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Conventional and Conservation Tillage: Influence on Seasonal Runoff, Sediment, and Nutrient Losses in the Canadian Prairies

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Conservation tillage has been widely promoted to reduce sediment and nutrient transport from agricultural fields. However, the effect of conservation tillage on sediment and nutrient export in snowmelt-dominated climates is not well known. Therefore, a long-term paired watershed study was used to compare sediment and nutrient losses from a conventional and a conservation tillage watershed in the Northern Great Plains region of western Canada. During the treatment period, dissolved nutrient concentrations were typically greater during spring snowmelt than during summer rainfall events, whereas concentrations of sediment and particulate nutrients were greatest during rainfall events. However, because total runoff was dominated by snowmelt, most sediment and nutrient export occurred during snowmelt. Overall, conservation tillage reduced the export of sediment in runoff water by 65%. Similarly, concentrations and export of nitrogen were reduced by 41 and 68%, respectively, relative to conventional tillage. After conversion to conservation tillage, concentrations and exports of phosphorus (P) increased by 42 and 12%, respectively, with soluble P accounting for the majority of the exported P, especially during snowmelt. Our results suggest that management practices designed to improve water quality by reducing sediment and sediment-bound nutrient export from agricultural fields and watersheds can be less effective in cold, dry regions where nutrient export is primarily snowmelt driven and in the dissolved form. In these situations, it may be more appropriate to implement management practices that reduce the accumulation of nutrients in crop residues and the surface soil.

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Increasing nutrient enrichment of surface water bodies and the subsequent decline in water quality is an issue that is gaining greater recognition across North America, and the Canadian prairie province of Manitoba is no exception. Of particular concern is the health of Manitoba's largest lake, Lake Winnipeg. At approximately 24,500 km^2 in area, Lake Winnipeg is the sixth largest freshwater lake in Canada and the tenth largest in the world. The health of this aquatic ecosystem has deteriorated over the past three decades, with evidence pointing to excessive nutrient enrichment from nitrogen (N) and phosphorus (P) as the primary cause (Lake Winnipeg Stewardship Board, 2006). High concentrations of N and P for prolonged periods of time have the potential to fuel excessive plant growth (i.e., eutrophication) and cause significant changes to the community structure and biodiversity of higher trophic levels in freshwater and marine environments (Schindler, 1977; Sharpley et al., 1994; Leavitt et al., 2006). The majority of nutrients entering Lake Winnipeg come from nonpoint sources, including natural ecosystems, atmospheric deposition, and agricultural and urban activities (Lake Winnipeg Stewardship Board, 2006). To reduce the transport and delivery of N and P from agricultural watersheds that drain into Lake Winnipeg, it is critical to improve our understanding of how sediment and nutrient losses in the Lake Winnipeg watershed are related to land management, soil characteristics, topography, and local climatic conditions

Beneficial management practices (BMPs) (i.e., farming practices designed to minimize risk to the environment without sacrificing economic productivity) are often recommended to reduce agriculture's contribution to sediment and nutrient loading. Conservation tillage (e.g., zero-till, minimum tillage, incomplete tillage, reduced tillage, etc.), broadly defined as any tillage system with at least 30% of the residue from the previous crop remaining on the soil surface after seeding (Lal, 2003), is one BMP that has

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Abbreviations: BMP, beneficial management practices; FWMC, flow-weighted mean concentration; NO_x, nitrate + nitrite; PN, particulate nitrogen; PP, particulate phosphorus; SWE, snow water equivalent; TDN, total dissolved nitrogen; TN, total nitrogen; TDP, total dissolved phosphorus; TP, total phosphorus; TSS, total suspended sediment.

been widely promoted across Canada (Carter, 1994; Larney et al., 1994) and around the world (Lal, 2000; Holland, 2004). By influencing surface hydrology and water erosion, conservation tillage significantly reduces the transport of sediment and sediment-bound nutrients (and other contaminants) in surface runoff and waterways, especially during the critical period between planting and canopy development (e.g., Baker and Laflen, 1983; Fawcett et al., 1994; Sharpley et al., 1994). However, adverse effects of conservation tillage on dissolved nutrient export have also been reported. Numerous studies have reported that dissolved nutrient transport can be greater in surface runoff or ground water from conservation, reduced-till, or no-till systems than from conventional tillage systems (e.g., Baker and Laflen, 1983; McDowell and McGregor, 1984; Langdale et al., 1985; Sharpley and Smith, 1994; Bundy et al., 2001; Zhao et al., 2001; Daverede et al., 2003). Suggested reasons for higher soluble nutrient losses include (i) the stratification of nutrients at the soil surface due to reduced mixing of fertilizers or manures by tillage and (ii) the release of nutrients from plant residue that remains on the soil surface after harvest. Most previous studies, however, were conducted in humid regions of North America or Europe, where nutrient transport occurs predominantly through rainfall runoff and dissolved nutrient losses account for a small portion of the total loss. Therefore, despite higher losses of soluble nutrients, total nutrient loads were still, on average, significantly reduced using conservation tillage systems.

In cold-climate regions, snowmelt runoff often exceeds rainfall runoff during the course of a year, and the effects of conservation tillage on the export of nutrients from agricultural land during snowmelt runoff may not be the same as for rainfall-induced runoff. Snowmelt runoff is usually less erosive than rainfall-induced runoff (Ginting et al., 1998; Ulen, 2003) because snowmelt has lower kinetic energy than raindrops and occurs over soil that is often still frozen (Rekolainen et al., 1997). However, previous research in western Canada has reported that soil losses due to snowmelt can be greater than that due to rainfall (Chanasyk and Woytowich, 1987; van Vliet and Hall, 1991; McConkey et al., 1997). Plus, snowmelt runoff typically extends over a longer time period than individual rainfall runoff events, and the long duration of the soil–plant–water contact encourages soluble reactions. As a result, the loss of sediment, nutrients, and contaminants during the snowmelt period can be substantial in cold-climate regions common to North America (e.g., Hansen et al., 2002) and Northern Europe (e.g., Rekolainen et al., 1997). In the Canadian prairies, Glozier et al. (2006) reported that, on average, more than two thirds of the runoff flow and N and P export in south-central Manitoba occurred during the snowmelt period, with the majority of nutrients exported in dissolved form. Additional studies from the Canadian prairie province of Alberta also report that >90% of annual runoff was generated during the spring snowmelt (Little et al., 2007), with dissolved P in snowmelt waters being the dominant source of P export in that region (Ontkean et al., 2005; Little et al., 2006). Despite growing concerns over the contribution of dissolved nutrients to fresh surface waters in cold-climate regions (Ulen et al., 2007), there is relatively little information available regarding the quantitative effects of tillage in reducing sediment, N, or P losses in environments where snowmelt is a major component of annual runoff (Gaynor and Findlay, 1995; Ulen, 1997; Ginting et al., 1998; Lundekvam and Skoien, 1998; Hansen et al., 2000; Ulen, 2003; Puustinen et al., 2005; Thoma et al., 2005; Ulen and Kalisky, 2005; Lundekvam, 2007; Puustinen et al., 2007; Panuska et al., 2008). Plus, much of the available literature regarding conservation tillage and water quality may be less relevant to the Northern Great Plains region of the United States and Canada, a region characterized by neutral to high pH soil, relatively flat landscapes, low summer precipitation, and runoff processes dominated by snowmelt over frozen soils in the spring. The overall effectiveness of conservation tillage in reducing sediment and nutrient losses under these conditions is not well known.

In addition to testing BMPs within specific regions, the methodology used in testing the effectiveness of individual BMPs to reduce sediment and nutrient loading is also an important consideration. Conservation tillage BMPs have typically been tested at the plot scale, with their environmental and economic performance extrapolated to the larger field or watershed scale. Although plots are very useful in understanding processes and making treatment comparisons, plot scale testing may not address, or accurately predict, the entire suite of compounding variables that occur at the field or watershed scale (Park et al., 1994). The paired watershed approach (e.g., Spooner et al., 1985; Clausen and Spooner, 1993: Clausen et al., 1996; Loftis et al., 2001; Ranaivoson et al., 2005; Michaud et al., 2007) is recommended for use when assessing and comparing the effects that different management systems have on runoff and associated sediment and nutrient losses from a watershed, especially when replication is not practical. This approach has not been widely used in measuring the effectiveness of agricultural BMPs; however, it has been used for well over 50 yr in forestry research (Andreassian, 2004). Using paired watersheds, treatment effects are identified at the watershed scale, typically giving more representative results than those extrapolated from small plots to larger areas, and, most importantly, any changes in a water quality parameter can be attributed to the treatment alone rather than to differences in the watersheds (Clausen et al., 1996). Although tillage comparison studies have been conducted in cold-climate regions of Canada, the northern prairie states of the United States, and the Nordic countries of Europe, no previous research has looked specifically at the long-term impact of conventional and conservation tillage systems on water quality during spring snowmelt and summer rainfall periods at the watershed scale. Therefore, the objective of this study was to use a paired watershed approach to compare annual and seasonal runoff, sediment, and N and P losses from conventional and conservation tillage under conditions typical of the Northern Great Plains of western Canada.

Materials and Methods

Background Information and Study Area

The paired watershed method requires a minimum of two watersheds (control and treatment) and two periods of study (calibration and treatment). During the calibration period, the two watersheds are treated identically, and paired water quality data are collected. During the treatment period, one watershed is treated with the BMP, whereas the control watershed remains under the same management. At the end of the treatment period, an ANCOVA is used to compare the paired watersheds (Clausen et al., 1996).

In the current study, two adjacent/paired agricultural watersheds (Fig. 1) were monitored between 1993 and 2007. The paired watersheds are located in southern Manitoba, Canada (49°20′N, 98°22′W) near the town of Miami (approximately 150 km southwest of Winnipeg). They are within the larger South Tobacco Creek watershed, which is situated on the edge of the Manitoba Escarpment in the upper reaches of the Red River Valley. This region is referred to as the Pembina Hills Upland and is a transition area between the lower Manitoba Plain and the higher Saskatchewan Plain (Michalyna et al., 1988). Soils are primarily clay-loam and were formed on moderately to strongly calcareous glacial till that overlay shale bedrock. The dominant soil series in the study area are Dark Gray Chernozems (Mollisols). The climate is classified as subhumid continental with short, cool summers and long, cold winters. The mean annual temperature is ~3°C, and the mean annual precipitation is ~550 mm, of which 25 to 30% occurs as snow (Environment Canada, 2009). The two watersheds are 4.2 ha (conventional tillage or control watershed) and 5.1 ha (conservation tillage or treatment watershed) in area (Fig. 1). They were delineated using detailed topographic maps generated from aerial photos, Global Positioning Systems, and Light Detection and Ranging data. Both watersheds are north facing, with undulating landscapes and slope gradients of approximately 5%. To avoid confusion, the two watersheds are referred to as "conventional" and "conservation" regardless of the time period (i.e., pre- or postconversion).

