Published online July 17, 2007

Relationships between Soil and Runoff Phosphorus in Small Alberta Watersheds

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Field-scale relationships between soil test phosphorus (STP) and flow-weighted mean concentrations (FWMCs) of dissolved reactive phosphorus (DRP) and total phosphorus (TP) in runoff are essential for modeling phosphorus losses, but are lacking. The objectives of this study were (i) to determine the relationships between soil phosphorus (STP and degree of phosphorus saturation (DPS)) and runoff phosphorus (TP and DRP) from field-sized catchments under spring snowmelt and summer rainfall conditions, and (ii) to determine whether a variety of depths and spatial representations of STP improved the prediction of phosphorus losses. Runoff was monitored from eight field-scale microwatersheds (2 to 248 ha) for 3 yr. Soil test phosphorus was determined for three layers (0 to 2.5 cm, 0 to 5 cm, and 0 to 15 cm) in spring and fall and the DPS was determined for the surface layer. Average STP (0 to 15 cm) ranged from 3 to 512 mg kg^{-1}, and DPS (0 to 2.5 cm) ranged from 5 to 91%. Seasonal FWMCs ranged from 0.01 to 7.4 mg L^{-1} DRP and from 0.1 to 8.0 mg L^{-1} TP. Strong linear relationships (r^2 = 0.87 to 0.89) were found between the site mean STP and the FWMCs of DRP and TP. The relationships had similar extraction coefficients, intercepts, and predictive power among all three soil layers. Extraction coefficients (0.013 to 0.014) were similar to those reported for other Alberta studies, but were greater than those reported for rainfall simulation studies. The curvilinear DPS relationship showed similar predictive ability to STP. The field-scale STP relationships derived from natural conditions in this study should provide the basis for modeling phosphorus in Alberta.

The intensification of livestock production has led to concentration of phosphorus (P) in localized areas. Excess phosphorus in soil is vulnerable to transport to surface waters via surface runoff, and this can cause degradation in water quality by accelerating eutrophication. Diffuse losses from agriculture have been identified as the largest nonpoint source of phosphorus to water bodies in the United States (USEPA, 2002) as well as impacting water bodies in many parts of Canada (Chambers et al., 2001), including Alberta (Anderson et al., 1998).

The prediction of phosphorus losses from land has been a major focus of research during the past decade. Many researchers have reported a direct linear relationship between phosphorus concentrations in soil and levels of dissolved phosphorus in runoff (Sharpley et al., 1977, 1978; Daniel et al., 1994; Pote et al., 1996; Torbert et al., 2002). However, most of these relationships have been derived from rainfall simulations at laboratory or small-plot scales and may not adequately represent relationships from natural rainfall at field, catchment, or watershed scales since variables are site and soil specific (Young and Mutchler, 1976; Mannaerts, 1992). Laboratory- and plot-derived relationships must be validated at field scales as complex and scale-dependent hydrological processes govern the amount and forms of phosphorus loss (Bloschl et al., 1995; Le Bissonais et al., 1998; Nash et al., 2002). Furthermore, while many relationships have been developed to predict losses of dissolved phosphorus, water quality guidelines are based on total phosphorus (TP) as dissolved and particulate forms contribute to eutrophication (Wetzel 2001). Conventional methods of filtering and analyzing a water sample for dissolved phosphorus forms can overestimate biologically available phosphorus (Fisher and Lean, 1992; Hudson et al., 2000); thus, TP is recommended as a more meaningful measurement of phosphorus in surface waters (Wetzel, 2001).

Although strong relationships between soil test phosphorus (STP) and runoff phosphorus have been observed at lab and plot scales, results from field-scale research have been confounded by variation in soil types, hydrology, and management. Sharpley et al. (1996) reported that the relationship between STP and dissolved reactive phosphorus (DRP) in overland flow at the field scale varied with soil type, management, and runoff episodes. Sharpley et al. (2002) found that extraction coefficients (slopes of the regression lines) increased with greater erosion or reduced soil cover due to greater interaction

Published in J. Environ. Qual. 36:1289–1300 (2007).
doi:10.2134/jeq2006.0502
Received 16 Nov. 2006.
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Abbreviations: DPS, degree of phosphorus saturation; DP, dissolved phosphorus; DRP, dissolved reactive phosphorus; FWMC, flow-weighted mean concentration; PP, particulate phosphorus; PSI, phosphorus sorption index; STP, soil test phosphorus; TP, total phosphorus.

