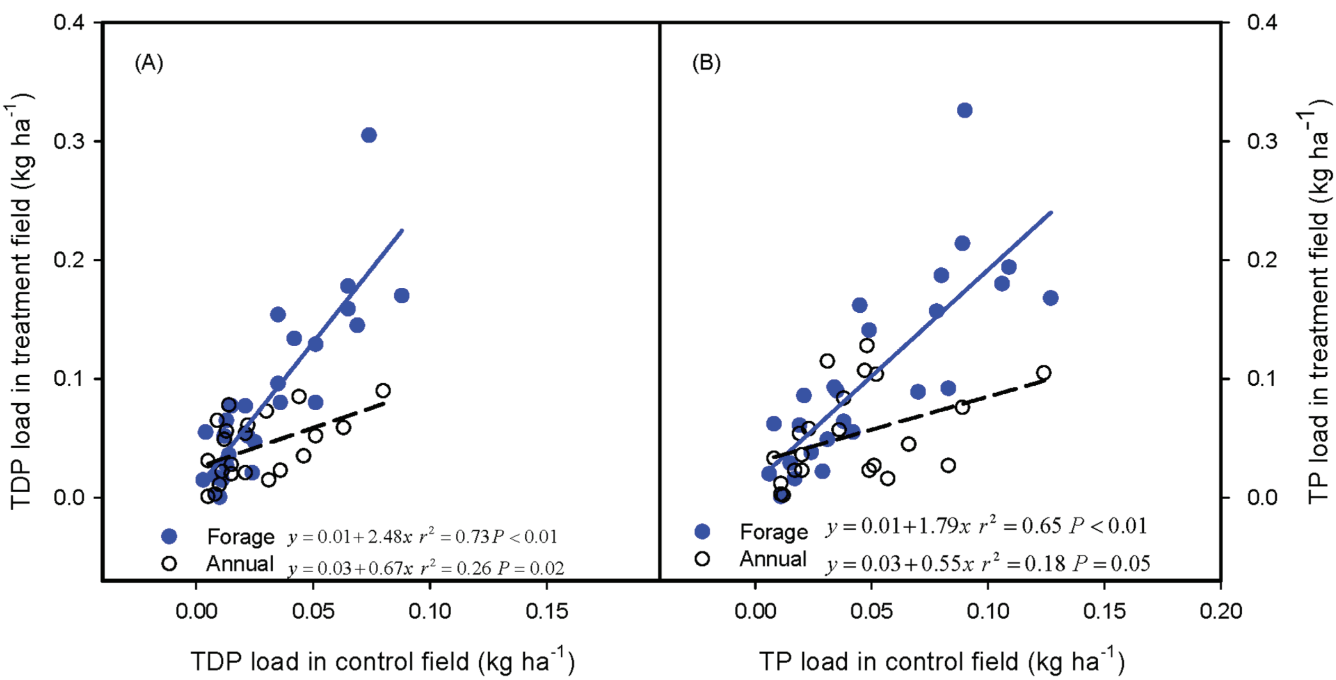

Fig. 6. Relationships between the control and treatments for load of P as (A) total dissolved P and (B) total P during the perennial forage and annual crop phases in the same field.

large quantities of P release from the forage residue under the freeze–thaw field conditions justified the larger TDP and TP concentrations and loads.

The potential P release, as demonstrated by water-extractable P from the frozen and thawed alfalfa residue conducted in the laboratory, under frozen conditions was much higher than TDP export under field conditions (3.79 vs. 0.45 kg ha^{-1}), indicating that only a portion of the potential P release was transported beyond the field boundary. In a laboratory study conducted under typical snowmelt conditions, Elliott (2013) reported that P released from crop residue can be adsorbed by the underlying soil. Soil sorption, reduced snow–residue contact under field conditions, and loss of nutrients released by freeze–thaw before snow accumulation would account for the difference between the potential P release by the PF residues in the laboratory and the P loss observed under field conditions in our study.

Concentrations and Loads of Particulate Nitrogen, Particulate Phosphorus, and Sediment in Runoff

The FWMCs and loads of particulate N, particulate P, and sediment were not affected significantly by the AC and PF treatments (Table 2; Table 4). During rainfall runoff in early spring or late fall, perennials can substantially reduce water erosion by providing soil cover compared with annual crops (Schilling and Spooner, 2006; Zhou et al., 2010). In the current study of snowmelt runoff, water erosion was very small, partly due to the gently sloping study region and because most of the snowmelt runoff occurred on soils that were at least partially frozen (Tiessen et al., 2010). This low rate of water erosion was the main reason for the lack of difference in particulate N, particulate P, or sediment between the AC and PF treatments.