Cropping and Tillage Practices

Agricultural activities that occurred in the paired watersheds are summarized in Table 1. During the preconversion or calibration period (1993–1996), both watersheds were managed using the same conventional tillage system and cropped with cereals and oilseeds. The sequence of conventional tillage operations typically included one primary tillage operation with a deep-tiller (in the spring or fall), one or two secondary tillage operations (usually a light cultivator, sometimes a tandem disc), and one or two harrowing (spring-tooth-harrow) operations. Fertilizer was applied at recommended rates during secondary tillage operations in the spring or banded at time of planting. During the postconversion period (1997–2007), the conventional tillage watershed was managed as it was during the calibration period, with tillage operations remaining essentially constant over the 15-yr period. However, after conversion, the treatment/conservation tillage watershed received no further

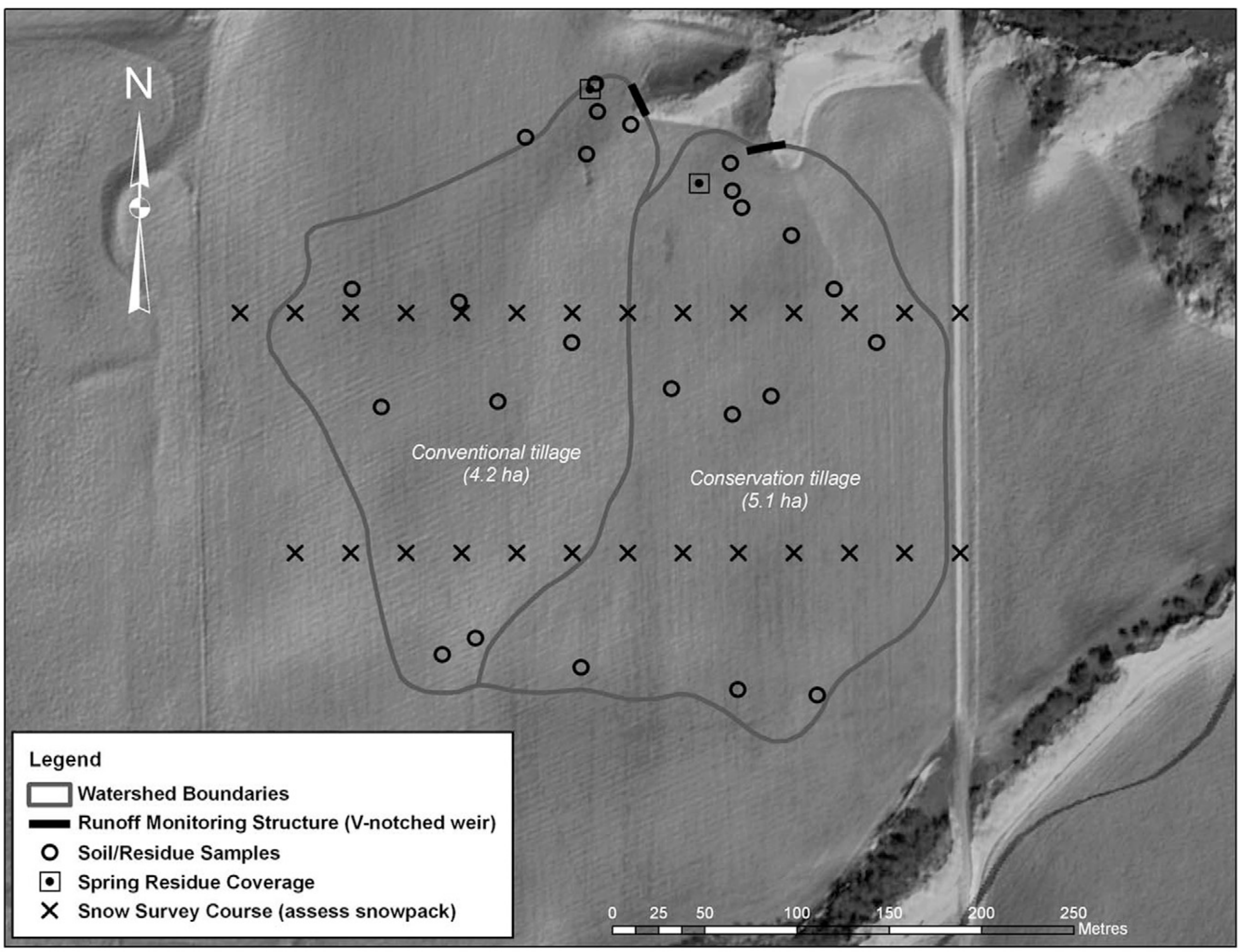

Fig. 1. Map of the paired watersheds: conventional (west/control) and conservation (east/treatment) tillage.

Table 1. Summary of the agricultural activities conducted in the paired watersheds.

Period	Year	Watershed	Seasonal tillage and implement				Timing of fertilizer application and placement			Crop†
			Spring		Fall		With seed	Broadcast	Banded	
			1	2	1	2	kg ha^{-1} of N/P_2O_5/K_2O/S			
Preconversion/ calibration	1993	both	light-duty cultivator	harrow/ packers			0	0	0	flax
	1994	both	light-duty cultivator	harrow/ packers	heavy duty cultivator		16/33/0/9 (4/5)‡	0	84/0/0/0 (3/5)	wheat
	1995	both	heavy-duty cultivator	light-duty cultivator	light-duty cultivator		0	22/34/0/22 (4/5)	73/0/0/0 (4/5)	canola
	1996	both	light-duty cultivator	anhydrous rig (with knives)	light-duty cultivator		6/28/0/8 (4/5)	0	56/0/0/0 (3/5)	wheat
Postconversion-transitional	1997	conventional	light-duty cultivator	harrow/ packers	heavy-duty cultivator		0	0	56/0/0/0 (3/5)	flax
		conservation					0	56/0/0/0 (3/5)	0	flax
	1998	conventional	light-duty cultivator	harrow/ packers	heavy-duty cultivator	harrow/ packers	0	0	67/0/0/0 (2/5)	flax
		conservation			harrow/packers		0	67/0/0/0 (2/5)	0	flax
	1999	conventional	light-duty cultivator	harrow/ packers	heavy-duty cultivator	anhydrous rig (with knives)	11/34/0/0 (3/5)	0	67/0/0/0 (3/10)	wheat
		conservation					0	78/34/0/0 (3/5)	0	wheat
	2000	conventional	light-duty cultivator	harrow/ packers	heavy-duty cultivator		90/39/0/17 (2/5)	0	0	canola
		conservation	liquid fertilizer (coulter, knife)	harrow/ packers			0	0	90/34/0/17 (1/5)	canola
	2001	conventional	light-duty cultivator	harrow/ packers	heavy-duty cultivator		0	56/34/0/0 (3/5)	0	oats
		conservation			harrow/ packers		0	56/34/0/0 (3/5)	0	oats
	2002	conventional	light-duty cultivator	harrow/ packers	harrow/ packers	heavy-duty cultivator	0	56/0/0/0 (2/5)	0	flax
		conservation			harrow/ packers		0	56/0/0/0 (2/5)	0	flax
	2003	conventional	light-duty cultivator		heavy-duty cultivator		0	73/28/0/11 (2/5)	0	wheat
		conservation					0	73/28/0/11 (2/5)	0	wheat
Postconversion-treatment	2004	conventional	light-duty cultivator		heavy-duty cultivator		0	90/39/0/17 (3/5)	0	canola
		conservation					0	90/39/0/17 (3/5)	0	canola
	2005	conventional	cultivator after N application		1 pass harrows to spread chaff	heavy-duty cultivator	0	0	67/0/0/0 (1/5)	barley
		conservation			1 pass harrows to spread chaff		0	0	67/0/0/0 (1/5)	barley
	2006	conventional	cultivator after N application		deep cultivator		0/11/0/0 (3/5)	0	73/0/0/0 (1/5)	canola
		conservation					0/11/0/0 (3/5)	0	73/0/0/0 (1/5)	canola
	2007	conventional	cultivator after N banded		end of experiment		11/11/11/0 (4/4)	0	78/0/0/0 (4/4)	wheat
		conservation			end of experiment		11/11/11/0 (4/4)	0	78/0/0/0 (4/4)	wheat

† The cropping and seeding equipment used in the paired watersheds has changed slightly during the history of the study. Before conversion, a double-disc press drill was used during seeding operations on both watersheds. After conversion, the same double-disc press drill was used on the conventional tillage watershed until 2006, when a new hoe press drill was purchased by the producer and was subsequently used on both watersheds. A zero-till disc drill was used on the conservation tillage watershed in 5 of 7 yr from 1997 to 2003, and a hoe-press drill with a rodweeder attachment and a double-disc press drill were used in 2000 and 2002, respectively. In 2004 and 2005, a double-disc press drill was used during seeding operations on the conservation tillage watershed.

‡ Values in parentheses are week and month of application.

primary tillage and very little secondary tillage (in 4 of the 10 yr, a light harrowing was conducted in the fall to spread harvest residues after the straw was baled). Over the course of the study, wheat (*Triticum* spp.) was grown five times, flax (*Linum usitatissimum*) and canola (*Brassica napus L.*) were grown four times each, and oats (*Avena sativa*) and barley (*Hordeum vulgare*) were each grown once.

Due to the limitations of the producers' seeding equipment, fertilizer was broadcast or injected (N only) in the spring or side-banded with the seed (Table 1). The direct loss of broadcast N and P fertilizer is a concern on conservation tilled fields because the fertilizer is not incorporated after application, and therefore it is more susceptible to runoff losses. Direct losses of surface-applied fertilizer greater than 20% have been reported from conservation tilled fields when rainfall-induced runoff occurred within a few days of application, with the risk of loss decreasing significantly for each subsequent runoff event (Carpenter et al., 1998; Douglas et al., 1998; Hansen et al., 2002). In our study, postconversion, N fertilizer was broadcast in the spring on the conservation tillage watershed in 7 of 11 yr, whereas P fertilizer was broadcast in 4 yr (Table 1). Over the entire study period, however, there were no rainfall-induced runoff events that occurred within 2 wk after fertilizer application (most were >4 wk after fertilizer application). There was also no evidence of significant increases in N or P runoff losses in years when fertilizer was broadcast because flow-weighted mean concentrations (FWMCs) and total export of N and P were not related to applied fertilizer N and P, annually or seasonally (data not presented). Also, because the majority of nutrient export in our study occurred during the snowmelt period (i.e., before spring applications of fertilizer), we do not believe that the direct loss of broadcast fertilizer was a major contributor toward N and P export within the two watersheds.