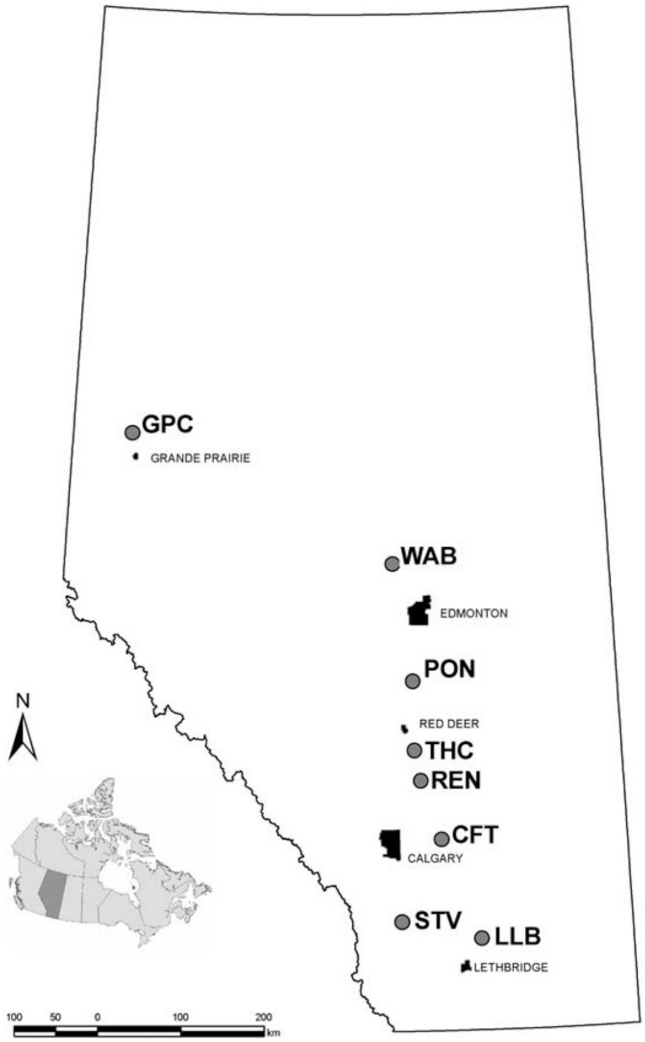

Fig. 1. Microwatershed sites in Alberta, Canada.

between soil and overland flow, and they suggested that an erosion function may also be necessary to predict soil phosphorus release. Sharpley (1995) and Sharpley et al. (1996) concluded that field-scale coefficients are too variable to allow the use of a single or average relationship for all soils under the same management due to the inherent variability among soils and to the soil-specific nature of soil phosphorus release to overland flow. However, Vadas et al. (2005a) proposed that a single extraction coefficient could be used to approximate DRP release from soil to runoff, based on lab-scale and plot-scale results from 30 soil types. Since extraction coefficients from field-scale studies are not well documented, an understanding of the relationship between STP and phosphorus in runoff in conditions representing local climate, soil type, land use, and management is needed.

While most researchers have reported poor relationships between STP and TP at the field-plot scale (Andraski and Bundy, 2003; Kleinman et al., 2004), Schroeder et al. (2004) found stronger relationships between STP and TP (r^2 = 0.69) than between STP and DRP (r^2 = 0.56) at the field-plot scale. Kleinman et al. (2004) found that boxes packed with disturbed field soil yielded increased concentrations of TP relative to the grassed field plots from which the soil had been taken. This was attributed to reduced infiltration, increased surface flow, bare soil conditions, and increased erosion for the lab-scale packed boxes relative to the field plots. Erosion is much more scale-dependent than dissolution and is therefore difficult to replicate at the lab scale. However, as TP is used in determining the trophic status of surface waters and in water quality guidelines, it is important to estimate TP losses from agriculture.

The degree of phosphorus saturation (DPS) may also be an important factor in determining runoff P losses. The DPS is a measure of how saturated soil sorption sites are with phosphorus, and is influenced by a number of variables, including aluminum, iron, calcium, clay, organic matter, pH, and carbon/phosphorus ratio. Sharpley (1995), Pote et al. (1996), and Hooda et al. (2000) reported that soils with similar STP levels have yielded different amounts of runoff phosphorus due to differences in phosphorus sorption capacity (PSC). Vadas et al. (2005a) found a split-line relationship where DRP rapidly increased at DPS values greater than 12.5% for noncalcareous soils.

The question of whether an environmentally oriented soil sampling method is more appropriate for understanding the relationship between STP and phosphorus in runoff has not been resolved, particularly for Alberta conditions. Kleinman et al. (2000) proposed a soil chemical approach for determination of soil P sorption thresholds (i.e., change points) related to soil P transfer to waterways. These thresholds are based on P sorption saturation levels in the soil and they delineate a critical soil P loading level above which any added P may be lost more readily via surface runoff or leaching. Split-line models have been used to determine thresholds where the relationship between STP or DPS and dissolved reactive P (DRP) in runoff or drainage are split into two sections, one with greater P loss per unit soil P than the other (Hesketh and Brookes, 2000; McDowell and Trudgill, 2000). Quantity/intensity (Q/I) relationships such as these have been used to identify change points in several recent studies (McDowell and Sharpley, 2001; Maguire and Sims, 2002a, 2002b; Indiati and Sequi, 2004; Nair et al., 2004; Casson et al., 2006).

The main objective of this study was to determine the field-scale relationship between STP and runoff TP and DRP from field-sized catchments or "microwatersheds" under spring snowmelt and rainfall conditions in Alberta. We also examined whether a variety of depths and spatial representations of STP improved the prediction of phosphorus losses, and we explored the use of the DPS as an alternate method of predicting phosphorus export at the field scale.

Materials and Methods

Site Description

Eight field-scale microwatershed sites with high runoff potential, uniform management, and no farmyard or non-agricultural influences were selected for the study. The sites included one ungrazed grassland site near Stavely, Alberta (STV); five cultivated, non-manured sites near Crowfoot Creek (CFT), Grande Prairie Creek (GPC), Renwick Creek (REN), Threehills Creek (THC), and Wabash Creek (WAB); and two cultivated, manured sites near Ponoka (PON) and Lower Little Bow River (LLB) (Fig. 1).

