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The Effects of Multiple Beneficial Management Practices on Hydrology and Nutrient Losses in a Small Watershed in the Canadian Prairies

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Most beneficial management practices (BMPs) recommended for reducing nutrient losses from agricultural land have been established and tested in temperate and humid regions. Previous studies on the effects of these BMPs in cold-climate regions, especially at the small watershed scale, are rare. In this study, runoff and water quality were monitored from 1999 to 2008 at the outlets of two subwatersheds in the South Tobacco Creek watershed in Manitoba, Canada. Five BMPs—a holding pond below a beef cattle overwintering feedlot, riparian zone and grassed waterway management, grazing restriction, perennial forage conversion, and nutrient management—were implemented in one of these two subwatersheds beginning in 2005. We determined that >80% of the N and P in runoff at the outlets of the two subwatersheds were lost in dissolved forms, ≈ 50% during snowmelt events and ≈ 33% during rainfall events. When all snowmelt- and rainfall-induced runoff events were considered, the five BMPs collectively decreased total N (TN) and total P (TP) exports in runoff at the treatment subwatershed outlet by 41 and 38%, respectively. The corresponding reductions in flow-weighted mean concentrations (FWMCs) were 43% for TN and 32% for TP. In most cases, similar reductions in exports and FWMCs were measured for both dissolved and particulate forms of N and P, and during both rainfall and snowmelt-induced runoff events. Indirect assessment suggests that retention of nutrients in the holding pond could account for as much as 63 and 57%, respectively, of the BMP-induced reductions in TN and TP exports at the treatment subwatershed outlet. The nutrient management BMP was estimated to have reduced N and P inputs on land by 36 and 59%, respectively, in part due to the lower rates of nutrient application to fields converted from annual crop to perennial forage. Overall, even though the proportional contributions of individual BMPs were not directly measured in this study, the collective reduction of nutrient losses from the five BMPs was substantial.

Technological advances over the past century have allowed agriculture to become more productive. Many modern farming practices, however, such as the use of synthetic fertilizers and pesticides and the enclosure of livestock in pastures and barns, have contributed to some degree of environmental degradation, including the decline of water quality (Coote and Gregorich, 2000). In the Prairie province of Manitoba in Canada, deteriorating water quality in Lake Winnipeg—the 10th largest freshwater lake in the world—has been partly attributed to excessive nutrient loading (Lake Winnipeg Stewardship Board, 2006). To protect the health of Lake Winnipeg, actions must be taken to reduce nutrient losses from different sources, including those from agriculture.

For decades, beneficial management practices (BMPs) have been developed and promoted to reduce nutrient losses from agricultural land (Schnepf and Cox, 2006). Many of these BMPs were established in temperate and humid regions where nutrient losses from agricultural lands are mainly in particulate form and associated with rainfall runoff and erosion. In cold-climate regions such as much of the Canadian Prairies, annual precipitation falls predominantly in the form of rainfall. However, snowfall typically accounts for 20% of the total annual precipitation, and snow accumulates throughout the winter months, melting when temperatures increase in the spring. In addition, snowmelt often occurs on frozen soil with almost no infiltration, and, therefore, surface runoff is encouraged. Consequently, the magnitude of snowmelt-induced runoff often exceeds rainfall-induced runoff, and snowmelt runoff events often last longer than typical rainfall runoff events (Nicholaichuk, 1967; Granger and Gray, 1990; Chanasyk and Woytowich, 1986; Granger et al., 1984; Little et al., 2007). During the snowmelt period, low infiltration rates also result in prolonged saturated condition on the soil surface, encouraging the release of dissolved nutrients (e.g., Bechmann et al., 2005; Ontkean et al., 2005; Little et

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Abbreviations: %Rd, average percent reduction; ANCOVA, analysis of covariance; AvgFR, average flow rate; BMP, beneficial management practice; FWMC, flow-weighted mean concentration; MSC. monitoring station at Madill subwatershed outlet; MSH, monitoring station at holding pond; MST, monitoring station at Steppler subwatershed outlet; PkFR, peak flow rate; PN, particulate nitrogen; POC, particulate organic carbon; PP, particulate phosphorus; STC, South Tobacco Creek; TDN, total dissolved nitrogen; TDP, total dissolved phosphorus; TN, total nitrogen; TP, total phosphorus; UFV, unit flow volume; VolR, flow volume ratio; WEBs, Watershed Evaluation of Beneficial Management Practices.

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al., 2006; Ulen et al., 2007). Although snowmelt runoff is usually less erosive than rainfall runoff (due to the absence of raindrop splash to initiate the transport of soil particles), snowmelt-induced soil losses have been reported to exceed rainfall-induced soil losses in western Canada because of the large runoff volumes and low infiltration rates in snowmelt events (e.g., Chanasyk and Woytowich, 1986; van Vliet and Hall, 1991; McConkey et al., 1997).

Because of the different mechanisms between snowmelt and rainfall runoff, the effectiveness of a given BMP in reducing nutrient losses in a cold-climate region may be different from that in a temperate-climate region. For example, Salvano et al. (2009) tested the performance of three P risk indicators (Birr and Mulla's P Index, a preliminary P risk indicator for Manitoba, and a preliminary version of Canada's National Indicator of Risk of Water Contamination by Phosphorus) using water monitoring data from 14 watersheds in southern Manitoba, Canada. It was determined that all three P risk indicators performed poorly and need to be modified to suit the cold climate, soils, and landscapes in southern Manitoba. Similarly, numerous studies showed that adoption of conservation tillage is effective in reducing particulate P but may increase dissolved P in the surface runoff (e.g., Baker and Laflen, 1983; Sharpley et al., 1994; Bundy et al., 2001; Daverede et al., 2003). In temperate-climate regions, particulate P typically dominates the total P loss, and the reduction in particulate P more than offsets any increases in dissolved P. Therefore, the overall effect of conservation tillage is a decrease of total P loss. However, also in southern Manitoba, Tiessen et al. (2010) reported that total P export from a field under conservation tillage was greater than that from its paired conventionally tilled field because P loss from these fields was dominated by dissolved P in snowmelt runoff, which was greater under conservation tillage than under conventional tillage system. Similar results have been reported by researchers in Scandinavia (Ulen et al., 2010). Clearly, the effects and anticipated benefits from agricultural BMPs developed in temperate-climate regions need to be reevaluated for cold-climate regions.

Previous field studies on the effects of BMPs in cold-climate regions have been conducted primarily at the plot or infield scale, and many used the changes in soil nutrient concentrations resulting from BMP implementation to indicate its impact on nutrient losses from the field (e.g., Uusi-Kamppa, 2005; Vaananen et al., 2006; Miller et al., 2010b). Although these studies are crucial for understanding individual processes, it has been recognized that plot- or infield-scale research often fails to capture the complexities and interactions among BMPs, biophysical settings, and land use within a watershed (Schnepf and Cox, 2006; Hoffmann et al., 2009). It can therefore be difficult to relate results at the plot or in-field scale to overall improvements in receiving water quality for a region. Unfortunately, watershed-scale studies on the effects of BMPs on nutrient losses in cold-climate regions are still rare. Moreover, previous watershed-scale studies in cold-climate regions have dealt only with single BMPs (e.g., Sheppard et al., 2006; Eastman et al., 2010; Miller et al., 2010a; Tiessen et al., 2010, 2011), whereas in reality, multiple BMPs are often required and applied by producers to different fields in a watershed. We are not aware of any studies performed to quantify the effects of multiple BMPs at the watershed scale in cold-climate regions.

One difficulty of watershed-scale studies stems from the temporal variability of climate and, therefore, hydrology. Over short study periods (e.g., 2 to 3 yr), the effects of various BMPs are often overwhelmed by the natural variability of water quality due to climate and hydrology. To overcome this difficulty, a paired watershed design has been recommended in which two paired watersheds are examined simultaneously and BMP treatments are applied to only one watershed (Spooner et al., 1985; Clausen et al., 1996). To test the BMP effect, these authors recommend using an analysis of covariance (ANCOVA), in which the control watershed (without the implementation of BMPs) serves as a reference to account for temporal variations in water quality due to climate and hydrology, allowing for the effect of the BMP(s) on changes in water quality in the BMP treatment watershed to be quantified. Guidelines established by the USEPA for applying ANCOVA recommend the use of a single covariate, the water quality variable measured at the control watershed, to predict the matched variable measured at the treatment watershed (USEPA, 1993, 1997a,b). This simple ANCOVA method has been applied successfully in many studies to examine the BMP effects on watershed water quality (Meals, 2001; King et al., 2008; Tiessen et al., 2010). In their classic paper on the statistical power of pairing, Loftis et al. (2001) identified the need to incorporate other covariates into the ANCOVA (termed multivariate ANCOVA herein). Schilling and Spooner (2006) successfully used a multivariate ANCOVA to examine the effects of watershed-scale land use change on stream nitrate concentrations in the Walnut Creek watershed in Iowa, USA. Similarly, in New York, Bishop et al. (2005) used three hydrologic variables as covariates in their study to evaluate the effects of a suite of BMPs on streamwater phosphorus. The authors concluded that by incorporating additional hydrologic variables, the statistical power of the ANCOVA can be significantly increased and the minimum detectable treatment effect can be greatly reduced— therefore, the effect of BMP can be detected in a relatively short period.

The objective of this study was to use simple and multivariate ANCOVAs to quantify both the seasonal and overall effects of multiple BMPs recommended for use in Manitoba—a holding pond downstream of a beef cattle overwintering feedlot, riparian zone and grassed waterway management, grazing restriction, perennial forage conversion, and nutrient management—to reduce nutrient exports and concentrations in surface runoff to receiving waters at the small watershed scale under cold-climate conditions typical of the Canadian Prairies.

Materials and Methods

Study Sites

To validate the performance of selected BMPs in a watershed setting, Agriculture and Agri-Food Canada launched the Watershed Evaluation of Beneficial Management Practices (WEBs) project in 2004 (AAFC, 2007b). A core component of the WEBs project was to quantify the biophysical impacts of BMPs on environment factors such as nutrient losses to water bodies. The effects of selected BMPs were examined in seven watersheds across Canada. This paper reports on the results for one of these seven watersheds, the South Tobacco Creek (STC) watershed, located near the town of Miami in southwest Manitoba, Canada, and within the drainage area of Lake Winnipeg (Fig. 1a). Detailed background information about the STC watershed was given in Tiessen et al. (2010, 2011). The dominant soils in the region are Dark Gray Chernozems (Mollisols), mostly clay loam in texture, formed on moderately to strongly calcareous glacial till that overlay shale bedrock (Soil Classification Working Group, 1998). Dominant landscapes in this region are undulating to hummocky landscapes (AAFC, 2007a). The climate is classified as subhumid continental with short cool summers and long cold winters. The long-term mean annual precipitation is ≈ 550 mm with 25 to 30% occurring as snowfall. The mean annual temperature is ≈ 3°C, and the monthly average temperatures are below zero from November through March (Environment Canada, 2011). Most of the land in the STC watershed is used for agricultural production, including cereal crops, oilseeds, perennial forages, and livestock.