Runoff Monitoring and Water Sampling

Runoff monitoring of the paired watersheds was conducted between 1993 and 2007. Sampling for nutrients took place in conjunction with flow measurements, allowing for calculations of nutrient export from each of the watersheds. The sampling design was event based, and sample collection was triggered by step changes in discharge. A compound angle v-notched weir was placed at the edge of each of the conventional and the conservation tillage watersheds at a location where the respective water courses entered a riparian area (Fig. 1). The water level at the weirs was measured using an ultrasonic sensor with a data logger. The data logger recorded water depth at 5-min intervals, along with the time that the water samples were taken. The water levels were then used to calculate flow, based on a standard v-notched weir flow equation (Smith, 1985). Throughout each runoff event, manual water levels were taken to ground truth the logger-collected water level data. Ambient air temperature was monitored on site, and a temperature correction was applied to the ultrasonic sensor water level measurements. Rainfall was monitored on site using a tipping bucket rain gauge, and snowfall was monitored at a nearby Environment Canada weather station (Miami-Orchard, 49°22′N, 98°17′W).

To characterize nutrient export throughout the snowmelt and growing seasons, water samples were taken during the rising limb, at the peak, and during the falling limb of each event. The number of samples collected per event typically ranged from 3 to >20, depending on the magnitude and length of the event. The auto-sampler (800SL; Sigma, Medina, NY) was activated based on changes in water level (i.e., flow) at the weir. The sampler intake was located at the apex of the v-notched weir, enabling the collection of samples during low and high flows. During low-flow events, additional samples were collected manually and used to augment those collected by the automated sampler. Water samples (2 L) were retrieved each day from the sampler, and a 120-mL aliquot for NH_3 determination was poured off and preserved using 1 mL of concentrated sulfuric acid (10%). All samples were packed on ice for transport to Environment Canada's National Laboratory for Environmental Testing in Saskatoon, Saskatchewan for analysis using standard analytical techniques (NAQUADAT, 1988; Eaton et al., 2005). This laboratory is accredited with the Canadian Association for Laboratory Accreditation Inc. and uses appropriate quality assurance and control protocols, including procedures to analyze reference standards (2 per 20 samples), independent spiked samples (1 per 20 samples), control standards (at the beginning and end of sample analysis), blanks (one per tray), and random duplicates (at least 1 per 20 samples). In addition, since 2004, blind duplicate samples have been sent to the Department of Fisheries and Oceans laboratory in Winnipeg, Manitoba, and all results agreed with those from the Environment Canada laboratory (data not presented). Total nitrogen (TN), total dissolved nitrogen (TDN), and nitrate + nitrite (NO_x) were determined colorimetrically as nitrite after automated cadmium reduction of nitrate to nitrite. For TN and TDN determination, organic N was oxidized to nitrate by digestion with alkaline potassium persulfate. Ammonia was determined colorimetrically as an ammonia salicylate complex after reaction with sodium salicylate, sodium nitroprusside, and sodium hypochlorite in a buffered alkaline medium. Total phosphorus (TP) and total dissolved phosphorus (TDP) were determined as orthophosphate by reduction using stannous chloride. A mixture of sulfuric acid and persulfate was used to release organically bound phosphates and to hydrolyze polyphosphates before analysis. Analyses for TDN, TDP, and NO_x were performed on filtered aliquots (<0.45 μm). Total suspended sediment (TSS) was determined as the mass of material remaining on a 0.45-μm filter paper after filtration. Particulate forms of nitrogen (PN) and phosphorus (PP) were determined by subtracting the dissolved nutrient fraction from the total.

Data Preparation

Initially, flow and concentration relationships were examined for the two watersheds, but the relationships between most water quality parameters and flow were not strong enough to be used for predictive purposes (data not presented). Therefore, as suggested by Bishop et al. (2005), concentrations of sediment and nutrients at 15-min intervals were estimated from actual sample concentrations through linear interpolation between sampling times. However, there were a few low-intensity events (rainfall and at the end of the snowmelt period) where fewer than three water samples were collected throughout the hydrograph. In these cases, linear interpolation between sampling times would have been unreliable. For runoff events where only two samples were collected, water quality data were averaged across the entire event for each parameter of interest. For runoff events where only one sample was collected, that sample concentration value was assumed to be constant throughout the event. Finally, similar to the method used by Little et al. (2007), if a runoff event was so low that it did not trigger the automated sampler, the last sample from the previous event (i.e., at the end of snowmelt-induced runoff events) or the seasonal average (e.g., summer rainfall) was used throughout that event. However, because these events were small in magnitude and infrequent, their influence on overall nutrient losses was minor.

Yearly runoff patterns at the paired watersheds displayed a spring melt peak (typically in March or April) and multiple rainfall event peaks (various times between May and November). Therefore, data were split into annual and seasonal (snowmelt and rainfall) time periods. Although these seasonal time periods may not be similar in length, they represent seasons that are hydrologically distinct. Total suspended sediment and nutrient loadings were then calculated as the product of the 15-min flow volumes (m^3) and actual or estimated nutrient concentrations (mg L^{-1}) and summed over the entire time period of each event, season, and year. Flow-weighted mean concentrations were calculated by dividing the total load for each event by the total event flow volume, again split into annual and seasonal time periods.

Statistical Analyses

The basis of the paired watershed approach is that a quantifiable relationship exists between the two watersheds for paired water quality data before conversion (Clausen and Spooner, 1993). The paired watershed method does not assume that the two watersheds are the same but that they respond in a predictable manner together, which is reflected in the significance of the regression relationship before conversion. Often, the analysis of paired samples shows that water quality is different between the watersheds before conversion. As suggested by Clausen and Spooner (1993), this difference confirms why the paired watershed approach should be used. Because the paired watershed approach statistically controls seasonal and yearly climatic and hydrological variability between the two test watersheds, it can be used to determine and document changes from BMP implementation (Clausen et al., 1996; Loftis et al., 2001).

Loftis et al. (2001) suggest that the greatest power of the paired watershed approach is obtained when the sample sizes for the calibration and treatment periods are approximately equal. Because it can take a number of years after conversion to a conservation tillage system for the soil to "stabilize" (Perfect et al., 1990; Miller et al., 1999), the data were separated into three principal time periods: (i) preconversion/calibration (1993–1996), (ii) postconversion-transitional (1997–2003), and (iii) postconversion-treatment (2004–2007) (Table 1). This gave calibration and treatment periods of equal length for analysis. Additionally, the prairie region of Canada typically has one snowmelt period (that lasts several days, if not weeks) and fewer than five rainfall-induced runoff events per year. This number of runoff events is much lower than the numbers reported in previous paired watershed studies conducted in more humid regions of North America, where more than 20 rainfall-induced runoff events can occur each year (e.g., Clausen et al., 1996; Bishop et al., 2005). To identify a sufficient number of independent data points for regression analysis, snowmelt hydrographs for the two watersheds were synchronized and separated using the method described by Ranaivoson et al. (2005). An entire snowmelt hydrograph is typically made up of numerous diurnal events, responding to daily fluctuations in temperature. Similarly shaped hydrographs from each watershed were assumed to be in response to the same daily changes in solar radiation and air temperature and split into paired events (even though they may have been slightly shifted in time). There were a total of 14 runoff events (nine snowmelt and five rainfall events) during the calibration period and 39 runoff events (22 snowmelt and 17 rainfall events) during the treatment period. During the treatment period, eight of these events (one snowmelt and seven rainfall events) were unmatched (i.e., runoff at one watershed but not at the other). These events were removed from the statistical analysis for the FWMCs because FWMCs cannot be estimated for nonevents. All events were included in the statistical analysis for total export because the export of a water quality parameter from a watershed with no flow is equal to 0 kg ha^{-1}.

All data were log-transformed to approach normality (of residuals) before statistical analysis. After log-transformation, some variables were still non-normal as determined by the PROC UNIVARIATE function in the Statistical Analysis System (SAS) package 9.1. An ANOVA was used to test that significant relationships existed for all paired water quality data (annual and seasonal) between the two watersheds before conversion. Due to the low number of paired events during the calibration period, there were fewer significant relationships between the two watersheds before conversion when the data were separated seasonally. If significant relationships do not exist before conversion, further ANCOVA analysis cannot be conducted (Clausen et al., 1996). Therefore, two statistical methods were used to determine whether or not there was an effect on water quality due to the conversion to conservational tillage. First, an ANCOVA was used to statistically compare annual FWMCs and total exports from the two watersheds (i.e., regression lines from the calibration and treatment periods were compared for slope and intercept) (Clausen and Spooner, 1993; Grabow et al., 1999). If significant differences in water quality parameters existed, the amount of the difference was calculated by comparing the predicted mean values (obtained from the calibration regression equation) with those observed on the treatment watershed after conversion to conservation tillage. The overall difference after conversion (due to the treatment) was then further expressed as a percentage change based on the mean predicted and observed values, where % change = [(observed mean − predicted mean)/predicted mean] × 100 (Clausen et al., 1996). Second, a nonparametric Kruskal-Wallis one-way analysis by ranks (NPAR1WAY function in SAS 9.1) was used to compare snowmelt- and rainfall-induced runoff, TSS, and nutrient FWMC and export between the two watersheds for the calibration and treatment periods. Nonparametric tests do not have the same stringent assumptions as those of parametric tests (i.e., normal distributions and homogeneity of variances) and can be used when the distribution of data is highly skewed or when severely unequal variances exist between groups (McClave and Dietrich, 1994). Due to the high variability inherent in field and watershed-based experiments, an α = 0.1 was used as the significance threshold for all statistical analysis. This higher probability level is consistent with that used in previous water quality studies (e.g., Hansen et al., 2000).