The microwatershed sites ranged in area from 2 to 248 ha (Table 1). Management characteristics ranged from no till at the CFT and THC sites, to reduced tillage at the REN site, and conventional tillage at the WAB, GPC, LLB, and PON sites (Table 1). The PON site received high rates of cattle manure, whereas the LLB site received moderate rates of cattle manure (Table 1). The STV site had not been grazed by cattle for at least 15 yr before the start of the study and had minimal grazing on the site since 1949; however, wildlife were prevalent in the area (Dr. Walter Willms, personal communication, 2007). Average slopes at the cultivated sites were similar (2%), with lower slopes at the LLB, WAB, and CFT sites (1%), and higher slopes at the THC (4%) site. The STV site had a steep slope (8%), as it was located in the foothills of western Alberta (Table 1). A natural gas company constructed an earth road that bisected the natural runoff pattern through the REN site in January 2004; therefore, only the 2003 data were used from this site.

Table 1. Characteristics and management information of the eight microwatershed sites.

Site	Area	Mean slope	Annual precipitation†	Est. annual runoff potential‡	Management§	Type of P application	Annual added P
	ha	%	———mm———				kg ha^{-1}
Ungrazed grassland site							
STV	2	8	500–550	113	na		
Non-manured sites							
CFT	248	1	350–400	12	NT	banded with seed	17–22
GPC	62	2	450–500	77	CT	banded with seed	10–21
REN	26	2	400–450	18	RT	banded with seed	22–28
THC	51	4	450–500	35	NT	banded with seed	15–25
WAB	33	1	500–550	26	CT	banded with seed	15–17
Manured sites							
LLB¶	88	1	350–400	14	CT	manure every 3 yr	
PON	30	2	500–550	36	CT	manure 1–2x per yr	

† Chetner and Agroclimatic Atlas Working Group (2003).

‡ Jedrych et al. (2002).

§ CT = conventional tillage, RT = reduced tillage, NT = no tillage before seeding, na = not applicable.

¶ Irrigated.

All sites had similar soil surface texture (loam), except for the GPC site, which was a clay loam (Table 2). Other soil characteristics are described in Table 2. Clay content in the surface horizons ranged from about 150 g kg^{-1} at the PON, REN, and STV sites to 290 g kg^{-1} at the GPC site (Table 2). Organic matter content ranged from 43 g kg^{-1} at the WAB site to 140 g kg^{-1} at the STV site.

Digital elevation models (DEMs) were used to identify microwatershed boundaries, contributing areas, and areas where flow and deposition were likely to occur. The $\ln(\alpha/\tan\beta)$ topographic index was also calculated, where α is the accumulated upslope contributing area that drains to a given point, and β is the local slope angle (Quinn et al., 1995).

Soil Sampling and Analysis

A minimum of six, three-point transects, plus additional points with a range of topographic index values, were sampled at each site to achieve a density of one sample per 1 to 5 ha. The exception was the 2-ha STV site where only three sampling points were selected. A satellite-based navigational system, or differential global positioning system (horizontal accuracy <1 m) was used to locate sampling points and navigate back to the same points. Fall sampling in 2002, 2003, and 2004 was conducted after all field operations were completed. A subsample of points (n = 5 to 10) identified by high wetness index values was sampled after seeding and fertilizing had been completed in the spring of 2003, 2004, and 2005.

An excavation method was used to obtain representative portions of fertilizer bands or manure and soil using a 19- by 50-cm frame placed diagonal to crop rows. The frame dimensions were changed after the fall of 2003 to 11 cm by two times the fertilizer bandwidth and placed perpendicular to the seed row. Soil samples were excavated from the 0- to 2.5-cm, 2.5- to 5-cm, and 5- to 15-cm layers. One frame per sampling point was used for non-manured fields, while two frames per sampling point were used at the remaining sites. The excavated soil layers were thoroughly mixed in the field, and a 500-g subsample was shipped in coolers to the laboratory.

Soil samples were dried and ground to pass through a 2-mm sieve and a 5-g subsample was removed for STP analysis. Samples taken in the fall of 2002 and the spring of 2003 were

Table 2. Summary of surface soil characteristics in the microwatersheds.

Site	Soil class	Texture (surface/subsurface)†	Mean organic matter	Mean clay	pH	Lower‡	Mid‡	Upper‡
			———g kg^{-1}———			———%———		
Ungrazed grassland site								
STV	Typic Haplustoll	L/CL	140	140	6.5	33	34	33
Non-manured sites								
CFT	Typic Haplustoll	L/SiL	53	210	6.4	9	55	36
GPC	Alfic Agricryoll	CL/C	75	290	6.0	17	65	17
REN	Typic Haplustoll	L/SL	66	150	5.7	32	52	15
THC	Typic Haplustoll	L/L	100	230	6.0	24	49	26
WAB	Alfic Agricryoll	L/CL	43	200	5.9	7	73	20
Manured sites								
LLB	Typic Haplustoll	L/CL	45	260	7.7	30	59	11
PON	Albic Agricryoll	L/CL	96	120	6.5	25	58	17

† C = clay, CL = clay loam, L = loam, SL = sandy loam, SiL = silty loam.

‡ Proportion of microwatershed within each landscape position.

analyzed for STP using the modified Kelowna extraction method (0.015 M NH_4F, 1.0 M HOAc, 0.5 M NH_4OAc) of Ashworth and Mrazek (1995) and the remaining samples were analyzed using the modified Kelowna extraction method (0.015 M NH_4F, 0.25 M HOAc, 0.25 M NH_4OAc) of Qian et al. (1991). Values of STP for the 0- to 5-cm and 0- to 15-cm soil layers were calculated by proportional weighting of the measured results. A large volume (20 to 25 L) of soil from the 0- to 15-cm layer collected at each site was used as a reference sample. The reference samples were dried, ground to pass through a 2-mm sieve, well mixed using a cement mixer, then subsampled using a sample splitter. Ten subsamples per site were analyzed at each laboratory used in the study. Soil test phosphorus values were then standardized to the reference sample results to account for differences in methodology, using factors calculated from the difference between STP concentrations at one lab relative to concentrations measured at the final lab. The mean adjustment factor was 1.14 with a standard deviation of 0.19 mg kg^{-1}.