Two small subwatersheds, the Madill and Steppler subwatersheds, within the larger STC watershed were examined in this study. The two subwatersheds are located approximately 3 km apart, and both are situated in the headwaters of the STC watershed (Fig. 1a). The Madill subwatershed has a drainage area of 207 ha (Fig. 1b). During the experimental period (1999–2008), no BMP was implemented, and land use (mainly annual crop land) has remained largely unchanged. The Steppler subwatershed has a drainage area of 205 ha, most of which is operated by a single producer. The farm site is located inside the subwatershed and consists of farm buildings and a cattle feedlot for overwintering/feeding (1.9 ha, Fig. 1c). The producer operates a mixed farm: growing cereal grains and oilseeds and managing a beef cattle herd of approximately 100 cows. The farm is divided into several fields separated by two small intermittent watercourses traversing the farm. Fields are seeded to either cereal grains or oilseeds on a rotational basis. Five BMPs—a holding pond downstream of a beef cattle overwintering feedlot, riparian zone and grassed waterway management, grazing restriction, forage conversion, and nutrient management—were initiated in the Steppler subwatershed in 2005 (Table 1, Fig. 1c) to reduce the environmental impact of agricultural practices. These BMPs are recommended for use in Manitoba by the local government or soil and water conservation groups (e.g., MSFAC, 2007; MAFRI, 2009).

Overall, the Madill and Steppler subwatersheds were similar in size, climate, landscapes and land uses. The main differences between these two subwatersheds are that (i) most annual cropped fields in the Madill subwatershed were under conservation tillage, whereas those in the Steppler subwatershed were

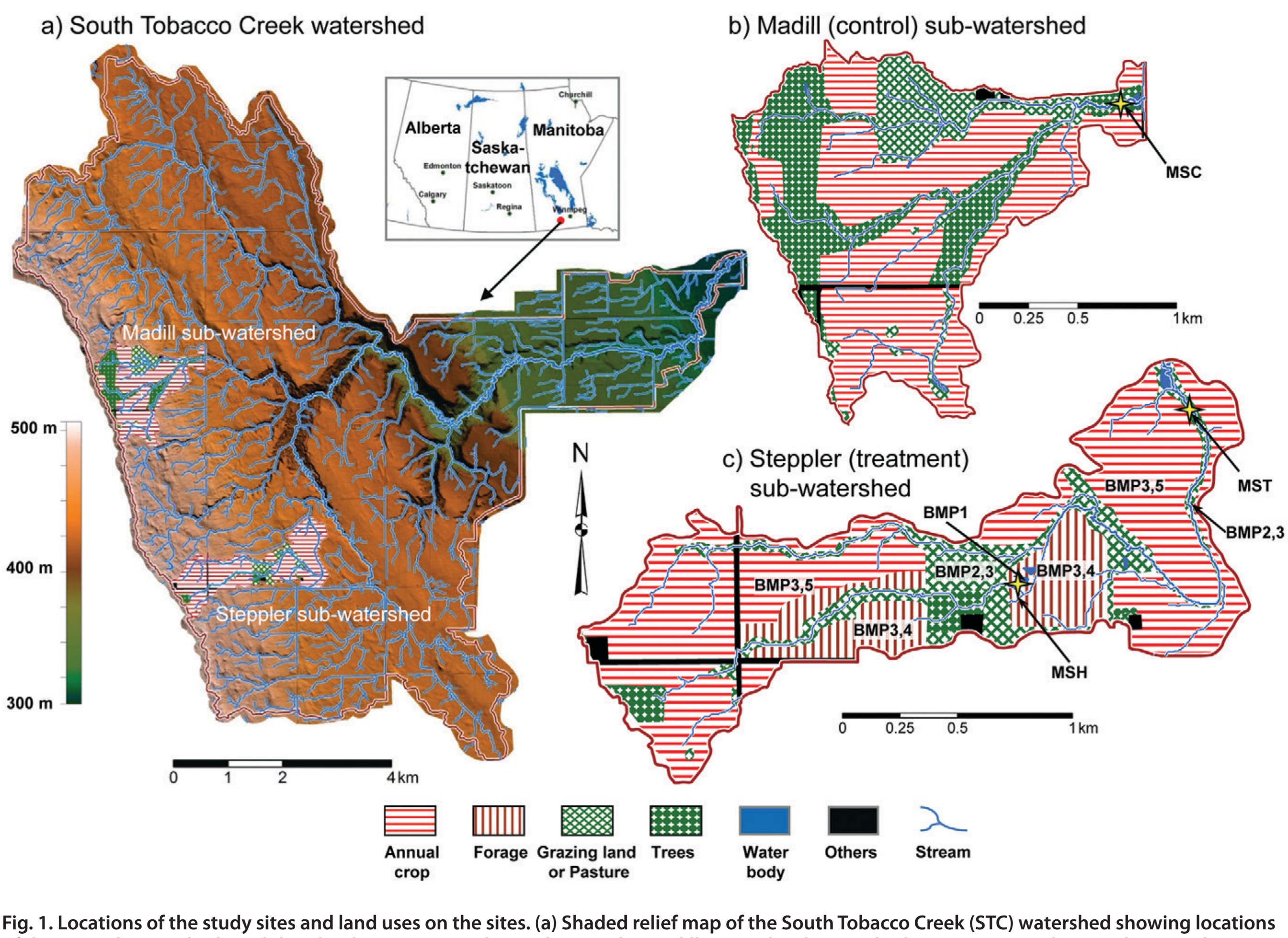

Fig. 1. Locations of the study sites and land uses on the sites. (a) Shaded relief map of the South Tobacco Creek (STC) watershed showing locations of the two subwatersheds and their land uses in 2002. (b) Land use at the Madill (control) subwatershed in 2008. (c) Land use at the Steppler (treatment) subwatershed in 2008 and beneficial management practices (BMPs) implemented at the Steppler (treatment) subwatershed since 2005. MSC, MST and MSH are water monitoring stations at the outlets of the control and treatment subwatersheds and the inlet of holding pond, respectively. BMP1 to 5 are holding pond, riparian management, grazing restriction, forage conversion, and nutrient management BMP, respectively (see Table 1 for details).

Table 1. Beneficial management practices (BMPs) implemented at the Steppler (treatment) subwatershed during the post-BMP period.

	BMP	Affected area		Year initiated	Operation period	Description
		ha	%†			
1	Holding pond downstream of a beef cattle overwintering feedlot	2	1	2005	2006–2010	Located immediately downstream of the beef cattle overwintering feedlot with a beef cattle herd of ~100 cows. Runoff from the feedlot site was directed to the holding pond via ditches. The holding pond was designed to retain all runoff water.
2	Riparian zone and grassed waterway management	43	21	2005	2005–2010	Various measures including widening and fencing the riparian area and grassed waterway, mechanical harvesting, and rotational grazing.
3	Grazing restriction	205	100	2005	2005–2008	Grazing was not allowed within the Steppler subwatershed except for the riparian areas and the pastured areas in one field, where grazing was only allowed for 2 wk in the spring and 2 wk in the summer.
4	Perennial forage conversion	26	13	2005	2006–2008	Convert annual cropland to perennial forage field (alfalfa).
5	Nutrient management	121	59	2005	2005–2010	Reduce fertilizer and manure application on annual cropland based on crop needs and soil testing.

† Percentage of the total catchment area of the Steppler subwatershed.

mainly under conventional tillage (i.e., primary tillage involving the use of a heavy duty chisel plow); (ii) the riparian areas of the Madill subwatershed were wide and mostly vegetated with trees, whereas those of the Steppler subwatershed were narrower and contained pasture lands without trees; and iii) the streams in the Madill subwatershed were incised in the landscape, whereas those in the Steppler subwatershed were less incised and shallow. Despite these differences, however, the similarity between the two watersheds and the ANCOVA method allows for the Madill subwatershed to be used as a control to test the effects of BMPs implemented at the Steppler subwatershed (the treatment watershed).

Sample Collection and Laboratory Analysis

Monitoring stations were established at the outlets of the Madill and Steppler subwatersheds in 1999. These stations—MSC for the Madill (control) subwatershed and MST for the Steppler (treatment) subwatershed—correspond to the inflow water monitoring stations described by Tiessen et al. (2011) in their examination of the effects of small reservoirs on retaining sediments and nutrients. Because the same raw data were used, detailed descriptions about sample collection and laboratory analysis can be found in Tiessen et al. (2011). Briefly, water levels in the two reservoirs were monitored on continuous basis using electronic water-level recorders. The water levels, in conjunction with the hydraulic parameters of each reservoir, were used to calculate the inflow and outflow hydrographs (hourly data). Water quality samples were collected using an auto-sampler (Sigma 800SL, American Sigma, Medina, NY; or 900MAX, Hach Company, Loveland, CO) triggered using a float system. During low flow events, additional samples were collected manually and used to augment the auto-sampler collected samples. Water quality sampling was conducted between 1999 and 2008 (i.e., the study period). However, no water quality samples were taken in 2003. Construction of the holding pond below the cattle overwintering site and the widening of the riparian areas were performed in 2005, so that data collected in 2005 were excluded from the analysis. Overall, there were 5 yr (1999–2002 and 2004) of data for the period before the BMP implementation (the pre-BMP period) and 3 yr (2006–2008) of data for the period after the BMP implementation (the post-BMP period).

After sample collection, sample bottles were extracted from the auto-sampler, packed on ice, and sent to the Fisheries and Oceans Canada's Freshwater Institute Laboratory in Winnipeg, MB, for analyses of total phosphorus (TP), total dissolved phosphorus (TDP), particulate phosphorus (PP), total nitrogen (TN), total dissolved nitrogen (TDN), particulate nitrogen (PN), ammonia (NH_3), nitrate and nitrite (NO_x), and particulate organic carbon (POC). Methods used for the laboratory analyses were described in detail by Tiessen et al. (2011).

Data Preparation

Hydrographs of the two subwatersheds were split into paired runoff events following a procedure similar to that described by Tiessen et al. (2011). The time durations of each pair of events were kept the same for the two watersheds. Each runoff event was determined as either a snowmelt event or a rainfall event based on the climate data (temperature and precipitation) recorded at a nearby Environment Canada weather station (Miami-Orchard, 49°22′ N, 98°17′ W). Diurnal fluctuations of runoff during snowmelt period were not considered separate runoff events. Similarly, a single rainfall runoff event could include multiple peaks with lower flow rates between the peaks. Therefore, a typical runoff event in both spring and summer would have a rising limb starting from a flow rate of zero, one to several peaks with large flow rates, and a falling limb ending at a flow rate of zero. Initially, 71 events were defined for the entire study period (8 yr). However, four rainfall events (one in 2000 and three in 2004) were unmatched (zero flow flux on one subwatershed). These unmatched events were considered to be the result of differences in precipitation between the two sites, not the effects of BMPs and were therefore eliminated from the analyses. In addition, two rainfall events in 2007 were not sampled and were also eliminated from the analyses. Consequently, a total of 65 paired events (19 snowmelt and 46 rainfall events) were included in the analyses.