Other Field Measurements

To confirm that the two systems used in this study fell within the standard definition of conventional (<30% residue) and conservation (>30% residue) tillage systems, percent residue coverage after seeding was measured each year, using the line transect method (Laflen et al., 1981), at four points within 100 m of one permanent location in each watershed (Fig. 1). Soil samples were collected from the paired watersheds after harvest in the fall, but before fields were tilled. In both watersheds, soil samples were collected from four locations within each of three landscape positions (upper, mid-, and lower slope) (Fig. 1). At each location, four to seven soil samples were collected from three depths (0–5, 0–15, and 15–60 cm). Soil samples were composited by depth for each individual sampling location and sent to AgVise Laboratories (Northwood, ND) and analyzed for nitrate-N, Olsen-P, and organic matter using standard methods. To determine the quantity of water available for runoff within each watershed, snow depth and density were measured in late winter, just before the spring snowmelt. On each watershed, snow depth was measured with a meter stick from each sampling location across two referenced transects (Fig. 1). Snow density was determined by taking snow cores across the two transects and weighing snow samples of a known volume. Average snow depth and density were then used to calculate an equivalent depth of water stored on each watershed before snowmelt. All sampling locations were georeferenced and resampled each year. Additional statistical analyses were conducted to test for differences between the two watersheds for percent residue cover, pre-snowmelt moisture, nitrate-N, Olsen-P, and organic matter (using one-way ANOVA).

Results and Discussion

As is typical for the Canadian prairies, year-to-year variability in precipitation was high during the study. During the calibration period, an average of 371 mm (SD, 87 mm) of rain fell at the paired watershed site, ranging from a high of 480 mm in 1993 to a low of 269 mm in 1994 (data not presented). During the treatment period, there was an average of 404 mm (SD, 111 mm; maximum 492 mm in 2005, minimum 242 mm in 2006) of rain per year. Similarly, year-to-year variability for snowfall was high during both the calibration and treatment periods. An average of 148 cm (SD, 46 cm; maximum 199 cm in 1995, minimum 100 cm in 1994) and 109 cm (SD, 21 cm; maximum 122 cm in 2006, minimum 78 cm in 2007) of snow fell during the calibration and treatment periods, respectively. The long-term averages for this region are ~413 mm of rain per year and ~131 cm of snow per year (Environment Canada, 2009).

During the treatment period, the percent residue coverage after seeding was significantly greater in the conservation tillage watershed than in the conventional tillage watershed (Table 2). Overall, residue coverage after seeding averaged 56% under conservation tillage and 19% for conventional tillage. These values are consistent with residue measurements taken within the two watersheds during the postconversion-transitional period between 1997 and 2003 (data not shown). Despite greater residue coverage under conservation tillage, the tillage system did not influence the amount of water stored in the snow before snowmelt, and there were no real differences in the pre-melt snow water equivalent (SWE) between the two watersheds (Table 2). Previous studies have reported that more snow typically accumulates under conservation tillage systems than conventional systems, with differences due to the trapping of snow by stubble (e.g., Pomeroy and Gray, 1995; Hansen et al., 2000). Similar to our study, Elliott et al. (2001) reported little differences in average snow accumulation between no-tilled and conventionally tilled cropping systems in Saskatchewan. The absence of differences in pre-melt SWE between the conservation and conventional tillage systems in the current study can be attributed to the low overall intensity of tillage operations used (e.g., the study from Minnesota by Hansen et al. [2000] used a moldboard plow for the primary conventional tillage operation) and snowfall that averaged >1 m yr^{-1}. The magnitude of the snow trapping effect is expected to be greatest in regions where there is very little snow (<30 mm pre-melt SWE), such as the brown and dark brown soil zones of the Canadian prairies, where snow can be blown off exposed surfaces that are not protected by stubble (Pomeroy and Gray, 1995). Therefore, under southern Manitoba conditions, pronounced differences in snow

Table 2. Summary of background information collected at the paired watersheds during the treatment period (2004–2007).

Watershed	Year	Residue cover	Snow water equivalent	Nitrate-N			Olsen-P			Organic matter		
				0–5 cm	0–15 cm	15–60 cm	0–5 cm	0–15 cm	15–60 cm	0–5 cm	0–15 cm	15–60 cm
		%	mm	kg ha^{-1}			mg kg^{-1}			%		
Conservation tillage	2004	73	71	8.6	4.4	1.7	25.3	21.3	5.0	4.9	4.5	2.0
	2005	50	76	12.5	7.2	1.9	25.0	15.3	6.7	5.2	3.7	2.1
	2006	45	91	15.4	7.6	1.3	29.0	19.0	8.0	4.4	3.3	1.5
	2007	56	92	3.8	7.1	6.2	33.8	20.8	8.9	4.6	3.5	1.5
	Avg.	56a†	82	10.1	6.6b	2.8	28.3a	19.1a	7.1	4.8a	3.8	1.8
Conventional tillage	2004	20	75	8.2	5.1	1.5	16.3	11.3	4.7	4.2	3.7	1.8
	2005	25	59	12.9	9.2	3.1	15.0	10.3	3.6	5.0	3.6	2.0
	2006	15	94	14.6	10.9	1.3	19.0	15.3	7.7	3.9	3.4	1.6
	2007	15	93	4.5	8.2	8.2	22.3	15.6	7.0	3.9	3.4	1.6
	Avg.	19b	80	10.0	8.3a	3.5	18.2b	13.1b	5.8	4.3b	3.5	1.8

† Within columns, average values followed by different letters (for each parameter) are significantly different.

trapping between these conservation and conventional tillage systems would not be expected.

During the 4 yr of the treatment period, average concentrations of nitrate-N in the surface soil (0–15 cm) were greater under conventional tillage than conservation tillage (Table 2). However, there were no differences during the treatment period with respect to the concentration of nitrate-N in the 0- to 5-cm or 15- to 60-cm soil depths. In Manitoba, these nitrate-N levels are considered very low for grain and oilseed production within both tillage systems (Manitoba Agriculture, Food and Rural Initiatives, 2007). Concentrations of P in the surface soil samples were also influenced by tillage system. However, in contrast to N, Olsen extractable-P was significantly greater in the conservation tillage watershed than in the conventional tillage watershed in the 0- to 5-cm and the 0- to 15-cm soil depths. There were no differences in Olsen-P between the two watersheds at the 15- to 60-cm soil depth. Overall, Olsen-P levels were rated as moderate to high for both tillage systems (Manitoba Agriculture, Food and Rural Initiatives, 2007). Organic matter was also significantly greater in the conservation tillage watershed than in the conventional tillage watershed in the 0- to 5-cm soil depth, but there were no differences between watersheds at 0 to 15 and 15 to 60 cm. The results for P and OM are consistent with previous research reporting that conservation tillage systems can lead to the stratification of less mobile nutrients at the soil surface, due to reduced mixing of residue, fertilizers, or manures by tillage (Baker and Laflen, 1983; Selles et al., 1999; Franzluebbers, 2002; Sharpley, 2003; Lupwayi et al., 2006). The accumulation of nutrients near the soil surface in reduced tillage systems does not have an agronomic effect, but it does increase nutrient availability for export and loss to surface water during snowmelt and rainfall periods.

It is also important to understand the amount, timing, and driving forces of concentration and total export of TSS and nutrients that can enter and affect downstream aquatic ecosystems. In both watersheds, there was considerable inter-year variability for FWMCs of TSS and nutrients (Table 3). On average, concentrations of dissolved nutrients in runoff were higher during snowmelt than rainfall events, whereas concentrations of TSS and particulate nutrients were greatest during rainfall events in the treatment period. However, the seasonal patterns for the concentrations of particulate nutrients and sediments during the treatment period were not always consistent with those during the calibration period. Even though snowfall accounted for only 25% of total annual precipitation during the study period, snowmelt runoff accounted for 80 to 90% of total annual runoff export from these two watersheds (Table 4). Because snowmelt was the dominant hydrological process, the vast majority of TSS, particulate, and dissolved nutrient export occurred during the snowmelt period. Additionally, dissolved nutrients were the dominant form of nutrients exported from the two watersheds, especially during the spring snowmelt period when >80% of N and P were exported in the dissolved form (Table 4). This is consistent with recent studies in western Canada (e.g., Ontkean et al., 2005; Little et al., 2006). The low contribution of particulates to total nutrient losses within snowmelt-induced runoff was expected and is reflective of the frozen soil conditions during the snowmelt period. However, the proportion of nutrients lost in particulate forms during rainfall runoff events was lower than expected. This is probably due to the relatively flat landscapes, low-intensity tillage systems, and low precipitation typical of the Canadian prairies.

Runoff and Suspended Sediment

Using the corresponding hydrographs for individual events, linear regressions for the runoff export behavior of each watershed relative to the other were developed for all runoff events during the calibration and treatment periods. During the treatment period, there were no significant differences between calibration and treatment period regression slopes or intercepts for annual runoff using the full-form ANCOVA model (Table 5; Fig. 2a). As suggested by Clausen and Spooner (1993) and Grabow et al. (1999), further analysis was conducted using the reduced-form ANCOVA model (i.e., single slope, interaction term removed) to test for differences in y-intercepts between the calibration and treatment watersheds. Using this reduced-form ANCOVA model, there were still no significant differences for annual runoff exports between the two watersheds (Table 5). This indicates that converting to conservation tillage did not alter overall runoff response in this study.

The similarity between the two watersheds with respect to runoff export is also evident when the data were separated into snowmelt- and rainfall-induced runoff periods and analyzed using nonparametric statistics. There were no significant differences between the conservation and conventional tillage watersheds for snowmelt-induced runoff during the calibration and treatment periods (Table 6). Because there were few differences between tillage systems with regard to the pre-melt SWE, these results were not surprising. There were also no significant differences between the paired watersheds for rainfall-induced runoff during the calibration period. However, during the treatment period, the conservation tillage watershed produced significantly less rainfall-induced runoff than the conventionally tilled watershed. In Minnesota, Hansen et al. (2000) report similar seasonal results to our study, suggesting that conservation tillage practices in cold regions are effective in reducing runoff during the cropping season but less effective during the snowmelt period. However, Ranaivoson et al. (2005) report that “no-till” (which included a pass with chisel plow after corn) resulted in more snowmelt-induced runoff, compared with conventional tillage (moldboard plowing in the fall). Similarly, van Vliet et al. (1993) and Elliott et al. (2001) reported that equivalent quantities of snow generated more runoff under zero-tillage then conventional tillage. Elliott et al. (2001) also report that differences in snowmelt-induced runoff between tillage systems decreased with time, suggesting that infiltration slowly improved in soils under no-tillage (Elliott and Efetha, 1999). Clearly the influence of conventional and conservation tillage on runoff volume during the snowmelt period varies with site, environmental conditions, intensity of tillage, and duration of the tillage treatment.