The phosphorus sorption capacity was characterized at six transects per site for the 0- to 2.5-cm layer using samples from the fall of 2003. A subsample of six points sampled in the fall of 2002 and the fall of 2004 at each of the manured sites was also analyzed. A calcium chloride method was used to measure the phosphorus sorption index (PSI) of each soil (Casson et al., 2006). The DPS was determined as the ratio between STP to PSI plus STP (Indiati and Sequi, 2004). The PSI results from the fall of 2003 were used in the DPS calculations for the fall of 2002 and 2004 at the non-manured sites. The soils at the non-manured sites did not receive any organic amendments during the study so it was assumed that the PSI values would remain stable with time.

Soil Test Phosphorus Sampling Strategies

Five sampling strategies of STP were calculated for each soil layer:

- Site mean. All sampled points were used to calculate the site mean.
- Landform area-weighted mean. The areal extent of the upper, middle, and lower landforms within each catchment was calculated from the DEM (Table 2) and mean STP levels from each landform class were weighted by the proportion of each landform within each microwatershed.
- Runoff contributing area. Points with high wetness index values representing 20% of all points were used to calculate STP.
- Representative random sample. The results of points sampled in depressions and on upper slopes were omitted and a random selection was made from the remaining points located in middle and lower slope positions for a minimum of 15 points per site or one sample per 3.5 ha.
- Random sample. The mean of a random subsample of 15 points per field was used for this representation of STP.

Only the fall samples from the 3 yr were used to calculate the STP sampling strategy means, and the STV site data were not included in the sampling strategies because there were only three sampling points at the 2-ha site.

Water Measurement and Sampling

Most sites were instrumented with circular flumes (Samani et al., 1991). The PON site was initially instrumented with a 0.61-m H-flume, which was replaced with a circular flume in June 2003. The STV site was bordered on the down-slope edge with a trough, which directed runoff water into a 0.15-m trapezoidal flume. Stage was recorded at 5-min intervals using a float potentiometer. Circular flumes were calibrated using the Water Ware software program developed by Samani et al. (1991). The resulting calibrations were then plotted in TableCurve 2D, version 3 (Jandel Scientific Software, 1994) to fit an appropriate curve to the data. Once a curve was selected and applied to the stage readings, a correction factor was applied to account for any inactive head in the flume.

The sites were also equipped with staff gauges and float potentiometers to record stage, Lakewood TP10K5 thermistors (Lakewood Systems Ltd., Edmonton, AB, Canada) to measure air temperature, and Davis tipping bucket rain gauges (Davis Instruments Corp., Hayward, CA), which were replaced with Texas tipping bucket rain gauges (Texas Electronics Inc., Dallas, TX) in May 2004. Sites were powered with two 15-W solar panels, and rechargeable 12-V batteries. Each site was equipped with integrated dataloggers and cellular communications technology obtained from ROM Communications that allowed real-time monitoring of the sites (ROM Communication Inc., Kelowna, BC, Canada). When flow or precipitation was detected, data were reported on a website and field staff alerted. The STV site was equipped with a Lakewood Ultralogger (Lakewood Systems Ltd., Edmonton, AB, Canada), a float potentiometer, and a meteorological station, and a technician collected all flow data and water samples from this site. Staff gauge readings were recorded at all sites during field visits and were used as backups for the real-time flow data recorded by the ROM dataloggers.

Water samples were taken by ISCO 6700 automated water sampling devices (Teledyne Isco Inc., Lincoln, NE), equipped with 24, 1-L ProPaks and disposable polyethylene inserts. The ISCO samplers were programmed to sample 100 mL every 15 min once changes in stage were detected.

Water samples were retrieved daily during runoff events and immediately transported in coolers to the laboratory. Water samples were analyzed within 24 h for pH and electrical conductivity, and within 30 d for TP (persulfate digestion: APHA 4500E). Subsamples were filtered on arrival (0.45-μm filter) and analyzed within 48 h for DRP using the ascorbic acid method of Murphy and Riley (1962), and within 30 d for dissolved phosphorus (DP) (persulfate digestion: APHA 4500E). Selected samples were analyzed for additional parameters, including total suspended solids (TSS). Blanks filled with deionized water, as well as a prepared standard of known phosphorus concentration, were submitted to the lab with each batch of samples as part of a quality assurance/quality control program.

Data Analysis

Runoff Phosphorus Calculations

To calculate flow-weighted mean concentrations (FWMCs), water chemistry data were linearly interpolated to 1-min intervals using Proc Expand in SAS (SAS Institute Inc., 2003). The interpolated concentration data were then matched to the flow data and instantaneous loads were calculated for matching values by multiplying flow and concentration data. The area under the curve was then integrated to estimate total loads and flow volumes using a SAS area macro. Seasonal FWMCs were then calculated by dividing the total load for all events by the total flow volume. Where possible, missing flow data were supplemented by manual staff gauge readings. However, in some cases, mean concentrations had to be substituted for days with missing flow data.