Three hydrologic variables—flow volume ratio (VolR), average flow rate (AvgFR) and peak flow rate (PkFR)—were calculated as suggested by Bishop et al. (2005). Flow volume ratio (dimensionless), which characterizes the imbalances in hydrology for matched events between the two subwatersheds, was calculated as the flow volume on the treatment subwatershed divided by that on the control subwatershed for paired events. Unit flow volume (UFV, $m^3\ ha^{-1}$), calculated as the flow volume divided by the catchment area, was used for comparisons between the subwatersheds. Average flow rate ($L\ s^{-1}$), which reflects the intensity of runoff event, was calculated as the event flow volume divided by the duration of the event. Peak flow rate (L s^{-1}), which indicates the magnitude of runoff event, was determined as the maximum flow rate in the hydrographs for the duration of that event. Nutrient concentrations at hourly intervals were estimated from actual sample concentrations through interpolation between sampling times (e.g., Bishop et al., 2005; Tiessen et al., 2011). Nutrient exports (also termed fluxes or loads, g ha^{-1}) were calculated for each event as the sum of products of hourly nutrient concentrations and UFV. Flow-weighted mean concentrations (FWMC, mg L^{-1}) were calculated for each event as the total nutrient exports divided by total flow volume.

Statistical Analysis

Both the hydrologic variables and the nutrient loss variables were highly skewed (skewness normally >1.5). The natural log transformation was used to normalize the data as commonly applied in watershed studies (e.g., USEPA, 1993) and reduced the skewness of most of the data to between −0.5 and 1. All statistical analyses described below were performed on the transformed data.

The effects of BMPs on the hydrologic variables and nutrient export and FWMC were initially examined using two simple ANCOVA models as recommended by USEPA (1993, 1997a,b):

$$Y_i = a + b\mathrm{Prd}_i + cX_i + \varepsilon_i \qquad [1]$$

$$Y_i = a + b\mathrm{Prd}_i + cX_i + d\mathrm{Int}_i + \varepsilon_i \qquad [2]$$

where i is the event index; Y_i and X_i are the parameters measured on the treatment and control watersheds, respectively, for event i; Prd_i is the dummy variable created to indicate the experimental period of event i [0 for the pre-BMP (calibration) period and 1 for the post-BMP (treatment) period]; a is the intercept and b, c, and d are coefficients for Prd, C, and Int, respectively; ε_i is the residual error; and Int_i is the interaction term, calculated as:

$$\mathrm{Int}_i = \mathrm{Prd}_i\left(X_i - m\right) \qquad [3]$$

where m is the average of X_i during the post-BMP period. Equations [1] and [2] are equivalent to the reduced and full ANCOVA models used in many paired watershed studies (e.g., USEPA, 1993; Grabow et al., 1999; Tiessen et al., 2010).

The two simple ANCOVA models did not account for the effects of hydrologic variations on the nutrient loss variables, and, therefore, the effects of BMPs may have been overwhelmed by noise created due to the hydrologic differences between the two subwatersheds or the temporal variations of hydrology. To reduce this noise, a procedure similar to that described by Bishop et al. (2005) was adopted for the multivariate ANCOVA. A multivariate regression model was used to predict each nutrient loss variable (nutrient export or FWMC) at the treatment subwatershed (dependent variable, Y). The complete model was

$$\begin{aligned} Y_i = a + b\mathrm{Prd}_i + cX_i + d\mathrm{Int}_i + e\mathrm{VolR}_i + f\mathrm{AvgFR}_i \\ + g\mathrm{PkFR}_i + \varepsilon_i \end{aligned} \qquad [4]$$

in which the same nutrient loss variable measured at the control subwatershed (X), the interaction between the treatment (BMP implementation) and X (Int), and the three hydrologic variables (VolR, AvgFR and PkFR) were used as covariates (independent variables); e, f, and g are coefficients for VolR, AvgFR, and PkFR, respectively. Not all covariates in Eq. [4] were always necessary or beneficial for testing the effect of BMPs. To determine the effectiveness of the hydrologic covariates, Eq. [1] and [2] were used to test for effects of BMP implementation on the hydrologic covariates. In addition, we examined correlations among the covariates and between the covariates and nutrient loss variables. The multivariate ANCOVA was conducted as a multivariate regression analysis using the Reg procedure in SAS (SAS Institute, 2002). Data for the snowmelt and rainfall events were analyzed separately and in combination (all events). In each case, covariates (excluding Prd and X) were omitted if (i) they were significantly affected by the BMPs, or (ii) if they did not make a significant contribution to the model by increasing the determination coefficient (R^2) of the model (the Maxr option in the Reg procedure in SAS), or (iii) if their influences were not significant (t test, $P \leq 0.10$). The remaining covariates, together with Prd, X, and the intercept term (a), constituted the best multivariate ANCOVA model that (i) predicted the nutrient loss variables on the treatment subwatershed (i.e., Y_i) most effectively and (ii) described the effects of BMPs most accurately.

The best multivariate ANCOVA model for each nutrient loss variable was used to calculate a BMP-induced average percent reduction (%Rd) of that variable, following the method described by Grabow et al. (1999) and Bishop et al. (2005):

$$\%\mathrm{Rd} = \frac{\exp\left(\overline{Y_0}\right) - \exp\left(\overline{Y_1}\right)}{\exp\left(\overline{Y_0}\right)} 100 \qquad [5]$$

where $\overline{Y_0}$ and $\overline{Y_1}$ were predictions made with a Prd value of 0 and 1, respectively, using the best multivariate ANCOVA model and subsequently averaged across the entire study period. The 90% confidence intervals for the percent reductions ($\%\mathrm{Rd}_{90U}$ and $\%\mathrm{Rd}_{90L}$ for the upper and lower confidence intervals, respectively) were determined using the same method as that used to calculate %Rd, with the value of b being replaced by its 90% confidence intervals, which in turn was computed in SAS from the standard error of b. For models whose interaction terms (Int) were found to be significant, the %Rd, $\%\mathrm{Rd}_{90U}$, and $\%\mathrm{Rd}_{90L}$ values were each calculated from two "filled-in" event datasets, one for no-BMP and one for BMP implemented, to account for the effects of interactions between BMP and event magnitude (Bishop et al., 2005). Because of the high variability inherent in the data, a $P = 0.10$ was used as the significance threshold for all statistical analyses (Hansen et al., 2000; Tiessen et al., 2011).

Evaluation of the Holding Pond and Nutrient Management BMPs

The reductions in nutrient exports and FWMCs determined by the multivariate ANCOVA were an overall estimation for all five BMPs. Because of the interactions between BMPs at different scales, assessing the effects of individual BMPs on nutrient export at the watershed outlet was difficult. For example, the riparian management and grazing restriction BMPs were implemented throughout much of the treatment subwatershed, and their impacts could not be separated from those of the other BMPs (Fig. 1c). The perennial forage conversion BMP is being evaluated on two pairs of fields in the subwatershed, but we anticipate that several more years of data collection will be required before the assessment of this BMP is complete. Therefore, in this study, we focused the evaluation on the holding pond and the nutrient management BMPs.

The feedlot area did not receive runoff water from the upstream catchment area, and the runoff from the feedlot area was directed to the holding pond via ditches. The holding pond was designed to retain all runoff water from the feedlot. The retained water was used to irrigate a nearby forage field outside the treatment subwatershed. To evaluate the contributions of the holding pond BMP toward the changes in water quality at the outlet of the treatment subwatershed, a monitoring station was established at the inlet of the holding pond (MSH) in 2005 after the holding pond was built (Fig. 1c). Runoff entering the holding pond was monitored and water quality samples were collected and analyzed using methods similar to those used for the MSC and MST water samples. It must be recognized that before the holding pond was built, not all runoff and nutrient exports from the feedlot area was able to reach MST. From the feedlot area to MST, the stream length was 2.3 km (Fig. 1c). During transport, runoff and nutrients may be retained or lost through various processes (e.g., sedimentation, diffusion, and leaching) in the riparian zone and in the stream. In addition, nutrients may be transformed to different forms (e.g., from particulate to dissolved or gaseous forms and from NH_3 to NO_x, or vice versa). Therefore, the effects of the holding pond can only be assessed indirectly. The reductions in runoff and nutrient exports at MST due to the holding pond (%Rd_h) were approximated by

$$\%\mathrm{Rd_h} = \frac{kE_\mathrm{h}}{E_\mathrm{t} + kE_\mathrm{h}}100 \qquad [6]$$

where E_t and E_h are the total runoff (m^3) or nutrient export (g) measured at MST and MSH, respectively, and k is the fraction of runoff or nutrient export from the feedlot (MSH) that is delivered directly to MST, whereas 1 – k represents the fraction that is lost, in the absence of the holding pond. The value of factor k ranges from 0 to 1 and may be different for flow volume and nutrient exports or vary temporarily. The exact values of factor k for different variables were unknown. However, the feedlot was adjacent to a stream, and net losses in flow volume and nutrients in streams were usually small (Fig. 1c). Therefore, the values of factor k were likely close to 1 for most variables examined in this study. When k = 1, the %Rd_h reaches its maximum value (denoted as %Rd_{hmax}), which is also a measure of potential contribution of the feedlot toward the runoff or nutrient exports at MST. The contribution of holding pond toward the reductions of nutrient exports at MST (%Ctb_h) was approximated by

$$\%\mathrm{Ctb_h} = \frac{\%\mathrm{Rd_h}}{\%\mathrm{Rd}}100 \qquad [7]$$

where %Rd_h is the reduction of nutrient export due to the holding pond and %Rd is the reduction of nutrient export observed at MST (Eq. [5]). Flow-weighted mean concentrations at MSH ($FWMC_h$) and MST ($FWMC_t$) were used to calculate a ratio (R_{FWMC}) to characterize the differences in FWMCs between the two water monitoring stations:

$$R_{\mathrm{FWMC}} = \frac{\mathrm{FWMC_h}}{\mathrm{FWMC_t}} \qquad [8]$$

The nutrient management BMP was extensively applied in the treatment subwatershed. To assess the effects of the nutrient management BMP, a simplified budget analysis was performed to estimate the nutrient balances on cropped fields in the two subwatersheds:

$$B = I_{\mathrm{f,m}} - R_\mathrm{h} \qquad [9]$$

where B is the N or P balance (kg ha^{-1} yr^{-1}), $I_{f,m}$ is the N or P inputs from fertilizer and manure applications (kg ha^{-1} yr^{-1}), and R_h is the N or P removal due to crop harvesting (kg ha^{-1} yr^{-1}). Fertilizer and manure applications and crop yields were recorded for all fields in both subwatersheds throughout the entire study period. The amount of fertilizer applied was converted to net fertilizer-N and -P inputs based on the fertilizers' N and P contents, respectively, taking into account the time and method of application (MSFAC, 2007). The amount of manure applied was also converted to net N and P inputs based on generalized manure-N and -P concentrations in Manitoba, respectively, taking into account the manure type and time and method of application (MAFRI, 2009). Similarly, crop yield was converted to N and P removals due to crop harvesting based on generalized values for typical N and P concentrations in Manitoba crops (MSFAC, 2007). The N and P balances were calculated as net N and P inputs subtracted by N and P removals, respectively. The N and P inputs, removals and balances were determined on an annual basis for each field in the two subwatersheds, which was categorized as either an annual-cropped field or a perennial forage field. The data were then averaged within each subwatershed for given crop categories and also for all cropped fields. The annual N and P input, removal, and balance data were averaged for the pre-BMP and post-BMP periods, and a two-way t test was used to test the significance level of the difference between the two periods.