Total suspended sediment followed a different pattern than runoff, as conservation tillage significantly reduced TSS export by 65% when all runoff events were considered within one dataset (Table 5; Fig. 2b). However, there were no similar differences between the two watersheds for FWMCs of TSS (using the full- or reduced-form ANCOVA models).

Table 3. Summary of annual and seasonal flow-weighted mean concentrations of sediment, total nitrogen, particulate nitrogen, total dissolved nitrogen, nitrate + nitrite, ammonia, total phosphorus, particulate phosphorus, and total dissolved phosphorus for the paired watersheds.

Period	Year	Season	Conservation tillage									Conventional tillage								
			Sediment	TN†	PN	TDN	NO_x	NH_3	TP	PP	TDP	Sediment	TN	PN	TDN	NO_x	NH_3	TP	PP	TDP
			mg L^{-1}									mg L^{-1}								
Preconversion/calibration	1993	annual	ND‡	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
		snowmelt	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
		rainfall	51.2	1.14	0.70	0.44	0.01	0.06	0.57	0.17	0.40	37.6	1.02	0.57	0.46	0.01	0.06	0.50	0.16	0.35
	1994	annual	49.7	3.68	2.18	1.50	0.40	0.08	1.20	0.18	1.02	105.0	2.78	1.11	1.66	0.31	0.11	0.94	0.21	0.72
		snowmelt	15.7	1.96	0.43	1.53	0.61	0.07	1.37	0.17	1.20	23.8	2.56	0.38	2.18	0.60	0.09	1.34	0.07	1.27
		rainfall	93.4	5.89	4.43	1.46	0.14	0.08	0.99	0.20	0.79	139.9	2.87	1.42	1.45	0.19	0.12	0.76	0.28	0.49
	1995	annual	68.7	2.49	0.62	1.86	1.11	0.10	0.46	0.13	0.33	71.2	2.48	0.55	1.93	1.19	0.12	0.38	0.14	0.24
		snowmelt	68.1	2.39	0.49	1.90	1.16	0.10	0.44	0.13	0.31	69.3	2.49	0.51	1.98	1.25	0.12	0.36	0.13	0.23
		rainfall	79.1	4.29	3.17	1.12	0.09	0.07	0.85	0.19	0.66	105.9	2.25	1.14	1.12	0.13	0.10	0.68	0.24	0.44
	1996	annual	597.6	9.25	3.17	6.08	4.32	1.57	0.93	0.41	0.52	321.7	8.13	1.85	6.28	3.39	2.10	0.73	0.33	0.40
		snowmelt	597.6	9.25	3.17	6.08	4.32	1.57	0.93	0.41	0.52	321.7	8.13	1.85	6.28	3.39	2.10	0.73	0.33	0.40
		rainfall	NR§	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Postconversion-treatment	2004	annual	17.2	1.83	0.53	1.29	0.52	0.23	0.64	0.11	0.53	150.9	7.44	1.07	6.37	5.16	0.25	0.48	0.20	0.28
		snowmelt	14.9	1.81	0.51	1.30	0.53	0.23	0.63	0.10	0.53	151.0	7.44	1.07	6.37	5.16	0.25	0.48	0.20	0.28
		rainfall	127.9	2.49	1.49	1.00	0.05	0.04	0.91	0.29	0.61	128.0	7.96	1.05	6.91	5.49	0.34	0.52	0.19	0.33
	2005	annual	53.2	2.60	0.74	1.86	0.45	0.38	0.88	0.18	0.70	84.6	4.81	0.76	4.05	2.51	0.19	0.47	0.14	0.33
		snowmelt	7.8	2.54	0.49	2.06	0.64	0.51	0.87	0.15	0.72	16.0	7.96	0.44	7.52	5.67	0.37	0.49	0.09	0.40
		rainfall	143.1	2.70	1.24	1.46	0.10	0.10	0.89	0.23	0.65	137.5	2.39	1.01	1.37	0.08	0.06	0.46	0.18	0.28
	2006	annual	9.0	2.36	0.18	2.19	0.91	0.16	0.91	0.05	0.86	88.5	7.37	0.53	6.85	5.17	0.40	0.41	0.11	0.30
		snowmelt	9.0	2.36	0.18	2.19	0.91	0.16	0.91	0.05	0.86	88.5	7.37	0.53	6.85	5.17	0.40	0.41	0.11	0.30
		rainfall	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
	2007	annual	21.8	ND	ND	5.33	1.26	2.12	0.83	0.18	0.65	77.8	ND	ND	6.38	4.80	0.38	0.32	0.14	0.18
		snowmelt	21.4	ND	ND	5.33	1.27	2.12	0.83	0.18	0.65	52.1	ND	ND	7.57	5.81	0.44	0.28	0.11	0.18
		rainfall	393.9	5.86	3.84	2.02	0.55	0.55	1.01	0.54	0.47	184.9	3.06	1.66	1.40	0.59	0.12	0.48	0.29	0.19
	average																			
	1993–1996	annual	238.7	5.14	1.99	3.15	1.95	0.58	0.86	0.24	0.62	166.0	4.46	1.17	3.29	1.63	0.78	0.68	0.23	0.45
	(calibration)	snowmelt	227.1	4.53	1.36	3.17	2.03	0.58	0.91	0.24	0.68	138.3	4.39	0.92	3.48	1.74	0.77	0.81	0.18	0.63
		rainfall	74.6	3.77	2.77	1.01	0.08	0.07	0.80	0.19	0.62	94.5	2.05	1.04	1.01	0.11	0.09	0.65	0.22	0.42
	2004–2007	annual	25.3	2.26	0.48	2.67	0.79	0.72	0.81	0.13	0.68	100.4	6.54	0.79	5.91	4.41	0.31	0.42	0.15	0.27
	(treatment)	snowmelt	13.3	2.24	0.39	2.72	0.84	0.76	0.81	0.12	0.69	76.9	7.59	0.68	7.08	5.45	0.37	0.42	0.13	0.29
		rainfall	221.6	3.68	2.19	1.49	0.23	0.23	0.93	0.36	0.58	150.1	4.47	1.24	3.23	2.06	0.17	0.48	0.22	0.27

† NO_x, nitrate + nitrite; PN, particulate nitrogen; PP, particulate phosphorus; TDN, total dissolved nitrogen; TDP, total dissolved phosphorus; TN, total nitrogen; TP, total phosphorus.

‡ ND, no data.

§ NR, no runoff.

Table 4. Summary of annual and seasonal runoff and export of sediment, total nitrogen, particulate nitrogen, total dissolved nitrogen, nitrate + nitrite, ammonia, total phosphorus, particulate phosphorus, and total dissolved phosphorus for the paired watersheds.

Period	Year	Season	Conservation tillage										Conventional tillage									
			Runoff	Sediment	TN†	PN	TDN	NO_x	NH_3	TP	PP	TDP	Runoff	Sediment	TN	PN	TDN	NO_x	NH_3	TP	PP	TDP
			$m^3\ ha^{-1}$	kg ha^{-1}									$m^3\ ha^{-1}$	kg ha^{1}								
Preconversion/ calibration	1993	annual	ND‡	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
		snowmelt	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
		rainfall	156	8.0	0.18	0.11	0.07	0.002	0.01	0.09	0.03	0.06	128	4.8	0.13	0.07	0.06	0.001	0.01	0.06	0.02	0.04
	1994	annual	381	18.9	1.40	0.83	0.57	0.15	0.03	0.46	0.07	0.39	439	46.1	1.22	0.49	0.73	0.14	0.05	0.41	0.09	0.32
		snowmelt	214	3.4	0.42	0.09	0.33	0.13	0.02	0.29	0.04	0.26	132	3.1	0.34	0.05	0.29	0.08	0.01	0.18	0.01	0.17
		rainfall	167	15.6	0.98	0.74	0.24	0.02	0.01	0.16	0.03	0.13	307	43.0	0.88	0.44	0.44	0.06	0.04	0.23	0.09	0.15
	1995	annual	1127	77.4	2.80	0.70	2.10	1.25	0.11	0.52	0.15	0.37	846	60.2	2.09	0.46	1.63	1.01	0.10	0.32	0.12	0.20
		snowmelt	1071	73.0	2.56	0.52	2.04	1.25	0.10	0.47	0.14	0.33	801	55.5	1.99	0.41	1.58	1.00	0.10	0.29	0.11	0.18
		rainfall	56	4.4	0.24	0.18	0.06	0.01	0.004	0.05	0.01	0.04	45	4.7	0.10	0.05	0.05	0.01	0.005	0.03	0.01	0.02
	1996	annual	165	98.7	1.53	0.52	1.00	0.71	0.26	0.15	0.07	0.09	295	94.9	2.40	0.55	1.85	1.00	0.62	0.22	0.10	0.12
		snowmelt	165	98.7	1.53	0.52	1.00	0.71	0.26	0.15	0.07	0.09	295	94.9	2.40	0.55	1.85	1.00	0.62	0.22	0.10	0.12
		rainfall	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Postconversion-treatment	2004	annual	991	17.1	1.81	0.53	1.28	0.52	0.22	0.63	0.11	0.53	826	124.7	6.15	0.89	5.26	4.27	0.21	0.40	0.17	0.23
		snowmelt	970	14.4	1.76	0.50	1.26	0.52	0.22	0.62	0.10	0.52	823	124.3	6.13	0.88	5.24	4.25	0.21	0.40	0.17	0.23
		rainfall	21	2.7	0.05	0.03	0.02	0.001	0.001	0.02	0.01	0.01	3	0.4	0.02	0.003	0.02	0.02	0.001	0.001	0.001	0.001
	2005	annual	887	47.2	2.30	0.66	1.65	0.40	0.33	0.78	0.16	0.62	1027	86.8	4.94	0.78	4.16	2.58	0.20	0.49	0.15	0.34
		snowmelt	589	4.6	1.50	0.29	1.21	0.37	0.30	0.51	0.09	0.42	447	7.2	3.56	0.20	3.36	2.53	0.16	0.22	0.04	0.18
		rainfall	298	42.6	0.80	0.37	0.43	0.03	0.03	0.26	0.07	0.19	580	79.7	1.38	0.59	0.80	0.05	0.04	0.27	0.11	0.16
	2006	annual	748	6.7	1.77	0.13	1.64	0.68	0.12	0.68	0.04	0.64	1188	105.1	8.76	0.63	8.13	6.14	0.48	0.48	0.13	0.36
		snowmelt	748	6.7	1.77	0.13	1.64	0.68	0.12	0.68	0.04	0.64	1188	105.1	8.76	0.63	8.13	6.14	0.48	0.48	0.13	0.36
		rainfall	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2007	annual	603	13.1	ND	ND	3.21	0.76	1.28	0.50	0.11	0.39	573	44.6	ND	ND	3.66	2.75	0.22	0.18	0.08	0.10
		snowmelt	603	12.9	ND	ND	3.21	0.76	1.28	0.50	0.11	0.39	463	24.1	ND	ND	3.50	2.69	0.21	0.13	0.05	0.08
		rainfall	1	0.2	0.003	0.002	0.001	0.0003	0.0003	0.001	0.0003	0.0003	111	20.5	0.34	0.18	0.15	0.07	0.01	0.05	0.03	0.02
	average																					
	1993–1996	annual	558	65.0	1.91	0.69	1.23	0.71	0.13	0.38	0.10	0.28	527	67.1	1.90	0.50	1.41	0.71	0.26	0.32	0.10	0.21
	(calibration)	snowmelt	484	58.4	1.50	0.38	1.12	0.70	0.13	0.31	0.08	0.22	409	51.2	1.58	0.34	1.24	0.69	0.24	0.23	0.07	0.16
		rainfall	95	7.0	0.35	0.26	0.09	0.01	0.01	0.08	0.02	0.06	120	13.1	0.28	0.14	0.14	0.02	0.01	0.08	0.03	0.05
	2004–2007	annual	807	21.0	1.96	0.44	1.94	0.59	0.49	0.65	0.10	0.55	904	90.3	6.62	0.77	5.30	3.93	0.28	0.39	0.13	0.26
	(treatment)	snowmelt	727	9.7	1.68	0.31	1.83	0.58	0.48	0.58	0.08	0.49	730	65.2	6.15	0.57	5.06	3.90	0.26	0.31	0.10	0.21
		rainfall	80	11.4	0.21	0.10	0.11	0.01	0.008	0.07	0.02	0.05	173	25.1	0.44	0.19	0.24	0.03	0.013	0.08	0.03	0.05