Statistical Analysis

Statistical analyses of the soil and water data were completed using SAS version 9.1 (SAS Institute Inc., 2003). Differences between means were tested using the Least Squares Means test in the PROC MIXED procedure, with variance components as the variance structure, and a Fisher's protected LSD test. The REG procedure was used to relate measures of STP to seasonal FWMCs of runoff phosphorus and the Type III sums of squares in the Mixed procedure was used to determine if there were significant differences in slopes and intercepts between regression equations. A significance level of 0.05 was used throughout this study. A PROC NLIN split-line model was used to determine the environmental soil P thresholds (change points). The NLIN procedure required estimation of linear ($d + ex$) and quadratic ($a + bx + cx^2$) estimation parameters, and solved for the threshold between the linear and quadratic regressions by iterative re-evaluation of the equation. The STP values that corresponded to change points were subsequently determined from the relationships between STP and runoff P.

Results and Discussion

Soil Test Phosphorus

Mean values of STP in the 0- to 15-cm layer in the fall of 2002 ranged from 3 to 512 mg kg^{-1}, with the lowest value at the ungrazed grassland (STV) site and the highest value at the heavily manured PON site (Table 3). Mean STP values at the five cultivated, non-manured sites differed by only 15 mg kg^{-1}. Temporal differences in STP at the non-manured sites during the 3-yr period were generally not significant, except for significant increases between the fall of 2002 and the spring of 2003 at the GPC site (data not shown). At the manured sites, mean STP levels were an order of magnitude greater than at the non-manured sites. Soil test phosphorus levels at the manured sites declined with time after manure application, although temporal differences were only significant between the spring of 2003 and the fall of 2004 at the PON site (Nolan et al., 2007). Manure was applied in the fall of 2002 at the PON site and applied to alternate halves of the LLB microwatershed in the spring and fall of 2002, the fall of 2004, and the spring of 2005. No increase in STP was observed at the LLB site after the fall 2004 manure application because six of the nine points sampled in the spring of 2005 did not receive manure additions in the fall of 2004 due to wet soil conditions. Increases were observed when the three manured points were considered separately.

Table 3. Mean values of various sampling strategies for soil test phosphorus (STP) in the 0- to 2.5-cm and 0- to 15-cm soil layers at microwatershed sites in the fall of 2002.

Site	Site mean	Landform area weighted†	Runoff contributing area	Representative random	Random
	mg kg^{-1}				
0 to 2.5 cm					
STV‡	5	–	–	–	–
CFT	43a§	41	40a	39a	35a
GPC	45a	45	42a	44a	44a
REN	38a	36	43a	39a	39a
THC	44a	42	51a	43a	43a
WAB	37a	38	41a	35a	37a
LLB	316a	327	269a	309a	276a
PON	648a	654	680a	662a	673a
0 to 15 cm					
STV	3	–	–	–	–
CFT	34a	34	27a	33a	30a
GPC	33a	32	24b	32ab	33a
REN	20a	20	24a	20a	22a
THC	26a	24	32a	26a	25a
WAB	35a	34	40a	32a	34a
LLB	269a	279	216a	265a	257a
PON	512a	512	582a	522a	532a

† Calculated using an area-weighted mean, and as a result could not be statistically compared to the other STP representations.

‡ Limited samples were collected from the site; therefore, representations could not be calculated other than the site mean.

§ Means within the same row followed by the same letter are not significantly different at $P < 0.05$.

Mean STP values in the 0- to 2.5-cm layer in the fall of 2002 were an average of 12 mg kg^{-1} greater than the 0- to 15-cm layer at the non-manured sites and 92 mg kg^{-1} greater at the manured sites. However, mean STP values were significantly greater in the 0- to 2.5-cm layer than in the 0- to 15-cm layer, except at the LLB, PON, and CFT sites, and no significant differences were observed between the 0- to 2.5-cm layer and the 0- to 5-cm layer at all sites (Nolan et al., 2007). Guertal et al. (1991) measured up to three times more STP in the 0- to 2-cm layer than in the 0- to 8-cm layer in no-till conditions. Phosphorus tends to be more concentrated near the soil surface because of its limited mobility in soil (Sharpley et al., 1978; Sharpley, 1985), especially under reduced- or no-till management (Sharpley et al., 1993).

Soil Test Phosphorus Sampling Strategies

There were few significant differences among the STP sampling strategies in the 0- to 2.5-cm and 0- to 15-cm soil layers in the fall of 2002 (Table 3). This was also true for the 0- to 5-cm layer (data not shown). Significant differences were observed in the 0- to 15-cm layer at the GPC site in the fall of 2002, 2003, and 2004, where the runoff contributing area STP was significantly less than the site mean and random STP values (Table 3), and in the 0- to 5-cm and 0- to 15-cm layers at the LLB site in the fall of 2004 where the runoff contributing area STP was significantly lower than the site mean and the representative random STP values (data not shown) because manure was not ap-

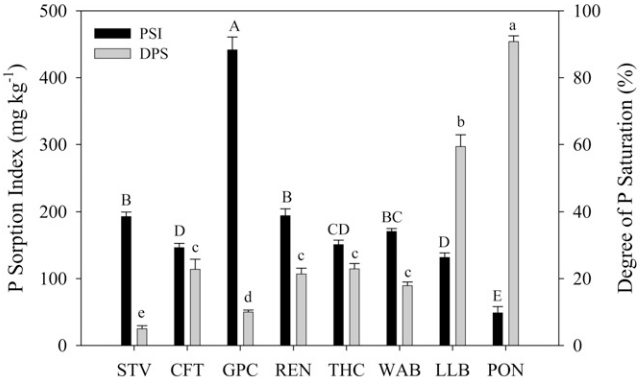

Fig. 2. Phosphorus sorption indices (PSI) and degree of soil phosphorus saturation (DPS) in the 0- to 2.5-cm soil layer at the microwatershed sites in the fall of 2003. Standard error bars are shown. Bars with the same letter above for that parameter are not significantly different (*P* < 0.05).