Management Implications

Annual crop systems integrate tillage, fertilizer inputs, and residue management practices that are substantially different from those for perennial forage systems. Tillage and residue management affect hydrologic properties and thus modify the potential for nutrients to transport from fields to streams. In addition to soil, fertilizer inputs and residue management govern the nutrient source in runoff to a large extent but play different roles in the annual and perennial cropping systems. The application of synthetic fertilizer, along with mineralization of nutrients in crop residues and soil, appear to be the major source of nutrients in snowmelt runoff from conventionally tilled annual cropping systems, while frozen and thawed young forage residue is probably the major nutrient source in a perennial forage system. Both fertilizer and plant residues are controllable factors and can be managed to reduce nutrient losses. For example, minimizing fertilizer inputs in annual crop systems and the amount of forage residue left on the soil surface during winter might effectively reduce nutrient exports. Therefore, it is possible to reduce nutrient losses from agricultural cropland by properly managing fertilizer inputs and crop residues when developing beneficial management practices.

Conclusions

Both ANOVA (spatial comparison) and ANCOVA (temporal comparison) results indicated that the AC and PF treatments had no effects on the flow-weighted mean concentrations and loads of sediment and particulate forms of N and P under snowmelt runoff conditions, but had significant effects on the concentrations and loads of NH_3, NO_x, TDP, and TP. Release of NH_4^+ and P from thawing forage residue were the probable reasons for significantly greater concentrations and loads of NH_3, TDP, and TP in the PF treatment than in the AC treatment. In comparison, fertilizer N inputs and enhanced mineralization of soil N by tillage in the AC treatment were the probable causes for its significantly greater concentrations and loads of NO_x. Although the concentrations of TDN and TN were significantly greater in the AC treatment than in the PF treatment, neither the load of TDN nor the load of TN was different between the AC and PF treatments because of the numerically greater VolR in the PF treatment. The difference in nutrient exports between the AC and PF treatments was due to the combined effects of hydrology and nutrient and crop residue management. In a cold climate where multiple freeze–thaw cycles frequently occur, the contribution of nutrients in plant residues to nutrient losses from agricultural cropland during spring snowmelt runoff cannot be ignored. When nutrients are released from plant residues by freezing, the introduction of perennial forages to a crop rotation may increase P losses in surface runoff during snowmelt.

Acknowledgments

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References

Alexander, R.B., R.A. Smith, G.E. Schwarz, E.W. Boyer, J.V. Nolan, and J.W. Brakebill. 2008. Differences in phosphorus and nitrogen delivery to the Gulf of Mexico from the Mississippi River Basin. Environ. Sci. Technol. 42:822–830. doi:10.1021/es0716103

Alvarez-Cobelas, M., D.G. Angeler, and S. Sánchez-Carrillo. 2008. Export of nitrogen from catchments: A worldwide analysis. Environ. Pollut. 156:261–269. doi:10.1016/j.envpol.2008.02.016

Bechmann, M.E., P.J.A. Kleinman, A.N. Sharpley, and L.S. Saporito. 2005. Freeze–thaw effects on phosphorus loss in runoff from manured and catch-cropped soils. J. Environ. Qual. 34:2301–2309. doi:10.2134/jeq2004.0415

Bishop, P.L., W.D. Hively, J.R. Stedinger, M.R. Rafferty, J.L. Lojpersberger, and J.A. Bloomfield. 2005. Multivariate analysis of paired watershed data to evaluate agricultural best management practice effects on stream water phosphorus. J. Environ. Qual. 34:1087–1101. doi:10.2134/jeq2004.0194

Bourne, A., N. Armstrong, and G. Jones. 2002. A preliminary estimate of total nitrogen and total phosphorus loading to streams in Manitoba, Canada. Rep. 2002-04. Water Qual. Manage. Sect., Manitoba Conservation, Winnipeg, MB, Canada.

Cade-Menun, B.J., G. Bell, S. Baker-Ismail, Y. Fouli, K. Hodder, D.W. McMartin, et al.. 2013. Nutrient loss from Saskatchewan cropland and pasture in spring snowmelt runoff. Can. J. Soil Sci. 93:445–458. doi:10.4141/cjss2012-042

Canadian Fertilizer Institute. 2001. Nutrient uptake and removal by field crops. CFI, Ottawa, ON. http://www.cfi.ca/_documents/uploads/elibrary/d160_NU_E_01%5B1%5D.pdf (accessed 29 May 2014).

Clausen, J.C., W.E. Jokela, F.I.I. Potter, and J.W. Williams. 1996. Paired watershed comparison of tillage effects on runoff, sediment, and pesticide losses. J. Environ. Qual. 25:1000–1007. doi:10.2134/jeq1996.00472425002500050011x

Elliott, J. 2013. Evaluating the potential contribution of vegetation as a nutrient source in snowmelt runoff. Can. J. Soil Sci. 93:435–443. doi:10.4141/cjss2012-050

Entz, M.H., R. Guilford, and R. Gulden. 2001. Crop yield and soil nutrient status on 14 organic farms in the eastern portion of the northern Great Plains. Can. J. Plant Sci. 81:351–354. doi:10.4141/P00-089

Environment Canada. 2014. Historical climate data. Environ. Can., Fredericton, NB. http://climate.weather.gc.ca/ (accessed 31 July 2014).