† NO_x, nitrate + nitrite; PN, particulate nitrogen; PP, particulate phosphorus; TDN, total dissolved nitrogen; TDP, total dissolved phosphorus; TN, total nitrogen; TP, total phosphorus.

‡ ND, no data.

Seasonally, there were no significant differences in the FWMC and export of TSS between the two watersheds for snowmelt- or rainfall-induced runoff during the calibration period (Table 6). However, during the treatment period, the conservation tillage watershed produced significantly lower FWMCs of TSS in snowmelt runoff waters compared with the conventional tillage watershed. In addition, conservation tillage significantly reduced TSS export in snowmelt- and rainfall-induced runoff, supporting the ANCOVA analysis that conservation tillage is a BMP that can be used in the Canadian prairies to reduce TSS export from agricultural fields.

The effectiveness of conservation tillage in reducing TSS losses has been well documented (e.g., Baker and Laflen, 1983; Clausen et al., 1996). However, previous studies have reported that conservation tillage reduces total losses of nutrients because of significant decreases in runoff volume and sediment mass. In our study, conservation tillage consistently reduced TSS export (annually and seasonally) but reduced runoff volume only during the summer. This is important because the snowmelt

Table 5. Summary of analysis of covariance for log-transformed flow-weighted mean concentrations and total runoff and export (per ha) of sediment, total nitrogen, particulate nitrogen, total dissolved nitrogen, nitrate + nitrite, ammonia, total phosphorus, particulate phosphorus, and total dissolved phosphorus for all runoff events during the calibration and treatment periods.

Parameter	Model‡	Calibration period (1993–1996)				Treatment period (2004–2007)				Calibration vs. treatment P value		Predicted mean	Observed mean	Change
		n	Slope	Intercept	R^2	n	Slope	Intercept	R^2	Slope	Intercept			
														%
FWMC§¶														
Sediment	full	14	1.01	–0.08	0.74***	31	0.91	–0.004	0.58***	0.73 NS#	0.88 NS	–	–	–
	reduced	14	0.93	0.06	0.74***	31	0.93	–0.04	0.58***	–	0.28 NS	–	–	–
TN††	full	14	1.06	–0.04	0.76***	26	–0.12	1.26	0.05 NS	<0.0001***	<0.0001***	5.6	3.3	–41
PN††	full	14	2.39	–1.41	0.78***	26	1.16	–0.15	0.29**	0.045*	0.046*	1.3	1.1	–20
TDN	full	14	1.06	–0.06	0.96***	31	0.21	0.85	0.16*	0.0003***	0.0004***	4.5	2.5	–44
NO_x	full	14	1.35	–0.36	0.89***	31	0.16	0.85	0.28**	<0.0001***	<0.0001***	4.0	0.73	–82
NH_3	full	14	0.74	0.26	0.99***	31	1.26	–0.26	0.33***	0.16 NS	0.17 NS	–	–	–
	reduced	14	0.96	0.04	0.91***	31	0.96	0.05	0.31***	–	0.095†	0.27	0.57	112
TP	full	14	0.82	0.19	0.59**	31	0.26	0.78	0.02 NS	0.18 NS	0.17 NS	–	–	–
	reduced	14	0.67	0.34	0.57**	31	0.67	0.36	–0.03 NS	–	0.012*	0.70	0.99	42
PP	full	14	0.60	0.40	0.40*	31	1.13	–0.13	0.49***	0.11 NS	0.12 NS	–	–	–
	reduced	14	0.93	0.07	0.29*	31	0.93	0.08	0.47***	–	0.20 NS	–	–	–
TDP	full	14	0.80	0.21	0.61***	31	0.50	0.52	0.08 NS	0.41 NS	0.40 NS	–	–	–
	reduced	14	0.72	0.29	0.61***	31	0.72	0.31	0.07 NS	–	0.007**	0.52	0.79	52
Export¶														
Runoff	full	14	0.90	0.50	0.80***	39	0.55	1.62	0.20**	0.59 NS	0.73 NS	–	–	–
	reduced	14	0.57	2.14	0.69***	39	0.57	1.53	0.20**	–	0.12 NS	–	–	–
Sediment	full	14	0.94	0.06	0.87***	39	0.32	0.70	0.53***	<0.0001***	<0.0001***	5.3	1.9	–65
TN††	full	14	0.78	0.22	0.86***	33	0.22	0.78	0.60***	<0.0001***	<0.0001***	0.51	0.16	–68
PN††	full	14	1.28	–0.28	0.90***	33	0.39	0.61	0.68***	<0.0001***	<0.0001***	0.12	0.04	–63
TDN	full	14	0.67	0.33	0.77***	39	0.20	0.81	0.27***	0.005**	0.006**	0.37	0.19	–50
NO_x	full	14	0.82	0.18	0.91***	39	0.09	0.91	0.46***	<0.0001***	<0.0001***	0.29	0.05	–81
NH_3	full	14	0.44	0.56	0.96***	39	0.88	0.13	0.11*	0.28 NS	0.28 NS	–	–	–
	reduced	14	0.53	0.47	0.93***	39	0.53	0.47	0.09*	–	0.20 NS	–	–	–
TP	full	14	0.77	0.23	0.63***	39	1.20	–0.20	0.69***	0.076†	0.077†	0.068	0.076	12
PP	full	14	0.57	0.43	0.65***	39	0.43	0.57	0.55***	0.29 NS	0.29 NS	–	–	–
	reduced	14	0.47	0.54	0.69***	39	0.47	0.52	0.20**	–	0.054†	0.019	0.012	–37
TDP	full	14	0.96	0.04	0.63***	39	1.75	–0.75	0.71***	0.015*	0.015*	0.049	0.066	36

* Significant at $P < 0.05$.

** Significant at $P < 0.01$.

*** Significant at $P < 0.001$.

† Significant at $P < 0.10$.

‡ The "full model" includes an interaction term and compares slope and y intercept. The "reduced model" does not include the interaction term and only compares y intercept (used when no significant differences with full model).

§ FWMC, flow-weighted mean concentration; NO_x, nitrate + nitrite; PN, particulate nitrogen; PP, particulate phosphorus; TDN, total dissolved nitrogen; TDP, total dissolved phosphorus; TN, total nitrogen; TP, total phosphorus.

¶ Regression results presented for FWMC include only those events when runoff occurred from both watersheds. Regression results for export include the full data set.

NS, nonsignificant.

†† Snowmelt events were not analyzed for TN and PN in 2007. Therefore, these events were not included in the regression analysis.