Reductions in nutrient balances in cropped fields result in nutrient reductions on land, either in soil profile or on soil surface. However, nutrient reductions on land are not the same as nutrient reductions at the watershed outlet. Therefore, the nutrient budget analysis can only be used as an indirect assessment of the management BMP on the reduction of nutrient loss at the subwatershed outlet. Note also that there could be substantial errors associated with the calculated values in this simplified nutrient budget given that N and P concentrations in manure and crop were not directly measured and some sources and processes of N and P inputs and removals (e.g., N inputs from precipitation and biological N fixation in perennial legume forage crops) were not taken into account. However, most such errors were systemic biases for both monitoring periods and should have little effect on the differences between pre-BMP and post-BMP periods. Therefore, even though the absolute values for the nutrient budget within each period may not be exact, our estimates of the differences (or changes) between periods should be valid.

Results and Discussion

Hydrologic Variables

In the Steppler (treatment) subwatershed and the Madill (control) subwatershed, the three hydrologic variables shared similar patterns in the comparisons between snowmelt events and rainfall events, and between the pre-BMP period and the post-BMP period (Table 2, Fig. 2a). For example, on an event basis, except for the median UFV values in the control subwatershed, the median values of the three hydrologic variables for the snowmelt events were all greater than the respective ones for the rainfall events (Table 2). However, more rainfall events than snowmelt events occurred so that, in some cases, the total or annual average UFVs for rainfall events were greater than those for snowmelt events (Fig. 2a). Also, except for the UFV for rainfall events at the control subwatershed, the three hydrologic variables all decreased from the pre-BMP to the post-BMP period. These general similarities between the two subwatersheds, especially those for the pre-BMP period, strengthened the foundation for this paired watershed study. However, we observed some noticeable differences between the two subwatersheds. For example, the median values of the event UFV and AvgFR at the control subwatershed were consistently greater than those at the treatment subwatershed (Table 2). The annual total UFV was greater at the treatment subwatershed in some years but was lower in some other years, compared with that at the control subwatershed (Fig. 2a). Also, at the treatment subwatershed, the total UFV for snowmelt events in the entire study period was greater than that for rainfall events, whereas at the control subwatershed, opposite trends were observed. These differences in hydrology reflect the differences in

Table 2. Event median values for the hydrologic variables, nutrient exports, and flow-weighted mean concentrations (FWMCs) at the outlets of the Madill (control) and Steppler (treatment) subwatersheds.†

Period	n	Hydrology			Nutrient export									Nutrient FWMC								
		UFV	AvgFR	PkFR	TP	TDP	PP	TN	TDN	PN	NH_3	NO_x	POC	TP	TDP	PP	TN	TDN	PN	NH_3	NO_x	POC
		$m^3 ha^{-1}$	$L s^{-1}$	$L s^{-1}$	$g ha^{-1}$									$mg L^{-1}$								
Madill (control) subwatershed; catchment area = 207 ha																						
All events																						
Entire study	65	71	36	80	27	17	4.4	182	164	18	2.7	123	172	0.29	0.23	0.03	2.2	2.0	0.14	0.03	1.4	1.3
Pre-BMP	45	87	45	81	35	24	4.8	286	259	23	3.0	159	236	0.28	0.23	0.04	2.2	2.0	0.14	0.03	1.4	1.5
Post-BMP	20	45	16	25	12	10	0.9	79	64	5	1.2	33	48	0.29	0.22	0.02	1.9	1.4	0.12	0.02	1.2	1.0
Snowmelt events																						
Entire study	19	174	89	88	70	51	10.2	430	368	48	17.8	268	455	0.39	0.29	0.08	3.5	3.4	0.44	0.16	2.5	3.0
Pre-BMP	12	185	155	102	115	99	11.8	784	723	54	23.9	453	507	0.38	0.29	0.09	4.0	3.6	0.44	0.19	2.5	2.8
Post-BMP	7	79	51	81	23	22	5.8	200	173	36	4.5	154	324	0.53	0.50	0.07	3.4	3.2	0.46	0.08	2.7	4.1
Rainfall events																						
Entire study	46	59	33	63	19	12	2.5	126	96	10	1.4	65	112	0.25	0.22	0.02	1.9	1.5	0.11	0.02	1.0	1.1
Pre-BMP	33	77	36	80	27	16	4.5	175	154	18	1.8	109	172	0.25	0.22	0.04	2.1	1.8	0.14	0.02	1.2	1.2
Post-BMP	13	99	14	59	29	27	2.3	300	292	13	2.1	277	123	0.24	0.22	0.01	1.2	1.1	0.06	0.01	0.6	0.8
Steppler (treatment) subwatershed; catchment area = 205 ha																						
All events																						
Entire study	65	37	22	72	13	11	1.3	80	62	7	1.6	17	61	0.35	0.30	0.03	2.0	1.6	0.16	0.05	0.4	1.4
Pre-BMP	45	46	26	111	19	16	2.5	96	88	14	2.1	32	94	0.39	0.34	0.04	2.5	2.2	0.18	0.05	0.5	1.7
Post-BMP	20	16	6	27	4	4	0.4	28	24	3	0.5	5	24	0.26	0.21	0.02	1.2	1.1	0.15	0.02	0.2	1.2
Snowmelt events																						
Entire study	19	85	74	183	31	28	2.6	385	336	14	8.6	113	94	0.48	0.45	0.04	4.0	3.7	0.18	0.12	2.3	1.7
Pre-BMP	12	147	111	232	66	62	3.9	561	542	21	10.5	420	162	0.51	0.46	0.05	4.6	4.4	0.27	0.14	3.1	1.9
Post-BMP	7	45	43	46	13	13	0.6	55	51	4	3.1	37	34	0.47	0.44	0.02	2.0	1.8	0.14	0.07	1.1	1.1
Rainfall events																						
Entire study	46	29	9	60	10	8	1.1	72	54	6	1.0	5	59	0.31	0.28	0.03	1.7	1.5	0.16	0.04	0.2	1.4
Pre-BMP	33	37	21	98	15	13	1.9	84	66	9	1.4	10	74	0.33	0.28	0.03	2.1	1.6	0.17	0.05	0.2	1.6
Post-BMP	13	27	12	31	6	5	1.2	41	34	8	1.0	9	65	0.24	0.20	0.02	1.2	1.1	0.15	0.02	0.1	1.2

† UFV, unit flow volume; AvgFR, average flow rate; PkFR, peak flow rate; TP, total P; TDP, total dissolved P; PP, particulate P; TN, total N; TDN, total dissolved N; PN, particulate N; POC, particulate organic C; BMP, beneficial management practice.

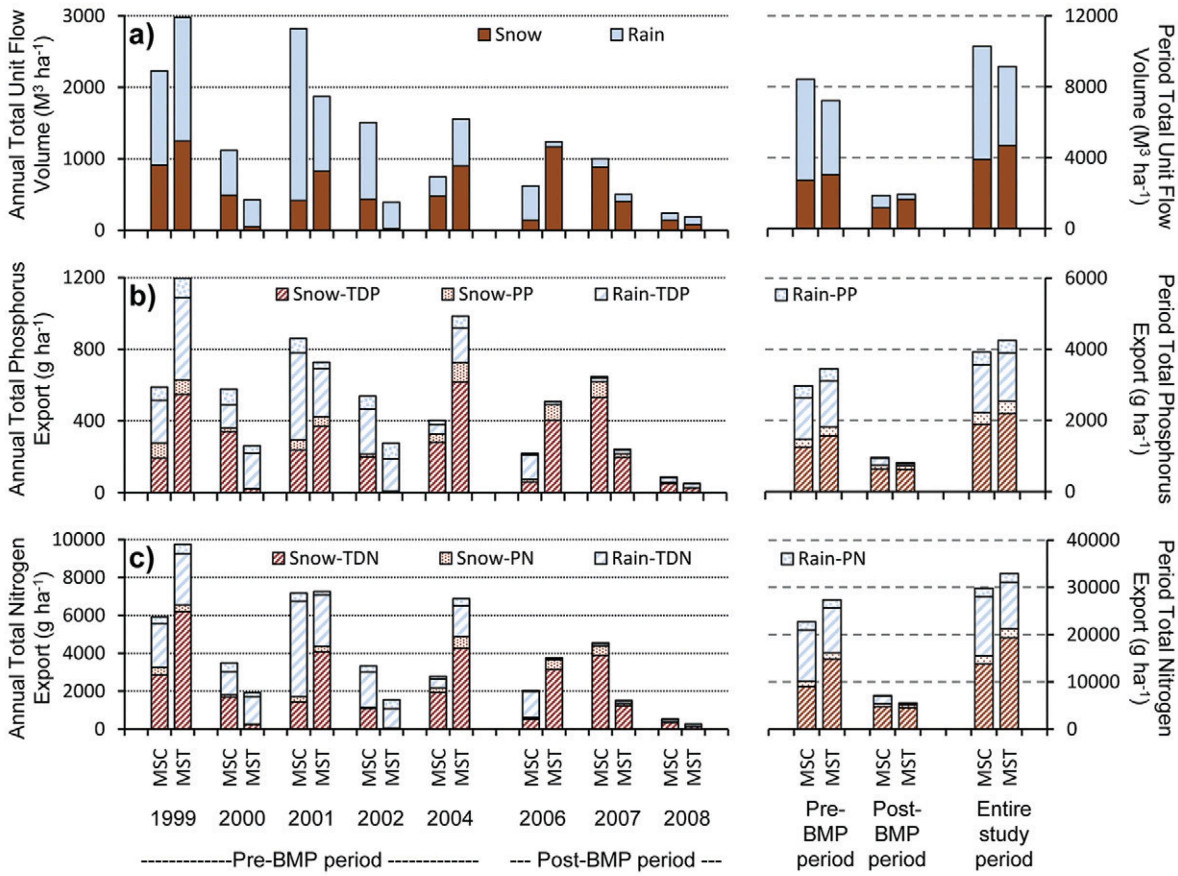

Fig. 2. Annual and period total unit flow volume (UFV) and P and N exports in different forms and in runoff events of different types measured at the outlet of the Madill (control) subwatershed (MSC) and the outlet of the Steppler (treatment) subwatershed (MST). BMP, beneficial management practice; PN, particulate nitrogen; PP, particulate phosphorus; TDN, total dissolved nitrogen; TDP, total dissolved phosphorus.

land use and topography between the two subwatersheds and suggest that using hydrologic variables as additional covariates could be beneficial in examining the effects of BMPs.