plied in the wet lower landform positions in the fall of 2004. The differences among the five STP sampling strategies in the 0- to 2.5-cm layer ranged from 3 to 9 mg kg^{-1} for the non-manured sites and from 32 to 70 mg kg^{-1} at the manured sites (Table 3). Soil test phosphorus in the 0- to 15-cm layer at the PON site was 1.1 times greater in the runoff contributing area samples compared with the site mean and the representative random samples, though they were not statistically different. This is lower than the fourfold increase in "effective" soil P status observed by Page et al. (2005) when they collected samples from areas with overland flow that were directly connected to the stream and compared to a site mean in a grassland catchment in the United Kingdom.

Despite reports of accumulation of phosphorus in lower landscape positions in Alberta (Penney et al., 2003), there were no significant differences by landform position at five of the seven cultivated sites and results at one of the sites was conflicting, with more phosphorus in the mid or upper landform positions (Nolan et al., 2007). As such, few differences were observed between the landform area-weighted representation and the site mean. Although these values could not be statistically compared as they were calculated from area-weighted means, the landform area-weighted values were similar to the other STP representations. This is partly due to the similarity in STP in different landforms at conventionally tilled sites and the low proportion of lower landform areal extents at reduced and no-till sites (Table 2), where greater differences in STP by landform position were observed (Nolan et al., 2007).

Page et al. (2005) noted that important information on the variability and spatial distribution of STP for a given sampling area can be lost when samples are averaged. However, Daniels et al. (2001) concluded that when sampling soil phosphorus in pastures, current sampling strategies for agronomic soil tests can adequately account for spatial variability to produce a single, appropriate estimate of STP, if the recommendations are followed with respect to the required number of samples. Similarly, Needelman et al. (2001) concluded that field mean STP in hog and poultry manure-amended fields could be used to characterize STP for applications that are not sensitive to small errors in STP estimates. In a study of manured and non-manured soils in Manitoba, Slevinsky et al. (2002) reported that there were no differences in STP levels measured in the 0- to 15-cm layer using a composite of 15 random points per field or using the average of four representative benchmark samples per field.

Degree of Soil Phosphorus Saturation

The PSI in the 0- to 2.5-cm layer was significantly higher at the GPC site than at any other site (442 mg kg^{-1}, Fig. 2) due to the greater clay content and more recent cultivation (Table 2). The range among PSI values at the five non-manured sites (296 mg kg^{-1}) was much larger than the range among STP values in the fall of 2003 (8 mg kg^{-1}; data not shown). The PSI at the heavily manured PON site (49 mg kg^{-1}) was significantly lower than at all other sites. The DPS in the 0- to 2.5-cm layer was significantly lower at the ungrazed grassland STV site (5%) than at any other site, while DPS at the GPC site (10%) was significantly lower than at the other cultivated sites (Fig. 2). The DPS was significantly higher at the heavily manured PON site (91%, Fig. 2) than at all other sites. Casson et al. (2006) showed that the PSI of medium- and coarse-textured Alberta soils decreased significantly with increasing manure rates while the DPS increased significantly to values >90% for a coarse-textured soil and >70% for a medium-textured soil after 8 yr of annual manure application. There were no temporal differences at the manured sites in DPS over the 3-yr period at any of the sites (Little et al., 2006).

Runoff Results

The majority of runoff (>90% across all sites) was generated from spring snowmelt. Rainfall runoff was only generated from the REN and LLB sites in 2003, the GPC and LLB sites in 2004, and the PON, STV, THC, and LLB sites in 2005. The LLB site also produced irrigation runoff in all 3 yr. Summer precipitation ranged from 75% below normal at the LLB site in 2003 to 88% above normal at the STV site in 2005 (Table 4). Only the PON site had below normal summer precipitation in all 3 yr. The LLB and STV sites had below normal winter precipitation in all 3 yr of the study (Table 4). Snowmelt runoff was not observed at the LLB, PON, and REN sites in 2004 and at the LLB and STV sites in 2005 (Table 5). In Alberta, total yearly runoff from small agricultural watersheds tends to be dominated by snowmelt (Nicholaichuk, 1967; Gill et al., 1998; Wuite and Chanasyk, 2003; Ontkean et al., 2005).

Spring DRP FWMCs at the non-manured sites ranged from 0.01 to 0.63 mg L^{-1} (Table 5), while the TP FWMCs ranged from 0.20 to 0.86 mg L^{-1}. Although there was some variability in the concentrations among years, the ranking of DRP and TP FWMCs among the sites were consistent each year, with the GPC site having the lowest FWMCs and the THC site the highest FWMCs. The low FWMCs at the GPC site may have been due to the low DPS (Fig. 2). This site had high clay content and may therefore have had more exchange sites available to bind phosphorus. The high FWMCs at the THC site may be due to significantly higher concentrations of STP in the lower landform positions (Nolan et al., 2007) and steeper slopes. Summer runoff was generated at the GPC, REN, and THC sites and DRP FWMCs ranged from 0.05 to 0.10 mg L^{-1} (Table 5), while the TP FWMCs ranged from 0.36 to 1.57 mg L^{-1}.