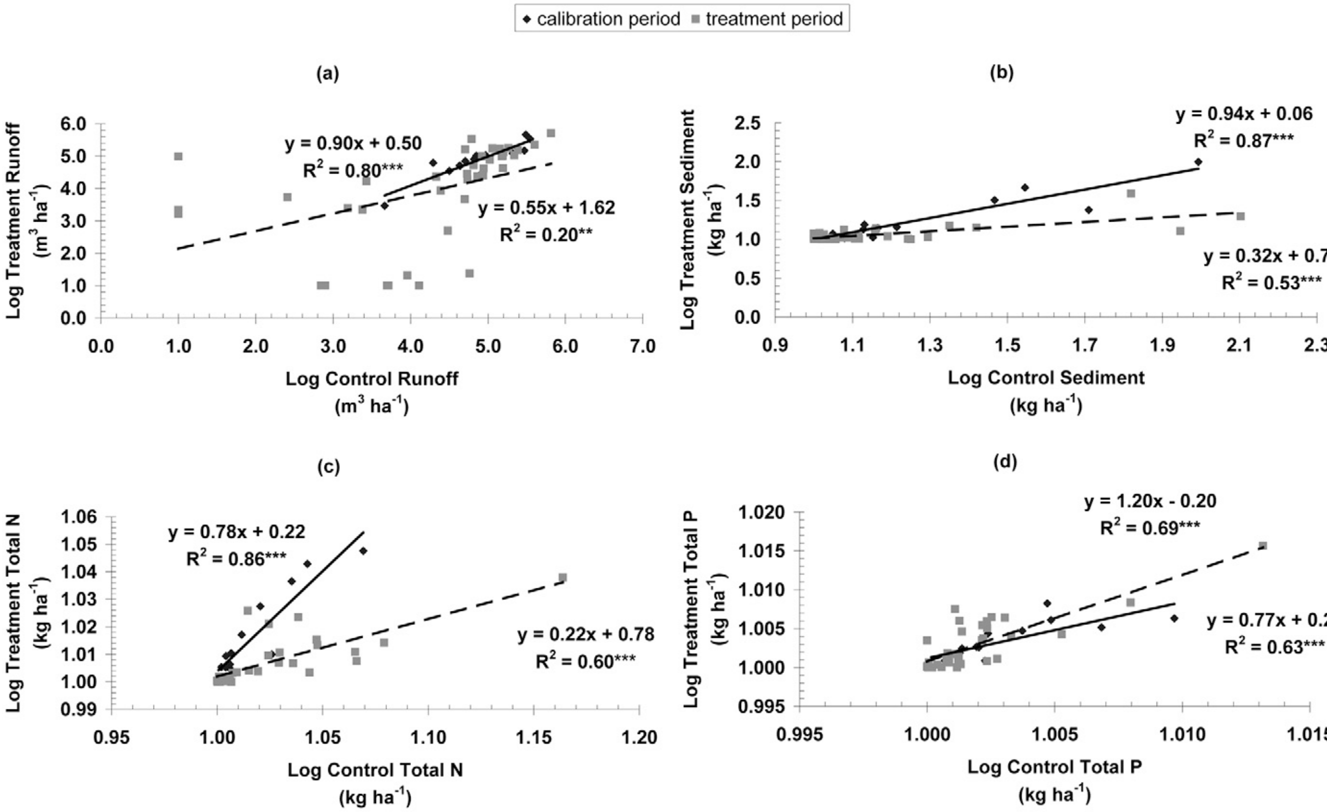

Fig. 2. Examples of ANCOVA analyses. Calibration and treatment period regressions for the treatment (conservation tillage) and control (conventional tillage) watersheds for all log-transformed samples from all years: (a) runoff and export of (b) total suspended sediment (TSS), (c) total N (TN), and (d) total P (TP). Statistical differences between calibration and treatment period slopes: (a) NS, (b) $p < 0.0001$*, (c) $p < 0.0001$***, and (d) $p = 0.076^{\dagger}$. NS, †, **, and *** indicate nonsignificance and significance at the 0.10, 0.01, and 0.001 probability levels, respectively.**

period accounted for >80% of the annual runoff in our study and, on average, at least half of the TSS exported from the two watersheds (Table 4). Another reason for the differences between our results and those in previous studies could be the watershed-scale nature of the current study. Based on the available literature, it appears that greater reductions in runoff volume, due to conservation tillage, are generally reported within plot studies than within watershed studies. As suggested by Clausen et al. (1996), the larger scale of watershed studies probably introduces additional heterogeneity that is not evident at the plot scale. Even though conservation tillage significantly reduced annual and seasonal TSS export, the total export of TSS during the study from both watersheds was extremely low (<0.1 Mg ha^{-1} yr^{-1}) and is consistent with previous studies in the Canadian prairies (e.g., McConkey et al., 1997). Even based on a sediment delivery ratio of >75%, the maximum soil losses from eroding slopes on either watershed were well below the 6 Mg ha^{-1} yr^{-1} threshold at which soil erosion losses would be considered unsustainable for this region of the Canadian prairies (van Vliet et al., 2005). However, the importance of suspended sediment (in particular fine sediment) in transporting associated nutrients, heavy metals, and pesticides suggests that these erosion rates are still of environmental concern to downstream water bodies (Bilotta and Brazier, 2008).

Nutrient Losses

National water quality guidelines for the protection of aquatic ecosystems in Canada have been developed by the Canadian Council of Ministers of the Environment (2002) for a wide range of contaminants that can enter aquatic ecosystems. In Manitoba, there are no water quality guidelines for concentrations of TN, but 1.0 mg L^{-1} is recommended in the two other Canadian prairie provinces of Alberta and Saskatchewan. The current water quality guideline for TP in streams and rivers in Manitoba has been set at 0.05 mg L^{-1} (Williamson, 2002). Overall, the average concentrations of TN and TP exceeded the guidelines recommended for freshwater streams in the Canadian prairies within both watersheds in all years of the study (Table 3). In fact, total N and P concentrations exceeded these guidelines in every sample taken over the course of the study, before and after conversion. Although concentrations of TN and TP in snowmelt and rainfall-induced runoff exceeded water quality guidelines, the total export of TN and TP from both watersheds (Table 4) was much lower than values reported previously for conventional and conservation tillage in the midwestern United States (e.g., Baker and Laflen, 1983; Sharpley and Smith, 1994). Even though losses of nutrients in the current study may be minor from an agricultural production standpoint, they are of ecological significance because as little as 1 to 2 kg P ha^{-1} yr^{-1} has been associated with the accelerated eutrophication of lakes in the United States (Sharpley and Rekolainen, 1997). Plus, the majority of nutrients exported from both watersheds was in the dissolved form, which is immediately available to aquatic organisms.

Nitrogen

Based on the full-form ANCOVA analysis of all runoff events, there was a significant difference between the calibration and treatment period regression slopes and intercepts for annual FWMCs and export of TN, PN, TDN, and NO_x (Table 5; Fig. 2c). For all four significant N parameters, there was a shift toward lower FWMCs and exports after conversion to conservation tillage. Overall, the FWMCs of TN, PN, TDN, and NO_x were decreased by 41, 20, 44, and 82%, respectively, after implementation of conservation tillage. Similarly, total export of TN, PN, TDN, and NO_x was reduced by 68, 63, 50, and 81%, respectively. In contrast, for NH_3 FWMCs and exports, the regression equations indicated a trend toward greater losses from the treatment watershed compared with the conventionally tilled control watershed, but these differences were not significant using the full-form ANCOVA model. Additional analysis using the reduced-form ANCOVA model determined that regression intercepts between the two watersheds for NH_3

Table 6. Summary of nonparametric analysis (Kruskal–Wallis Test) for seasonal flow-weighted mean concentrations and total runoff and export (per ha) of sediment, total nitrogen, particulate nitrogen, total dissolved nitrogen, nitrate + nitrite, ammonia, total phosphorus, particulate phosphorus, and total dissolved phosphorus during the calibration and treatment periods.

Parameter	Calibration period (1993– 1996)				Treatment period (2004–2007)					
	Snowmelt		Rainfall		Snowmelt			Rainfall		
	n	$P > \chi^2$	n	$P > \chi^2$	n	$P > \chi^2$		n	$P > \chi^2$	
FWMC‡§										
Sediment	5	0.83 NS¶	9	0.17 NS	21	0.001**	conventional > conservation	10	0.29 NS	–
TN#	5	0.96 NS	9	0.17 NS	16	<0.0001***	conventional > conservation	10	0.17 NS	–
PN#	5	0.63 NS	9	0.17 NS	16	0.31 NS	–	10	0.04*	conventional < conservation
TDN	5	0.76 NS	9	0.92 NS	21	<0.0001***	conventional > conservation	10	0.32 NS	–
NO_x	5	0.69 NS	9	0.92 NS	21	<0.0001***	conventional > conservation	10	0.50 NS	–
NH_3	5	0.35 NS	9	0.60 NS	21	0.93 NS	–	10	0.55 NS	–
TP	5	0.63 NS	9	0.17 NS	21	<0.0001***	conventional < conservation	10	0.002**	conventional < conservation
PP	5	0.69 NS	9	0.60 NS	21	0.61 NS	–	10	0.01*	conventional < conservation
TDP	5	0.63 NS	9	0.17 NS	21	<0.0001***	conventional < conservation	10	0.0002***	conventional < conservation
Export										
Runoff	5	0.45 NS	9	0.92 NS	22	0.96 NS	–	17	0.059†	conventional > conservation
Sediment	5	0.96 NS	9	0.92 NS	22	0.078†	conventional > conservation	17	0.047*	conventional > conservation
TN#	5	0.89 NS	9	0.46 NS	16	0.0002***	conventional > conservation	17	0.069†	conventional > conservation
PN#	5	0.83 NS	9	0.46 NS	16	0.26 NS	–	17	0.13 NS	–
TDN	5	0.89 NS	9	0.92 NS	22	0.0008***	conventional > conservation	17	0.036*	conventional > conservation
NO_x	5	0.63 NS	9	0.92 NS	22	<0.0001***	conventional > conservation	17	0.006**	conventional > conservation
NH_3	5	0.69 NS	9	0.92 NS	22	0.87 NS	–	17	0.018*	conventional > conservation
TP	5	0.31 NS	9	0.60 NS	22	0.021*	conventional < conservation	17	0.17 NS	–
PP	5	0.45 NS	9	0.92 NS	22	0.85 NS	–	17	0.081†	conventional > conservation
TDP	5	0.35 NS	9	0.92 NS	22	0.007**	conventional < conservation	17	0.36 NS	–

* Significant at $P < 0.05$.

** Significant at $P < 0.01$.

*** Significant at $P < 0.001$.

† Significant at $P < 0.10$.

‡ FWMC, flow-weighted mean concentration; NO_x, nitrate + nitrite; PN, particulate nitrogen; PP, particulate phosphorus; TDN, total dissolved nitrogen; TDP, total dissolved phosphorus; TN, total nitrogen; TP, total phosphorus.

§ Nonparametric analysis presented for FWMC includes only those events when runoff occurred from both watersheds.

¶ NS indicates nonsignificance.

Snowmelt events were not analyzed for TN and PN in 2007. Therefore, these events were not included in the nonparametric analysis.

were statistically different for FWMC, indicating that the switch to conservation tillage increased the mean FWMC of NH_3 in runoff waters by 112% (Table 5).

Seasonally, Kruskal-Wallis tests indicated that there were no significant differences between the two watersheds in the FWMC and export of any of the five N parameters tested for snowmelt- or rainfall-induced runoff during the calibration period (Table 6). However, during the treatment period, the conservation tillage watershed produced significantly lower FWMCs and export of TN, TDN, and NO_x in snowmelt runoff waters compared with the conventional tillage watershed, but there were no significant differences in FWMC or export of PN and NH_3. During rainfall runoff, there were fewer significant differences between the watersheds than in the spring snowmelt period. For FWMC, only PN was significantly different between watersheds, with the conservation tillage watershed having larger concentrations than the conventional tillage watershed. Conservation tillage significantly reduced total export of TN, TDN, NH_3, and NO_x during these same rainfall-induced events.