The effects of hydrology on nutrient exports were evidenced in that the annual total nutrient exports followed a similar pattern as that of the annual total UFV (Fig. 2). In fact, for the treatment subwatershed, all correlation coefficients between nutrient exports and hydrologic variables were significant at $P \leq 0.10$ (Table 3). The correlations between nutrient exports and the three hydrologic variables were greatest for AvgFR, followed by PkFR and VolR. For nutrient FWMC, the effects of the three hydrologic variables were different for snowmelt and rainfall events. For snowmelt events, most nutrient FWMCs (except for PP-, PN-, and POC-FWMC) were not significantly ($P > 0.10$) correlated with the hydrologic variables, probably because of the small sample size. For rainfall events, most nutrient FWMCs (except for PP-, PN-, and POC-FWMC) were significantly ($P \leq 0.10$) correlated with AvgFR and PkFR but not with VolR. The exceptions of PP-, PN-, and POC-FWMC from these general trends suggest the strong impact of the three hydrologic variables on the FWMCs of nutrients in particulate forms (Table 3). The lack of correlation between VolR and nutrient FWMCs can partially be explained because event flow volume has been used in computing the nutrient FWMCs. In addition, the effects of the three hydrologic variables may overlap as they were significantly correlated with each other ($P \leq 0.10$, Table 3). It is also possible that some other hydrologic variables (such as the timing of flow events) have played an important role in the nutrient loss process.

Based on the two simple ANCOVA models (Eq. [1] and [2]), during rainfall events, coefficients for X for all three hydrologic variables were significant at $P \leq 0.01$, indicating that the variation of these hydrologic variables observed at the treatment subwatershed can be well explained by those observed at the control subwatershed (Table 4). However, this was not the case for snowmelt events. The hydrological disconnection between the two watersheds for snowmelt events is likely the result of large variability of snowmelt-induced hydrologic conditions. The coefficients for Prd were nonsignificant ($P > 0.10$) for VolR and AvgFR, in either rainfall or snowmelt events, suggesting that BMP implementation had no significant effects on VolR and AvgFR (Table 4). The decreases of VolR and AvgFR observed at the treatment subwatershed were probably the result of the temporal variation of precipitation since similar decreases in VolR and AvgFR occurred at the control subwatershed, where no BMP was implemented (Table 2). In contrast, a significant decrease of PkFR ($P \leq 0.01$) occurred due to BMP implementation for rainfall events (Table 4). When both rainfall and snowmelt were pooled together (all events) for the simple ANCOVA analyses, the results were similar to those of the rainfall events, that is, BMP implementation had significant ($P \leq 0.10$) impact on PkFR but not on VolR or AvgFR. In addition, multivariate analyses with the complete model (Eq. [4]) showed that for snowmelt events, the effects of PkFR were nonsignificant ($P > 0.10$) for all nutrient exports and FWMCs (data not shown). Consequently, PkFR was dropped out of the best multivariate ANCOVA model used to examine the effects of BMPs.

Nutrient Exports

For both snowmelt and rainfall events, P and N exports in dissolved form were much greater than in particulate form (Table 2). For the entire study period, TDP and TDN exports were 5.0 and 7.9 times of the PP and PN exports, respectively, on the treatment subwatershed (Fig. 2). On the control subwatershed, the ratios were 4.7 and 7.4 for TDP/PP and TDN/PN, respectively. Although there were more rainfall events than snowmelt events, per-event nutrient exports for snowmelt events were much greater than for rainfall events. As a result, on both subwatersheds during the entire study period, the total exports of TDP and TDN in snowmelt events were greater than those in rainfall events and the total exports of PP and PN in snowmelt events were similar to those in rainfall events (Fig. 2). This highlights the importance of nutrient loss in dissolved form in the study area, especially during snowmelt events, a characteristic that has been identified previously in cold-climate regions (Tiessen et al., 2010; Ulen et al., 2010). Except for those

Table 3. Correlation coefficients between the hydrologic variables and between the hydrologic variables and nutrient exports and flow-weighted mean concentrations (FWMCs) at the outlet of the Steppler (treatment) sub-watershed.†

	Hydrology		Nutrient export									Nutrient FWMC								
	AvgFR	PkFR	TP	TDP	PP	TN	TDN	PN	NH_3	NO_x	POC	TP	TDP	PP	TN	TDN	PN	NH_3	NO_x	POC
									All events, *n* = 65											
VolR	0.71‡	0.54‡	0.63‡	0.63‡	0.59‡	0.59‡	0.58‡	0.62‡	0.53‡	0.51‡	0.62‡	0.21‡	0.17	0.20‡	0.18	0.15	0.29‡	0.10	0.16	0.26‡
AvgFR		0.81‡	0.93‡	0.93‡	0.91‡	0.92‡	0.91‡	0.91‡	0.89‡	0.86‡	0.91‡	0.41‡	0.37‡	0.45‡	0.50‡	0.47‡	0.46‡	0.43‡	0.50‡	0.44‡
PkFR			0.84‡	0.84‡	0.85‡	0.82‡	0.82‡	0.84‡	0.79‡	0.73‡	0.85‡	0.42‡	0.37‡	0.53‡	0.47‡	0.43‡	0.50‡	0.38‡	0.38‡	0.50‡
									Snowmelt events, *n* = 19											
VolR	0.77‡	0.77‡	0.69‡	0.69‡	0.61‡	0.68‡	0.68‡	0.62‡	0.52‡	0.61‡	0.62‡	0.11	0.10	0.08	0.12	0.11	0.09	–0.06	0.03	0.09
AvgFR		0.88‡	0.93‡	0.93‡	0.90‡	0.89‡	0.89‡	0.91‡	0.79‡	0.81‡	0.91‡	0.33	0.29	0.42‡	0.21	0.18	0.41‡	0.12	0.08	0.44‡
PkFR			0.87‡	0.87‡	0.84‡	0.84‡	0.84‡	0.85‡	0.71‡	0.78‡	0.84‡	0.30	0.27	0.41‡	0.21	0.18	0.39‡	0.07	0.12	0.39‡
									Rainfall events, *n* = 46											
VolR	0.69‡	0.39‡	0.59‡	0.58‡	0.56‡	0.54‡	0.53‡	0.60‡	0.51‡	0.45‡	0.59‡	0.19	0.14	0.24‡	0.12	0.06	0.36‡	0.06	0.08	0.32‡
AvgFR		0.80‡	0.92‡	0.91‡	0.90‡	0.91‡	0.90‡	0.90‡	0.90‡	0.84‡	0.91‡	0.36‡	0.28‡	0.49‡	0.47‡	0.42‡	0.50‡	0.40‡	0.43‡	0.49‡
PkFR			0.85‡	0.85‡	0.86‡	0.85‡	0.84‡	0.85‡	0.86‡	0.77‡	0.86‡	0.44‡	0.37‡	0.59‡	0.55‡	0.50‡	0.55‡	0.53‡	0.43‡	0.58‡

† AvgFR, average flow rate; PkFR, peak flow rate; TP, total P; TDP, total dissolved P; PP, particulate P; TN, total N; TDN, total dissolved N; PN, particulate N; POC, particulate organic C; VolR, flow volume ratio.

‡ Significant at $P \le 0.10$.

Table 4. Results of the simple analyses of covariance (ANCOVA) models for the hydrologic variables.†

	Reduced model (Eq. [1])			Full model (Eq. [2])		
	Vol	AvgFR	PkFR	Vol	AvgFR	PkFR
			All events, *n* = 65			
R^2	0.30***	0.40***	0.33***	0.30***	0.40***	0.34
Intercept	0.45	–0.68	2.25***	0.62	–0.69	2.75**
Prd	0.16	0.42	–0.90*	0.12	0.42	–0.98**
X	0.71***	0.95***	0.58***	0.67***	0.95***	0.45*
Int				0.10	0.00	0.28
			Snowmelt events, *n* = 19			
R^2	0.10	0.17	0.10	0.12	0.17	0.15
Intercept	2.59	1.46	3.27‡	3.11	1.59	4.70*
Prd	–0.11	–0.13	–0.59	–0.57	–0.30	–1.19
X	0.41	0.61	0.38	0.31	0.59	0.05
Int				0.38	0.12	0.71
			Rainfall events, n = 46			
R^2	0.32***	0.38***	0.47***	0.33***	0.38***	0.47
Intercept	0.31	–0.75	2.17**	0.12	–0.89	2.06*
Prd	0.08	0.41	–1.10**	0.07	0.40	–1.10**
X	0.68***	0.90***	0.58***	0.72**	0.94***	0.61**
Int				–0.13	–0.11	–0.08

* Significance level of $P \le 0.05$.

** Significance level of $P \le 0.01$.

*** Significance level of $P \le 0.001$.

† Vol, runoff flow volume; AvgFR, average flow rate; PkFR, peak flow rate; Prd, study period; Int, the interaction term in the model.

‡ Significance level of $P \le 0.10$.

Table 5. Results of the analyses of covariance using the reduced models for nutrient exports and flow-weighted mean concentrations (FWMCs).†

	Nutrient export									Nutrient FWMC								
	TP	TDP	PP	TN	TDN	PN	NH_3	NO_x	POC	TP	TD	P	TN	TDN	PN	NH_3	NO_x	POC
									All events, *n* = 65									
R^2	0.36***	0.33***	0.43***	0.42***	0.41***	0.45***	0.52***	0.43***	0.47***	0.40***	0.42***	0.33***	0.40***	0.46***	0.27***	0.48***	0.38***	0.29***
Intercept	0.17	0.33	−0.50	0.24	0.34	0.03	−0.10	−1.74*	0.30	−0.37**	−0.31*	−2.04***	0.58***	0.42***	−0.90***	0.95**	−0.87***	0.49***
Prd	−0.19	−0.28	−0.12	−0.22	−0.29	0.02	−0.19	−0.19	0.01	−0.42***	−0.44***	−0.59**	−0.59***	−0.59***	−0.37‡	−0.55*	−0.65*	−0.39*
X	0.75***	0.71***	0.74***	0.82***	0.80***	0.75***	0.81***	1.02***	0.78***	0.49***	0.55***	0.33***	0.48***	0.62***	0.32***	0.54***	1.20***	0.33***
									Snowmelt event, *n* = 19									
R^2	0.14	0.12	0.36*	0.23	0.22	0.33*	0.44**	0.25‡	0.36*	0.58***	0.56**	0.48**	0.46**	0.47**	0.41*	0.56**	0.34*	0.38*
Intercept	2.23	2.36‡	0.37	2.54	2.60	0.99	0.57	2.23	1.39	−0.33*	−0.41*	−1.56**	0.76*	0.74*	−0.69*	−0.66	0.57	0.33
Prd	−0.48	−0.46	−0.82	−0.73	−0.74	−0.61	−0.51	−1.19	−0.58	−0.37*	−0.33‡	−0.78*	−0.68**	−0.69**	−0.55‡	−0.53	−1.14*	−0.51‡
X	0.41	0.36	0.65*	0.57‡	0.56‡	0.64*	0.71**	0.60	0.69*	0.47***	0.44**	0.48*	0.55*	0.56*	0.48**	0.67***	0.54	0.47*
									Rainfall events, *n* = 46									
R^2	0.36***	0.32***	0.41***	0.39***	0.37***	0.44***	0.38***	0.38***	0.46***	0.31***	0.33***	0.30***	0.36***	0.38***	0.25**	0.23**	0.26**	0.28**
Intercept	0.00	0.23	−0.74‡	0.39	0.61	−0.21	−0.18	−1.40	0.08	−0.45*	−0.07	−2.11***	0.69***	0.52***	−0.92***	−2.40**	−1.09***	0.51**
Prd	−0.25	−0.45	0.10	−0.32	−0.48	0.28	−0.28	−0.42	0.23	−0.47**	−0.51**	−0.52‡	−0.72***	−0.70***	−0.31	−0.79**	−0.80‡	−0.35
X	0.73***	0.67***	0.73***	0.73***	0.68***	0.76***	0.73***	0.82***	0.78***	0.43**	0.71**	0.32**	0.21	0.31	0.31**	0.16	0.66*	0.33**

* Significance level of $P \le 0.05$.