The DRP and TP FWMCs from the STV site in 2003 were within the range of the non-manured sites despite an STP level that was about one-third of the non-manured sites (Table 5). Concentrations of DRP and TP were comparable to those reported by Timmons and Holt (1977) from native grasses in Minnesota. The relatively high values may be due to leaching of DRP from the large amounts of vegetation cover and surface thatch at this site. In addition, freezing and thawing of plant material dramatically increases the amount of nutrients that can be leached (Timmons et al., 1970; Bechmann et al., 2005). In 2004, the DRP and TP FWMCs were much lower, possibly due to the much smaller volume of runoff.

At the manured sites, levels of DRP and TP were greatest in the spring of 2003 following manure applications in the fall of 2002. Individual values at the PON site in the spring of 2003 were as high as 24 mg L^{-1} DRP and 108 mg L^{-1} TP, with FWMCs of 16.5 mg L^{-1} DRP and 23.5 mg L^{-1} TP. The manure was applied just before freeze up and poorly incorporated in late 2002. The PON site had a very high DPS (Fig. 2), suggesting that it had little capacity to bind phosphorus. In addition, TSS concentrations were elevated (data not shown) and accumulation of sediment in the flume was observed during field visits, indicating selective sampling of sediment from the H-flume. Therefore, samples with extreme TSS concentrations and TP/DP ratios greater than 10 were deemed to be outliers and removed from the dataset. Even with these extreme values removed, the spring 2003 TP FWMC was still three times greater than from any other runoff event.

In contrast, the LLB site had manure applied to the portion of the watershed nearest the flume in the spring of 2002, which allowed greater opportunity for phosphorus to be adsorbed by soil and mixed with the subsurface soil by intensive tillage following the spring manure application and fall harvest. The DRP FWMCs values at the LLB site were an order of magnitude lower than at the PON site. Previous studies have indicated that when soils have received surface applications of manure, the manure phosphorus overwhelms the soil phosphorus and becomes the major source of phosphorus to runoff instead of the soil (Pierson et al., 2001; Kleinman et al., 2002). Therefore, STP is often not an accurate representation of runoff-available phosphorus. However, the differences between amended and unamended soils are much less if the manure has been incorporated (Kleinman et al., 2002) or has had time to equilibrate with the soil (Eghball et al., 2002).

Summer runoff FWMCs at the manured sites were more variable, with individual event DRP FWMCs ranging from 0.84 to 3.01 mg L^{-1} at the LLB site and from 5.25 to 6.63 mg L^{-1} at the PON site. Summer 2003 and 2005 runoff values from the LLB site were much greater than in 2004 as the portion of the site nearest the outlet received manure in the spring of 2002 and the fall of 2004. Declines in summer runoff were likely related to decreased levels of STP due to the equilibration of the manure with the soil, dilution by tillage, and crop uptake.

Table 4. Precipitation differences from 30-yr normal data for each microwatershed site.

Site	Winter difference from normal precipitation			Summer difference from normal precipitation		
	2003	2004	2005	2003	2004	2005
	%			%		
Ungrazed grassland site						
STV	−38†	−61	−14	−42	74	88
Non-manured sites						
CFT	14	−21	−6	−30	−17	35
GPC	91	−5	−1	−44	77	−11
REN	8	−44	−9	−55	−5	19
THC	73	11	50	−59	23	5
WAB	64	3	−7	−47	47	−6
Manured sites						
LLB	−23	−42	−45	−75	−1	74
PON	86	−43	−3	−48	−28	−16

† Positive values are percent greater than the 30-yr normals and negative values are percent less than the 30-yr normals for each site. Data provided by Environment Canada (2005).

Table 5. Seasonal flow-weighted mean concentrations (FWMC) of dissolved reactive phosphorus (DRP) and total phosphorus (TP) from the eight microwatershed sites.

Site	Spring 2003		Summer 2003		Spring 2004		Summer 2004		Spring 2005		Summer 2005	
	DRP	TP	DRP	TP	DRP	TP	DRP	TP	DRP	TP	DRP	TP
	mg L^{-1}											
Ungrazed grassland site												
STV	0.18	0.52	–†	–	0.09	0.19	–	–	–	–	0.06	0.10
Non-manured sites												
CFT	0.24	0.38	–	–	0.17	0.30	–	–	0.30	0.53	–	–
GPC	0.01	0.20	–	–	0.08	0.34	0.09	0.36	0.19	0.41	–	–
REN	0.21	0.41	0.05	0.50	–	–	–	–	–	–	–	–
THC	0.63	0.77	–	–	0.31	0.52	–	–	0.53	0.86	0.10	1.57
WAB	0.20	0.58	–	–	0.18	0.30	–	–	0.14	0.41	–	–
Manured sites												
LLB	3.44	3.94	2.15	2.86	–	–	0.87	1.84	–	–	2.63	3.54
PON	16.5‡	23.5‡	–	–	–	–	6.28	6.59	7.39	8.00	5.25	5.26

† No runoff.

‡ Results from the spring runoff in 2003 at the PON site were excluded due to the recent application of manure that was poorly incorporated just before freeze up and the selective sampling of sediment by the ISCO due to sediment accumulation in the H-flume.

Table 6. Slopes and intercepts for relationships between the soil test phosphorus (STP) sampling strategies in the 0- to 15-cm layer and the flow-weighted mean concentrations (FWMCs) of dissolved reactive phosphorus (DRP) and total phosphorus (TP) in spring snowmelt runoff from the seven cultivated sites.