Fang, X., J.W. Pomeroy, C.J. Westbrook, X. Guo, A.G. Minke, and T. Brown. 2010. Prediction of snowmelt derived streamflow in a wetland dominated prairie basin. Hydrol. Earth Syst. Sci. 14:991–1006. doi:10.5194/hess-14-991-2010

Glozier, N.E., J.A. Elliott, B. Holliday, J. Yarotski, and B. Harker. 2006. Water quality characteristics and trends in a small agricultural watershed: South Tobacco Creek, Manitoba, 1992–2001. Environment Canada, Ottawa, ON.

Henry, H.L. 2008. Climate change and soil freezing dynamics: Historical trends and projected changes. Clim. Change 87:421–434. doi:10.1007/s10584-007-9322-8

Kelner, D.J., J.K. Vessey, and M.H. Entz. 1997. The nitrogen dynamics of 1-, 2- and 3-year stands of alfalfa in a cropping system. Agric. Ecosyst. Environ. 64:1–10. doi:10.1016/S0167-8809(97)00019-4

Li, S., J.A. Elliott, K.H.D. Tiessen, J. Yarotski, D.A. Lobb, and D.N. Flaten. 2011. The effects of multiple beneficial management practices on hydrology and nutrient losses in a small watershed in the Canadian prairies. J. Environ. Qual. 40:1627–1642. doi:10.2134/jeq2011.0054

Lin, Z., D.E. Radcliffe, L.M. Risse, J.J. Romeis, and C.R. Jackson. 2009. Modeling phosphorus in the Lake Allatoona watershed using SWAT: II. Effect of land use change. J. Environ. Qual. 38:121–129. doi:10.2134/jeq2007.0111

Little, J.L., S.C. Nolan, J.P. Casson, and B.M. Olson. 2007. Relationships between soil and runoff phosphorus in small Alberta watersheds. J. Environ. Qual. 36:1289–1300. doi:10.2134/jeq2006.0502

Liu, J., R. Khalaf, B. Ulén, and G. Bergkvist. 2013a. Potential phosphorus release from catch crop shoots and roots after freezing–thawing. Plant Soil 371:543-557. doi:10.1007/s11104-013-1716-y

Liu, K., J.A. Elliott, D.A. Lobb, D.N. Flaten, and J. Yarotski. 2013b. Critical factors affecting field-scale losses of N and P in spring snowmelt runoff in the Canadian prairies. J. Environ. Qual. 42:484–496. doi:10.2134/jeq2012.0385

Liu, K., J.A. Elliott, D.A. Lobb, D.N. Flaten, and J. Yarotski. 2014. Conversion of conservation tillage to rotational tillage to reduce phosphorus losses during snowmelt runoff in the Canadian Prairies. J. Environ. Qual. doi:10.2134/jeq2013.09.0365

Manitoba Agriculture, Food and Rural Initiatives. 2011. Manitoba crop highlights: 2011 Census of agriculture. Manitoba Agric., Food and Rural Dev., Winnipeg, MB, Canada. http://www.gov.mb.ca/agriculture/market-prices-and-statistics/crop-statistics/pubs/crop_highlights_census.pdf (accessed 31 July 2013).

Manitoba Agriculture, Food and Rural Initiatives. 2013. Phosphorus recommendations for field crops based on soil test levels and placement. Manitoba Agric., Food and Rural Dev., Winnipeg, MB, Canada. http://www.gov.mb.ca/agriculture/crops/soil-fertility/soil-fertility-guide/fertilizer-guidelines-for-soil-tests.html#table17 (accessed 10 Jan. 2013).

McBroom, M.W., R.S. Beasley, M. Chang, and G.G. Ice. 2008. Water quality effects of clearcut harvesting and forest fertilization with best management practices. J. Environ. Qual. 37:114–124. doi:10.2134/jeq2006.0552

Miller, J.J., T. Curtis, and D.S. Chanasyk. 2013. Comparison of runoff quantity and quality under annual cropping and forages. Water Qual. Res. J. Canada 48:40–54. doi:10.2166/wqrjc.2013.013

Miller, M.H., E.G. Beauchamp, and J.D. Lauzon. 1994. Leaching of nitrogen and phosphorus from the biomass of three cover crop species. J. Environ. Qual. 23:267–272. doi:10.2134/jeq1994.00472425002300020007x

Missouri Agricultural Experiment Station. 2012. Recommended chemical soil test procedures for the North Central Region. North Central Regional Res. Publ. 221 (revised). Missouri Agric. Exp. Stn., Columbia. http://extension.missouri.edu/explorepdf/specialb/sb1001.pdf (accessed 29 May, 2014).