** Significance level of $P \le 0.01$.

*** Significance level of $P \le 0.001$.

† TP, total P; TDP, total dissolved P; PP, particulate P; TN, total N; TDN, total dissolved N; PN, particulate N; POC, particulate organic C; Prd, study period.

‡ Significance level of $P \le 0.10$.

for the rainfall events at the control subwatershed, median event nutrient exports all decreased after BMP implementation (Table 2). That these decreases in nutrient exports occurred at the control subwatershed, where no BMP was implemented, suggests that there were differences in precipitation and hydrology between the pre-BMP and post-BMP periods. However, there was also a general trend for the magnitude of decreases in both the snowmelt and rainfall events to be greater at the treatment subwatershed than at the control subwatershed, indicating a reduction of nutrient exports due to BMP implementation on the treatment subwatershed (Table 2).

For the full ANCOVA models used to analyze results of nutrient exports (Eq. [2]), the interaction term (Int) in these models was nonsignificant ($P >$ 0.10) in all cases (data not shown) and there were very few differences between the reduced model (Eq. [1]) and the full model (Eq. [2]). Therefore, the following discussion is focused on the reduced model (Table 5). For snowmelt events, the reduced models for TP, TDP, TN, and TDN and the coefficients of X in the models for TP, TDP, and NO_x were nonsignificant (P > 0.10), likely because of the large variability of nutrient exports and the small sample size for snowmelt events. In all other cases (i.e., other nutrient export variables for snowmelt events and all nutrient export variables for rainfall events and for all events), the reduced model and the coefficients of X were significant at $P \le 0.10$ (Table 5). This indicates that nutrient exports observed at the treatment subwatershed can be explained by the model, in particular, by the respective nutrient exports observed at the control subwatershed. However, Prd was nonsignificant in all cases, indicating that the reduced model (as well as the full model) was not able to detect the effects of BMPs on nutrient exports. This can be clearly seen when the TP and TN exports for all events at the treatment subwatershed is plotted against that at the control subwatershed (Fig. 3a, 3b). For both TP and TN exports, the paired regression lines for the simple ANCOVA analysis were not much different, which suggests that BMP implementation at the treatment subwatershed had little impact on TP and TN exports. However, as both the pre-BMP and post-BMP periods were short in this study, it is possible that the BMP effects were masked by the variations in hydrology from event to event. The low R^2 values of the regression lines also indicated the large variation of the data.

Compared to their respective simple ANCOVA models (Table 5), the best multivariate ANCOVA models (Table 6) had much greater R^2 values (most at least doubled), indicating that nutrient exports at the treatment subwatershed are better explained after incorporating additional hydrologic variables. The presence of the covariates in the best multivariate ANCOVA model reflected the importance of the covariates. The VolR was in each of the best multivariate ANCOVA models for nutrient exports and was significant at $P \le$

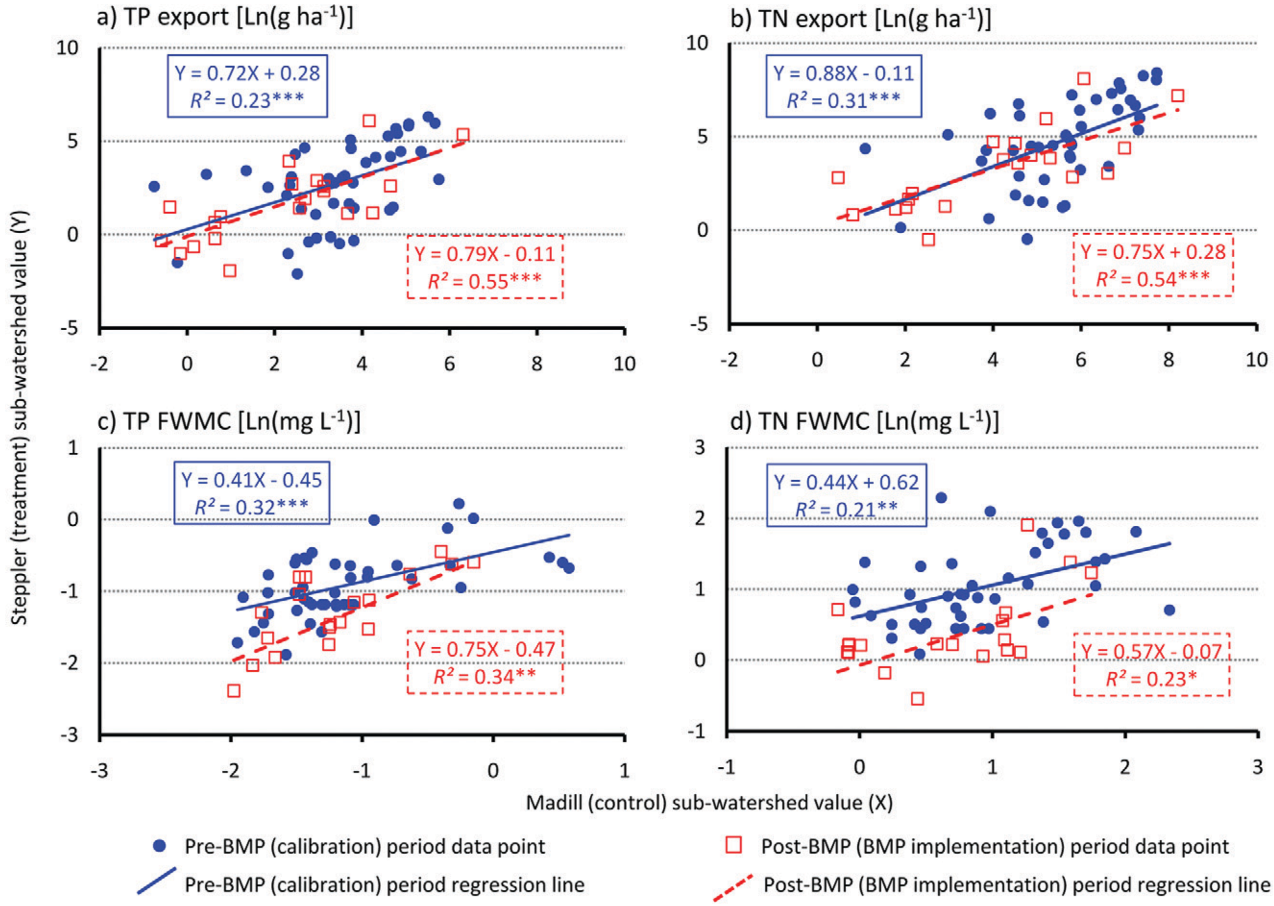

Fig. 3. Simple regression analyses of total phosphorous (TP) and total nitrogen (TN) exports and flow-weighted mean concentrations (FWMCs) for all runoff events, showing the effects of beneficial management practice (BMP) implementation without accounting for the effects of hydrologic covariates (*, **, and * denote that the regression is significant at $P \le 0.05$, 0.01, and 0.001, respectively).**

0.10 (Table 6). In fact, except for the models for particulate nutrient exports (PP, PN, and POC) and NH_3 exports in rainfall events, where AvgFR had a strong impact, VolR was significant at $P \le 0.001$. This indicates the strong impact of VolR on nutrient exports. In contrast, Int was not in any of the best multivariate ANCOVA models for nutrient exports, indicating that the effects of the interactions between Prd and X on nutrient exports were negligible, which agreed with the results of the simple ANCOVA models discussed earlier. Interestingly, although AvgFR correlated with nutrient exports better than did VolR (Table 3), AvgFR was not in the best multivariate ANCOVA models for most nutrient exports except for those for PP, PN, POC, and NH_3 exports in rainfall events (Table 6). Most important, the Prd was a significant factor ($P \le 0.10$) in two-thirds of the best multivariate ANCOVA models, and where it was nonsignificant ($P > 0.10$), the coefficient for Prd was negative in value, indicating a consistent trend of reduction due to BMP implementation. The differences in nutrient export reductions between snowmelt and rainfall events and between dissolved and particulate forms were not obvious, mainly because only a few paired comparisons were valid (i.e., Prd was significant in the models of the same nutrient export for both the rainfall and snowmelt events). For all runoff events combined, the average reductions of nutrient exports due to BMP implementation ranged from 38 to 45% (Table 6). In particular, on average, TP and TN exports reduced by 38 and 41%, respectively. At the 90% confidence level, TP export reduction was within the range of 20 to 51% and TN export reduction was within the range of 20 to 57%.

Nutrient Flow-Weighted Mean Concentrations

The overall trends of the median values for event nutrient FWMCs were similar to those for event nutrient exports (Table 2). The FWMCs of dissolved forms of P and N (i.e., TDP and TDN) were much greater than those of particulate forms (i.e., PP and PN) in both snowmelt and rainfall events at both subwatersheds. Also, with only two exceptions, the median values for event nutrient FWMCs in snowmelt events were greater than their respective values in rainfall events. Nutrient FWMCs all decreased at the treatment subwatershed after BMP implementation (Table 2). However, reductions of FWMCs were also observed on the control subwatershed for many nutrient variables. Therefore, FWMC reductions at the treatment subwatershed cannot be attributed to the effects of BMPs without further evidence (i.e., ANCOVA).