Our results are consistent with those reported previously and suggest that conservation tillage is a BMP that can be recommended to reduce overall N concentrations and exports in runoff water for western Canadian producers. In previous studies where total N export in overland flow was reduced, it was typically due to reductions in rainfall-induced runoff (and preferential flow increased) after switching to reduced tillage methods (e.g., Baker and Laflen, 1983; Sims et al., 1994; Sharpley and Smith, 1994; Power et al., 2001). In our study, conservation tillage reduced runoff during the summer (which may partly explain the lower losses of N during that period), but annual and snowmelt runoff volume were not significantly different between the two tillage systems. However, significantly less N was exported from conservation tillage than conventional tillage, annually and seasonally. In the absence of a hydrological impact on N transport during snowmelt, we suspect that the differences between the two watersheds after conversion were due to differences in N mineralization between the tillage treatments. Power et al. (2001), in a review, discuss the effectiveness of present-day farming systems in controlling nitrate losses and suggest that as a result of tillage, N mineralization increases and nitrates frequently accumulate in the soil. Similarly, Campbell et al. (2008) reported on a 40-yr crop rotation study and suggested that tillage significantly promotes N mineralization in the Canadian prairies. In our study, soil nitrate-N levels (0–15 cm) were consistently higher in the conventional tillage watershed than in the conservation tillage watershed during the treatment period (Table 2). Also, the conversion to conservation tillage had a much larger influence on the concentration and export of NO_x than NH_3 within surface runoff waters. These observations suggest that differences in N losses in our study are also due to higher rates of N mineralization under conventional tillage than under conservation tillage.

Phosphorus

Analysis of covariance showed that conservation tillage also had a significant effect on concentration and export of TP in runoff waters. However, the effect of conservation tillage on TP losses in runoff waters was opposite to its effect on N. When all runoff events were considered, significant differences between calibration and treatment period regression slopes or intercepts indicated a shift toward greater annual P losses after conversion to conservation tillage (Table 5; Fig. 2d). Overall, converting to conservation tillage increased the FWMC and export of TP by 42 and 12%, respectively.

Conversion to conservation tillage influenced the concentration and export of PP and TDP in runoff differently (Table 5). During the treatment period, converting to conservation tillage reduced the FWMC of PP by approximately 20%, but there were no significant differences between slopes or intercepts using the full- or the reduced-form ANCOVA model. For total annual export of PP, the reduced-form ANCOVA model indicated that differences in intercepts were statistically significant, and conservation tillage was calculated to have reduced the mean PP export by 37% annually (Table 5). For TDP, there were no significant differences between the conventional and conservation tilled watersheds for FWMC using the full-form ANCOVA model. Using the reduced-form ANCOVA model, it was determined that conservation tillage increased the FWMC of TDP by 52% during the treatment period. Similarly, for total export of TDP, there was a significant shift in the regression equation toward larger exports from the conservation tillage watershed during the treatment period. Converting to conservation tillage increased TDP export by 36%, which more than offset any decreases in PP export because dissolved P comprised the majority of P losses before and after conversion (Table 4).

Seasonally, nonparametric statistical analyses revealed no significant differences between the two watersheds in the FWMC and export of any of the three P parameters for snowmelt- or rainfall-induced runoff during the calibration period (Table 6). During the treatment period, the conservation tillage watershed produced significantly higher FWMCs and export of TP and TDP in snowmelt-induced runoff compared with the conventional tillage watershed, but there were no differences between tillage systems for PP. During rainfall-induced runoff events, the conservation tillage watershed produced significantly greater FWMCs of TP, PP, and TDP than the conventional tillage watershed. However, the conventional watershed produced significantly greater exports of PP, whereas there were no significant differences between watersheds for TP and TDP exported over the summer.

We suspect that conservation tillage had opposite effects on the export of PP and TDP in runoff water because of differences in their source and transport factors. Recent research in western Canada indicates that source-oriented factors, such as soil test P concentrations, are quite strongly associated with TP loss from prairie soils (Little et al., 2007; Sawka et al., 2007). However, the export of PP in runoff is not necessarily related directly to soil test P concentrations and is often much more dependent on the total export of eroded sediment (Daverede et al., 2003) and runoff event size (Sharpley et al., 2008). In the present study, the concentration and export of PP was highly correlated with that of TSS in both watersheds ($r > 0.85$). Because conservation tillage reduced TSS export, the export of PP was also reduced. Alternately, the export of TDP in runoff is directly related to the quantity and reactivity of P near the soil surface and increases as soil test P concentrations increase

(Sharpley et al., 1997). Concentrations of soil test P were greater in the surface soil under conservation tillage than under conventional tillage (Table 2) and would therefore contribute to greater TDP losses. The elevated concentrations of soil P could have been due in part to increased nutrient stratification under conservation tillage, where reduced tillage results in less mixing of P into deeper layers of soil (Selles et al., 1999).

Greater losses of soluble nutrients during snowmelt may also be due to the release of nutrients from plant residue that remains on the soil surface after harvest (Timmons et al., 1970; Rekolainen, 1989; Miller et al., 1994; Ulen 1997). This release of nutrients from crop (and weed) residue is especially important in cold-climate regions where freeze–thaw cycles increase cell rupture and release soluble nutrients, which are transported to surface waters during snowmelt (Bechmann et al., 2005; Roberson et al., 2007). Recent work in Manitoba has also shown that the contribution of residue and vegetative P (per unit area) to runoff losses may be larger than that from the soil and is most important in the early stages of the snowmelt period when soils are frozen (i.e., when the effective depth of interaction between soil and runoff water is reduced) and in years when runoff volumes are small (Saleh, 2008). Because fall tillage on the conventional treatment incorporates crop residues and weeds, vegetative residues are a second probable source of higher TDP losses under conservation tillage in our study (Table 2). Further research is necessary to quantify the relative contribution of soil and crop residue toward total P losses from agricultural watersheds during the snowmelt period in the Canadian prairies.

Our results regarding the impact of conservation tillage on PP and TDP losses from agricultural watersheds are consistent with previous studies reporting that conservation tillage can increase the export of TDP (e.g., Baker and Laflen, 1983). However, because the majority of TP transported from conventionally tilled land in previous studies was in the particulate form and bound to sediment, TP losses were usually reduced because losses of sediment and PP were controlled. For example, in the Southern Plains region of the United States, Sharpley and Smith (1994) reported that even though conversion to no-till increased concentration and export of TDP in runoff, concentrations of TP decreased from 3.1 to 0.4 mg L^{-1}, with exports of P reduced by 3.1 kg ha^{-1} yr^{-1}. Even in other cold-climate regions, Puustinen et al. (2005) and Ulen and Kalisky (2005) (in Finland and Sweden, respectively) report that total P loading from plot experiments was reduced by decreasing the amount and intensity of tillage, despite the fact that most erosion and P loading occurred outside of the growing season and dissolved P losses were greater under reduced tillage systems. In our study, the average yearly export of TDP was similar to that reported previously for conventional and conservation tillage in more humid regions, but the total export of TSS from both watersheds was extremely low in comparison. This resulted in very low PP export and, overall, in total P exports being much lower (<1 kg P ha^{-1} yr^{-1}) than those reported from conventional tillage studies (e.g., 4–20 kg P ha^{-1} yr^{-1}) in the American midwest (e.g., Baker and Laflen, 1983; Sharpley and Smith., 1994; Ginting et al., 1998; Sharpley et al., 2008). Because TDP was the dominant fraction of P exported from both watersheds in our study, any changes to TDP had a much larger effect on annual TP losses in this environment than in most previous studies. Similar results to ours were reported by Gaynor and Findlay (1995). In their plot study, conservation tillage effectively reduced soil erosion during rainfall but increased annual P losses because dissolved P accounted for ~90% of transported P in that region of southern Ontario. In Minnesota, Hansen et al. (2000) also reported that total P losses from runoff plots were higher for ridge-till and chisel plow systems than for a conventionally tilled, moldboard plowed system where soluble P averaged 75% of the total losses (from all tillage systems). This suggests that management practices designed to reduce losses of sediment and sediment-bound P from agricultural fields and watersheds can be much less effective in regions where P export is snowmelt driven and predominantly in the dissolved form.

From a transport perspective, once dissolved nutrients start to move with snowmelt water, they are very difficult to intercept due to the fact that most of the soil is frozen and there is little plant growth and nutrient uptake. Therefore, source management practices, such as reducing the quantity of soil nutrients near the soil surface by managing cropping systems, tillage systems, and nutrient application rates should be the most effective means for reducing the potential for dissolved nutrients to contaminate surface waters in Manitoba. As a result, in regions where the ratio of TDP/TP is high, some tillage may be a preferable management practice to reduce dissolved P (and hence TP) losses in runoff. For example, in Indiana, Smith et al. (2007) report that losses of soluble nutrients (N and P) were reduced in the first year after tilling a long-term, no-tillage field. In Manitoba and across the Northern Great Plains of western Canada, fall tillage perhaps once in a 3- or 4-yr rotation may be needed to reduce the risk of dissolved P losses in snowmelt waters. However, further research is required to test this theory. The benefits of conservation tillage (e.g., reduced wind, water and tillage erosion, reduced time and energy required for seedbed preparation, increased snow trapping and water use efficiency, potential sequestration of carbon, etc.) must be weighed against potentially greater export of P to surface water when assessing the overall effectiveness of conservation tillage systems in cold, dry environments.

Summary and Conclusions

Controlling nutrient losses, in particular N and P, from agriculturally dominated watersheds is dependent on our understanding and management of their source and transport factors. In particular, it is important to understand how these factors interact within local climates and landscapes when recommending BMPs to reduce and control nutrient export. Without this understanding, BMPs encouraged by education, incentives, and regulations may be ineffective and even counterproductive. In this study, the conversion to conservation tillage reduced the annual mean export of TSS by 65%. Similarly, conservation tillage reduced the concentration and export of TN by 41 and 68%, respectively. However, the effect of conservation tillage on P losses in runoff waters was opposite to that for TSS and TN. Converting to conservation tillage increased the annual concentration and export of TP by 42 and 12%, respectively. Overall, our results suggest that conservation tillage systems in the Canadian prairies are more susceptible to losses of soluble P (especially in snowmelt runoff), likely due to the accumulation of P at the soil surface and the leaching of P from crop residues. Because TDP was the dominant fraction of P exported from both watersheds in our study, any changes to TDP had a much larger effect on annual TP losses in this environment than it did in most previous studies. It is apparent from our results that management practices such as conservation tillage, that are designed to improve water quality by reducing sediment and sediment-bound nutrient export from agricultural fields and watersheds, can be less effective in cold, dry regions where nutrient export is snowmelt driven and primarily in the dissolved form. In these situations, it may be most practical to implement management practices that reduce the accumulation of nutrients in crop residues and surface soil.

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