Mohr, R.M., M.H. Entz, H.H. Janzen, and W.J. Bullied. 1999. Plant-available nitrogen supply as affected by method and timing of alfalfa termination. Agron. J. 91:622–630. doi:10.2134/agronj1999.914622x

Nielsen, A., D. Trolle, M. Søndergaard, T.L. Lauridsen, R. Bjerring, J.E. Olesen, and E. Jeppesen. 2012. Watershed land use effects on lake water quality in Denmark. Ecol. Appl. 22:1187–1200. doi:10.1890/11-1831.1

Olmstead, J., and E.C. Brummer. 2008. Benefits and barriers to perennial forage crops in Iowa corn and soybean rotations. Renew. Agric. Food Syst. 2397–102. doi:10.1017/S1742170507001937

Randall, G.W., D.R. Huggins, M.P. Russelle, D.J. Fuchs, W.W. Nelson, and J.L. Anderson. 1997. Nitrate losses through subsurface tile drainage in Conservation Reserve Program, alfalfa, and row crop systems. J. Environ. Qual. 26:1240–1247. doi:10.2134/jeq1997.00472425002600050007x

Randall, G.W., and D.J. Mulla. 2001. Nitrate nitrogen in surface waters as influenced by climatic conditions and agricultural practices. J. Environ. Qual. 30:337–344. doi:10.2134/jeq2001.302337x

Roberson, T., L.G. Bundy, and T.W. Andraski. 2007. Freezing and drying effects on potential plant contributions to phosphorus in runoff. J. Environ. Qual. 36:532–539. doi:10.2134/jeq2006.0169

SAS Institute. 2008. SAS OnlineDoc 9.2. SAS Inst., Cary, NC.

Schilling, K.E., M.K. Jha, Y. Zhang, P.W. Gassman, and C.F. Wolter. 2008. Impact of land use and land cover change on the water balance of a large agricultural watershed: Historical effects and future directions. Water Resour. Res. 44:W00A09. doi:10.1029/2007WR006644

Schilling, K.E., and J. Spooner. 2006. Effects of watershed-scale land use change on stream nitrate concentrations. J. Environ. Qual. 35:2132–2145. doi:10.2134/jeq2006.0157

Su, M., K. Kleineidam, and M. Schloter. 2010. Influence of different litter quality on the abundance of genes involved in nitrification and denitrification after freezing and thawing of an arable soil. Biol. Fertil. Soils 46:537–541. doi:10.1007/s00374-010-0449-9

Tatti, E., C. Goyer, M. Chantigny, S. Wertz, B.J. Zebarth, D.L. Burton, and M. Filion. 2014. Influences of over winter conditions on denitrification and nitrous oxide-producing microorganism abundance and structure in an agricultural soil amended with different nitrogen sources. Agric. Ecosyst. Environ. 183:47–59. doi:10.1016/j.agee.2013.10.021

Tiessen, K.H.D., J.A. Elliott, J. Yarotski, D.A. Lobb, D.N. Flaten, and N.E. Glozier. 2010. Conventional and conservation tillage: Influence on seasonal runoff, sediment, and nutrient losses in the Canadian prairies. J. Environ. Qual. 39:964–980. doi:10.2134/jeq2009.0219

van der Kamp, G., M. Hayashi, and D. Gallén. 2003. Comparing the hydrology of grassed and cultivated catchments in the semi-arid Canadian prairies. Hydrol. Processes 17:559–575. doi:10.1002/hyp.1157

Welsh, C., M. Tenuta, D.N. Flaten, J.R. Thiessen-Martens, and M.H. Entz. 2009. High yielding organic crop management decreases plant-available but not recalcitrant soil phosphorus. Agron. J. 101:1027–1035. doi:10.2134/agronj2009.0043

Xu, N., H.F. Wilson, J.E. Saiers, and M. Entz. 2013. Effects of crop rotation and management system on water-extractable organic matter concentration, structure, and bioavailability in a Chernozemic agricultural soil. J. Environ. Qual. 42:179–190. doi:10.2134/jeq2012.0126

Zampella, R.A., N.A. Procopio, R.G. Lathrop, and C.L. Dow. 2007. Relationship of land-use/land-cover patterns and surface-water quality in the Mullica River basin. J. Am. Water Resour. Assoc. 43:594–604. doi:10.1111/j.1752-1688.2007.00045.x

Zhou, X., M.J. Helmers, H. Asbjornsen, R. Kolka, and M.D. Tomer. 2010. Perennial filter strips reduce nitrate levels in soil and shallow groundwater after grassland-to-cropland conversion. J. Environ. Qual. 39:2006–2015. doi:10.2134/jeq2010.0151