With only a few exceptions, the results of the two simple ANCOVA models (results for the full model are not shown and results for the simple model are shown in Table 5) for nutrient FWMCs were similar to those for nutrient exports in that (i) the models were all significant at $P \le 0.10$, (ii) the interaction term (Int) was mostly nonsignificant in the full ANCOVA models, and (iii) X was mostly significant

Table 6. Results of the best multivariate analyses of covariance models for nutrient exports and flow-weighted mean concentrations (FWMCs) and the estimated reductions due to beneficial management practice implementation.†

	Nutrient export									Nutrient FWMC								
	TP	TDP	PP	TN	TDN	PN	NH_3	NO_x	POC	TP	TDP	P	T	TDN	PN	NH_3	NO_x	POC
All events, *n* = 65																		
R^2	0.94***	0.95***	0.85***	0.93***	0.94***	0.85***	0.88***	0.86***	0.86***	0.44***	0.48***	0.38***	0.46***	0.50***	0.30***	0.48***	0.46***	0.29***
Intercept	0.48**	0.52***	0.31‡	0.42	0.33	0.93***	0.68***	−1.62***	1.27***	−0.60***	−0.42*	−2.67***	0.46**	0.30*	−0.90***	−0.95**	−1.37***	0.49***
Prd	−0.47**	−0.54***	−0.55‡	−0.53**	−0.57***	−0.48‡	−0.60*	−0.51	−0.47‡	−0.38**	−0.47***	−0.56**	−0.57***	−0.56***	−0.45*	−0.55*	−0.56‡	−0.39*
X	0.92***	0.94***	0.76***	0.94***	0.97***	0.72***	0.83***	1.20***	0.74***	0.42***	0.43***	0.23*	0.31*	0.49***	0.26**	0.54***	0.95***	0.33***
Int	–	–	–	–	–	–	–	–	–	–	0.36‡	–	–	–	–	–	–	–
VolR	1.01***	1.04***	0.95***	1.01***	1.04***	0.91***	0.91***	1.18***	0.89***	–	0.06‡	–	–	–	0.10‡	–	–	–
AvgFR	–	–	–	–	–	–	–	–	–	0.05‡	–	0.11*	0.09*	0.08*	–	–	0.20**	–
%Rd	38**	41***	42‡	41**	43***	38‡	45*	40	38‡	32**	55***§	43**	43***	43***	36*	43*	43‡	32*
$\%Rd_{90U}$	51	53	64	57	57	61	64	65	60	44	61§	60	55	55	55	60	66	51
$\%Rd_{90L}$	20	27	6	20	26	2	15	−2	4	17	49§	19	28	28	10	17	4	6
Snowmelt events, *n* = 19																		
R^2	0.94***	0.93***	0.90**	0.93***	0.93***	0.90***	0.86***	0.83***	0.91***	0.80***	0.80***	0.48**	0.46**	0.47**	0.41*	0.56**	0.34*	0.38*
Intercept	0.58	0.63	0.29	0.60	0.54	0.59	0.43	0.36	0.79	−0.73**	−0.83***	−1.56**	0.76*	0.74*	−0.69*	−0.66	0.57	0.33
Prd	−0.40	−0.35	−0.88*	−0.71*	−0.70*	−0.70‡	−0.51	−1.18*	−0.67‡	−0.63***	−0.53**	−0.78*	−0.68**	−0.69**	−0.55‡	−0.53	−1.14*	−0.51‡
X	0.88***	0.87***	0.84***	0.93***	0.95***	0.83***	0.83***	0.97***	0.84***	0.28*	0.25*	0.48*	0.55*	0.56*	0.48**	0.67***	0.54	0.47*
Int	–	–	–	–	–	–	–	–	–	0.74**	0.68**	–	–	–	–	–	–	–
VolR	1.03***	1.04***	0.91***	0.95***	0.96***	0.91***	0.82***	0.93***	0.88***	–	–	–	–	–	–	–	–	–
AvgFR	–	–	–	–	–	–	–	–	–	0.06‡	0.06‡	–	–	–	–	–	–	–
%Rd	33	29	58*	51*	50*	50‡	40	69*	49‡	62***§	60**§	54*	49**	50**	42‡	41	68*	40‡
$\%Rd_{90U}$	55	54	78	69	69	72	72	86	71	68§	66§	72	66	67	65	72	85	64
$\%Rd_{90L}$	−2	−9	23	22	21	10	−29	34	8	56§	54§	24	24	25	5	−23	34	1
Rainfall events, *n* = 46																		
R^2	0.93***	0.95***	0.86***	0.91***	0.94***	0.85***	0.88***	0.85***	0.87***	0.31***	0.33***	0.30***	0.44***	0.44***	0.31**	0.31**	0.26**	0.28***
Intercept	0.40‡	0.44**	−1.57**	0.42	0.30	−0.16	−0.99‡	−1.58**	1.00*	−0.45*	−0.07	−2.11***	0.55**	0.36*	−0.89***	−2.96***	−1.09***	0.51**
Prd	−0.45*	−0.55**	−0.21	−0.48‡	−0.51*	−0.19	−0.22	−0.44	−0.20	−0.47**	−0.51**	−0.52‡	−0.67***	−0.63**	−0.49‡	−0.69*	−0.80‡	−0.35
X	0.96***	1.00***	0.40**	0.94***	0.98***	0.39**	0.57***	1.14***	0.40**	0.43**	0.71**	0.32**	0.08	0.25	0.21‡	0.09	0.66*	0.33**
Int	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
VolR	1.01***	1.06***	0.33‡	1.02***	1.07***	0.41*	0.41*	1.20***	0.38*	–	–	–	–	–	0.17*	–	–	–
AvgFR	–	–	0.66***	–	–	0.58**	0.56***	–	0.58**	–	–	–	0.10*	0.08*	–	0.12*	–	–
%Rd	36*	42**	19	38‡	40*	17	20	35	18	37**	40**	41‡	49***	47**	39‡	50*	55‡	29
$\%Rd_{90U}$	55	56	57	60	59	56	54	68	55	52	53	64	62	61	62	68	77	55
$\%Rd_{90L}$	9	24	−53	4	13	−56	−38	−30	−49	18	23	2	30	28	1	21	12	−10

* Significance level of $P \le 0.05$.

** Significance level of $P \le 0.01$.

*** Significance level of $P \le 0.001$.

† TP, total P; TDP, total dissolved P; PP, particulate P; TN, total N; TDN, total dissolved N; PN, particulate N; POC, particulate organic C; Prd, study period; Int, the interaction term in the model; VolR, flow volume ratio; AvgFR, average flow rate; %Rd, average percent reduction; $\%Rd_{90U}$, 90% confidence interval for the percent reduction for the upper confidence interval; $\%Rd_{90L}$ 90% confidence interval for the percent reduction for the lower confidence interval.

‡ Significance level of $P \le 0.10$.

§ A slightly different method was used to account for the significant effects of the interaction term (Int). See text for details.

(Table 5). These results indicate that nutrient FWMCs at the treatment subwatershed (Y) can be explained by nutrient FWMCs at the control subwatershed (X) in most cases and the interactions between Prd and X were mostly nonsignificant ($P > 0.10$). In most cases, however, the influence of Prd was significant ($P \leq 0.10$), especially with the reduced model (Table 5). For rainfall and snowmelt events, two-thirds of the best multivariate ANCOVA models for nutrient FWMCs were, in fact, the reduced ANCOVA model, which did not have any hydrologic covariate (Table 6). In contrast, those best multivariate ANCOVA models for nutrient exports all had at least one hydrologic covariate. For all events, most of the best multivariate ANCOVA models for nutrient FWMCs had one hydrologic covariate (AvgFR or VolR). However, the increases in R^2 values from the simple ANCOVA models to the best multivariate ANCOVA models were small compared with those for the nutrient exports. These further proved that hydrologic covariates were less critical to nutrient FWMCs than to nutrient exports. Nevertheless, for those nutrient FWMCs that did have a hydrologic covariate in the best multivariate models, R^2 values did improve from the simple ANCOVA models to the multivariate ANCOVA models, and more important, the impact of Prd (P value for its coefficient in the t test) generally increased. This suggests that it was still beneficial to incorporate these hydrologic variables in these models.

The percentage reduction values calculated from the best multivariate ANCOVA models for nutrient FWMCs agreed well with those for the nutrient exports, especially for cases in which these reductions for a specific nutrient form were both significant ($P \leq 0.10$) for nutrient export and FWMC (Table 6). This consistency between the reductions of nutrient FWMCs and exports was expected because flow volume was not significantly ($P > 0.10$) affected by BMP implementation (Table 4). The percentage reduction values for snowmelt and rainfall events were not much different from each other for the same nutrient FWMCs. Neither were there many differences between the percentage reduction values of dissolved and particulate forms of nutrients. Overall, for all runoff events, the average reduction of nutrient FWMC due to implementation of the five BMPs ranged from 32 to 55% (Table 6). In particular, on average, TP-FWMC and TN-FWMC were reduced by 32 and 43%, respectively. At the 90% confidence level, TP-FWMC reduction was within the range of 17 to 44% and TN-FWMC reduction was within the range of 28 to 55%.

Contributions of the Holding Pond

Data collected at the inlet of the holding pond (MSH) showed that runoff from the feedlot site overall could contribute a maximum of 4% toward the runoff at the subwatershed outlet (Table 7), whereas the area of the feedlot site was only 1% of the total area of the subwatershed (Table 1). This greater runoff contribution from the feedlot relative to the drainage area likely resulted from the low infiltration rate and limited water storage on the feedlot site, an effect reported in many previous studies (e.g., Miller et al., 2004). Interestingly, when analyzed separately, the potential contributions of the feedlot runoff were much greater in rainfall events than in snowmelt events (Table 7). This may be because during rainfall events, other areas in the subwatershed had much greater infiltration rates than the feedlot. Alternatively, during snowmelt events, soil was mostly frozen and, therefore, differences in infiltration rates between the feedlot and the rest of the subwatershed were small. Nevertheless, the reduction in runoff volume due to the holding pond was small in all cases, which agreed with the nonsignificant ($P > 0.10$) effect of BMPs on UFV in the simple ANCOVA (Table 4).

Flow-weighted mean concentrations of the nutrients measured at MSH were much greater than those measured at MST (ratios all ≥4, Table 7). As a result, although the runoff volume from the feedlot was only a small portion of that at MST, the calculated maximum reductions due to the holding pond were substantial. The maximum reductions for rainfall events were much greater than the respective reductions for snowmelt events. The greater reductions for rainfall events was likely due to the greater potential contribution of runoff from the feedlot in rainfall events than in snowmelt events (12% vs. 3%) as the ratios of FWMCs between MSH and MST within rainfall events and within snowmelt events were not that much different (Table 7). For rainfall events, the maximum reductions due to the holding pond (Table 7) exceeded the average reductions at MST determined by the multivariate ANCOVAs (Table 6), indicating that some of the nutrients leaving the feedlot were lost before they reached MST. Such losses of nutrients likely also occurred in snowmelt events but could have been limited

Table 7. Maximum reductions of runoff and nutrient exports at the Steppler (treatment) subwatershed outlet (MST) due to the holding pond beneficial management practice and the ratios of flow-weighted mean concentrations between those measured at the holding pond inlet (MSH) and those measured at the treatment subwatershed outlet.†

	Vol	TP	TDP	PP	TN	TDN	PN	NH_3	NO_x	POC
	Max. reductions (k = 1 in Eq. [6]) of runoff and nutrient exports at MST due to the holding pond (%)									
All events	4	24‡	21‡	35‡	24‡	22‡	32‡	64‡	5	25‡
Snowmelt events	3	14	12	26‡	15‡	14‡	24‡	55	2‡	18‡
Rainfall events	12	66‡	64‡	73	68‡	68‡	67	96	60	59
	Ratios of flow-weighted mean concentrations (Eq. [8])									
All events	–	12‡	11‡	16‡	12‡	12‡	11‡	175‡	25‡	8‡
Snowmelt events	–	6‡	5‡	17‡	8‡	8‡	11‡	203	4‡	8‡
Rainfall events	–	16‡	15‡	15‡	14‡	14‡	11‡	159‡	37‡	8

† Vol, runoff flow volume; TP, total P; TDP, total dissolved P; PP, particulate P; TN, total N; TDN, total dissolved N; PN, particulate N; POC, particulate organic C.

‡ Significant at $P \leq 0.10$ in the best multivariate analyses of covariance models (Table 6).

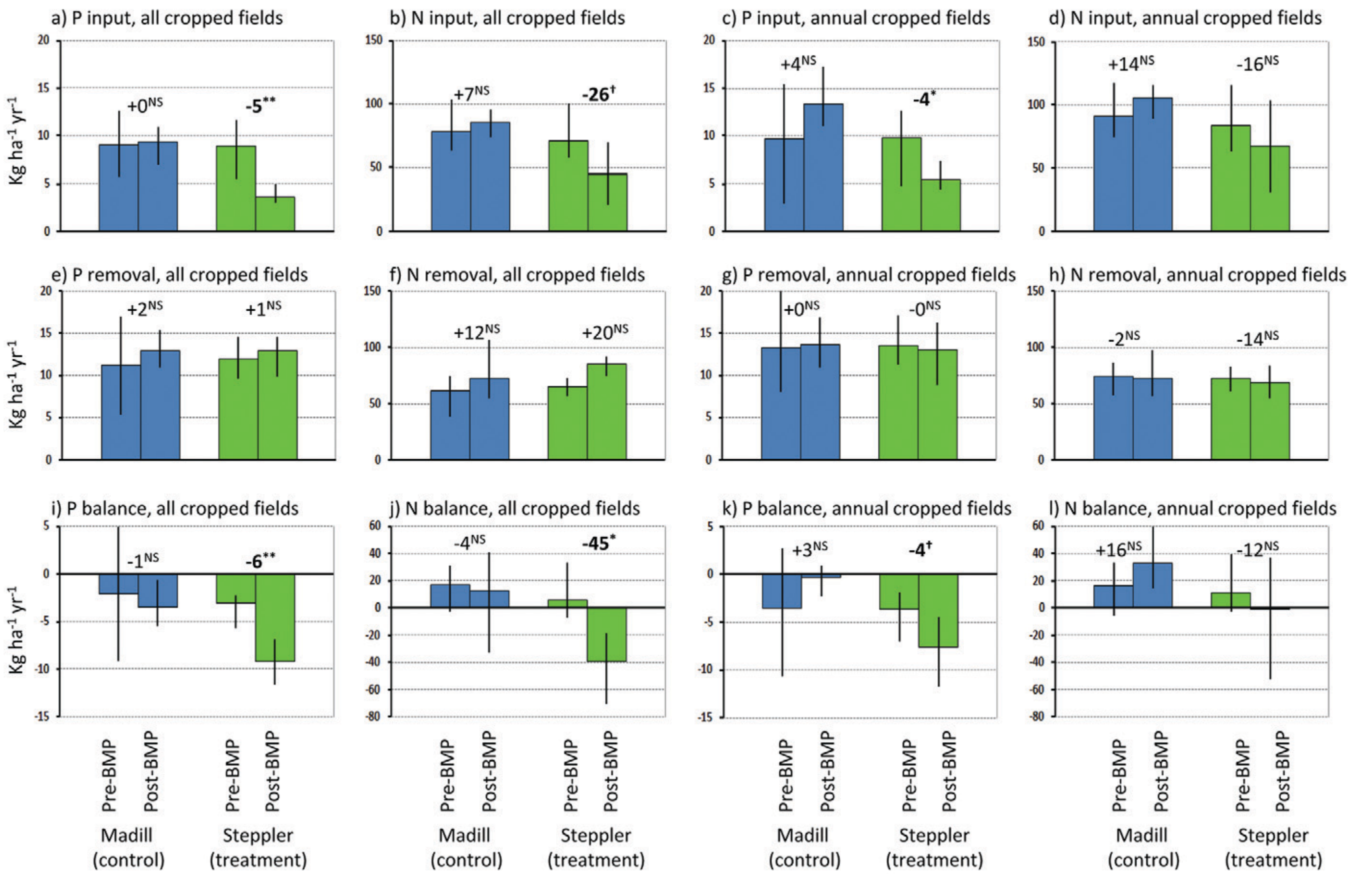

Fig. 4. Gross N and P inputs (from fertilizer and manure applications), removals (due to crop harvesting), and balances (= inputs – removals) estimated for cropped fields in the Madill (control) and Steppler (treatment) subwatersheds. The column height indicates the average value for the period; the vertical bar indicates the full range of the data in the period. The number above the column is the difference (+ for increase and – for decrease) in average values between the pre-beneficial management practice (BMP) and post-BMP periods. Significance level of the difference is determined using a two-way *t* test (NS, †, * and ** denote nonsignificant and significant at $P \le 0.10$, 0.05, and 0.01, respectively).

by cool temperatures and frozen stream banks. In addition, there could be transformations of nutrients, as evidenced in the lack of responses to the large $\%Rd_{hmax}$ values of NH_3 and particulate form nutrients (PP, PN, and POC) in the multivariate ANCOVAs of MST data (Table 6 and Table 7).

For all events, assuming that all TP and TN leaving the feedlot reached MST before the holding pond was built (i.e., $k = 1.0$ in Eq. [6]), the reductions of TP and TN due to the holding pond were 24 and 24%, respectively, which were 63 and 57% of the average reductions in TP and TN exports, respectively, at MST determined by the multivariate ANCOVAs (Table 7). In other words, the holding pond may have contributed a maximum of 63 and 57%, respectively, of the TP and TN export reductions observed at the treatment subwatershed outlet. Even if we assume that half of the TP and TN leaving the feedlot did not reach MST before the holding pond was built (i.e., $k = 0.5$ in Eq. [6]), the holding pond still contributed 36 and 33%, respectively, of the TP and TN export reductions observed at MST. Considering the small area of the feedlot (1% of the subwatershed, Table 1), the contributions of the holding pond toward the reductions of nutrient exports at MST were very large. However, the holding pond alone cannot explain all the reductions of nutrient exports at MST, and at least 37% of the TP and 43% of the TN export reductions observed at MST must be due to the other BMPs.

Effects of the Nutrient Management

The nutrient budget analysis showed that when all cropped fields were considered, there were no significant differences ($P > 0.10$) between the pre-BMP and post-BMP periods in N and P inputs at the control subwatershed, but at the treatment subwatershed, N and P inputs significantly ($P \le 0.10$) decreased by 36 and 59% (i.e., 26 and 5 kg ha^{-1} yr^{-1}), respectively, from the pre-BMP to the post-BMP period (Fig. 4a, 4b). Part of these decreases in N and P inputs were due to the perennial forage conversion since there was very limited application of synthetic fertilizer and no manure applied to the perennial forage conversion fields (data not shown). However, when only continuously annual cropped fields were taken into account, similar patterns of N and P inputs at the two subwatersheds were observed—between pre-BMP and post-BMP periods, there were no significant differences ($P > 0.10$) at the control subwatershed but there was a significant decrease ($P \le 0.10$) of P input at the treatment subwatershed (Fig. 4c, 4d). Despite the reductions in N and P application rates, crop yields remained similar and, therefore, differences in nutrient removals between the pre-BMP and post-BMP periods were nonsignificant ($P > 0.10$) in all cases (Fig. 4e, 4f, 4g, 4h).

Both nutrient inputs and removals contributed to the status of nutrient balances. At both subwatersheds, there was a surplus of N but a deficit of P in the pre-BMP period (Fig. 4i, 4j, 4k, 4l). This pattern was likely due to the low application rate of P fertilizer relative to that of N fertilizer (data not shown). Implementation of BMPs at the treatment subwatershed had significantly ($P \leq 0.10$) reduced the N and P inputs, resulting in deficits in the N and P balances, whereas the changes in N and P balances at the control subwatershed were nonsignificant ($P > 0.10$) (Fig. 4i, 4j, 4k, 4l). The nutrient budget deficits at the treatment subwatershed did not affect the yields significantly, even on annual cropped fields, largely due to crop uptake of nutrients from substantial reserves of soil nutrients that were measured in soil tests (data not presented). Therefore, the overall reductions in the nutrient balances were driven by the decreases of N and P inputs. In particular, a significant reduction in P balance occurred at the treatment subwatershed, which was due to the significant decrease of P input on annual cropped land. The results from the annual cropland at the treatment subwatershed seem to suggest that on fields with fertile soil, nutrient management can be used as a BMP to reduce the nutrient inputs to the environment without negatively affecting the yield, at least in a short term. It is clear that the nutrient management BMP has reduced nutrient inputs to the treatment subwatershed in this study and that this reduction in nutrient inputs likely has contributed to the reductions in nutrient losses at the subwatershed outlet. At this time, however, we cannot quantify the contributions of the decreased nutrient inputs to the observed nutrient loss reductions at either the field or watershed scale. Nutrient source tracking that is currently underway in the STC watershed should provide the data required to link the reduction in inputs to that at the subwatershed outlet.

Implications

The five BMPs examined in this study collectively reduced nutrient exports and FWMCs regardless of event type and nutrient form. In practice, however, it may be difficult to convince producers to adopt the full suite of five BMPs all at once. A recommendation of one or two of the more effective BMPs may be better received by producers. The major source of nutrient loss, the dissolved nutrients in snowmelt events, has not been well targeted in these BMPs. However, among the five BMPs, some are likely to be more effective in reducing nutrient losses in the particulate form (e.g., forage conversion), whereas some are likely to be more effective in reducing nutrient losses in the dissolved form (e.g., grazing restriction). Studies are underway in the STC watershed to quantify the effects of individual BMPs on reducing nutrient losses in different forms and at different scales. It is hoped that these studies will provide a basis for recommending the adoption of individual BMPs. They will also lead to the enhancement of current BMPs and development of new BMPs that preferentially reduce losses of dissolved N and P and will eventually increase the overall efficiency of nutrient loss reduction.

Conclusions

Both N and P in runoff at the outlets of the two subwatersheds were mainly in dissolved form (>80% for both N and P) and were mainly lost during snowmelt events (from 52 to 65%). Collective effects of the five BMPs—holding pond below a beef cattle overwintering feedlot, riparian zone and grassed waterway management, grazing restriction, perennial forage conversion, and nutrient management—on hydrology were mostly nonsignificant, but the implementation of these BMPs resulted in a significant reduction in nutrient losses to surface water in the treatment subwatershed. In particular, when all runoff events were considered, the BMPs resulted in decreases of TN and TP exports in runoff at the treatment subwatershed outlet by 41 and 38%, respectively. The corresponding reductions in FWMCs were 43% for TN and 32% for TP. In most cases, similar reductions in exports and FWMCs were determined for N and P in dissolved and particulate forms, or when rainfall and snowmelt runoff events were considered separately.

In the treatment subwatershed, retention of nutrients in the holding pond could account for as much as 63 and 57%, respectively, of the BMP-induced reductions in TN and TP. Improvements to nutrient management reduced N inputs onto arable cropland by 36% and P inputs by 59%, in part due to the reduced rates of nutrient application to fields converted from annual crop to perennial forage. Yet, the decrease of N and P inputs did not significantly affect crop yields, and the N and P removals due to crop harvesting were maintained at similar levels in the pre- and post-BMP period. As a result, there were significant decreases in N and P balances. The holding pond and nutrient management BMPs have clearly contributed substantially to the nutrient loss reductions observed at the outlet of the treatment subwatershed. Overall, even though the proportional contributions of each of the five BMPs were not individually measured in this watershed-scale study, the collective reduction of nutrient losses from these BMPs was substantial.

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