	DRP FWMC			TP FWMC		
STP sampling strategy	Slope	Intercept	r^2	Slope	Intercept	r^2
Mean of all point data	0.019	−0.340	0.94	0.020	−0.154	0.95
Landform area weighted	0.018	−0.315	0.93	0.020	−0.129	0.93
Runoff contributing area	0.017	−0.249	0.99	0.018	−0.055	0.99
Representative random	0.018	−0.311	0.96	0.019	−0.123	0.96
Random	0.019	−0.316	0.96	0.020	−0.129	0.96

Flow-weighted mean concentrations of DRP were not significantly different among runoff types; however, the REN and THC sites had significantly higher concentrations of TP and lower DP/TP ratios in rainfall runoff (Little et al., unpublished data, 2005) compared with snowmelt runoff. Concentrations and DP/TP ratios were not different between rainfall and snowmelt runoff at the manured PON and LLB sites. This may be related to greater sediment losses from the increased erosion of unfrozen soils and/or greater precipitation intensity from rainfall compared to snowmelt.

Relating Phosphorus Concentrations in Soil and Runoff

Seasonal FWMCs were used to relate phosphorus concentrations in soil and runoff. Spring snowmelt runoff results were related to the soil sampling results from the previous fall, while summer runoff events were related to the soil sampling results from the spring of the same year. Results from the spring runoff in 2003 at the PON site were excluded due to the recent application of manure that was poorly incorporated just before freeze up and the selective sampling of sediment by the ISCO due to sediment accumulation in the H-flume.

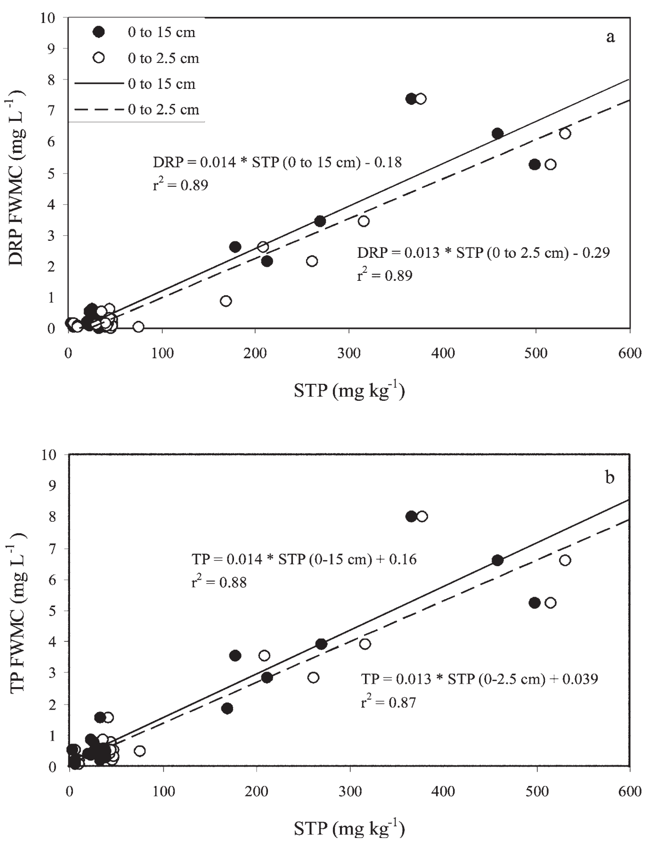

Fig. 3. Relationships between soil test phosphorus (STP) and the flow-weighted mean concentrations (FWMC) of (a) dissolved reactive phosphorus (DRP) and (b) total phosphorus (TP) from the microwatershed sites.

Soil Test Phosphorus Sampling Strategies Comparison

Strong linear relationships were found between all STP sampling strategies and the spring snowmelt FWMCs of DRP and TP (Table 6). Reports in the literature have suggested that soils in critical source areas can have greater influence on phosphorus loss in runoff than soils in other areas of the field (Gburek and Sharpley, 1998); however, in our study, there were no significant differences among the regression equations for all STP sampling strategies. Coefficients of determination for the site mean were similar or slightly greater using the landform area-weighted or runoff contributing area sampling strategy means. Representative random sampling and a random subset of samples also produced similar results to using the site mean. Differences among the five STP sampling strategies were minimal (Table 3), and this was reflected in the similarity among regression results (Table 6). This was partly due to the observation that few differences by landform position were detected and that variable management practices, such as the uneven distribution of manure at the LLB site or conventional tillage at the GPC and WAB sites, obscured expected differences in STP by landform position (Nolan et al., 2007). The similarity between regression equations may also be partly attributed to the observation that most of the runoff was generated from large spring snowmelt events, which generated runoff from a greater proportion of the field due to restricted infiltration on frozen soils compared with summer precipitation events.

Since the comparison of the STP sampling strategies, which included only the spring runoff data from the cultivated sites, showed no differences among the relationships of the sampling strategies (Table 6), it was decided to use the mean of all sampling points and include the summer runoff data to develop the STP and runoff phosphorus relationships.

Soil Test Phosphorus and Runoff Phosphorus Relationships

There were strong linear relationships between STP and DRP and TP FWMCs for the 0- to 2.5-cm and 0- to 15-cm soil layers (Fig. 3). The relationships for the 0- to 5-cm layer (not shown) were similar to the 0- to 2.5-cm layer. Due to the relatively narrow range of STP among the non-manured sites, the manured sites drive the relationships (Fig. 3). The relationships between STP in the 0- to 15-cm layer and FWMC DRP (r^2 = 0.0008) and TP (r^2 = 0.052) were extremely poor when the manured sites were omitted. The distribution of values improved with time since manure was not applied to the PON site after the fall of 2002 or between the fall of 2002 and the fall of 2004 at the LLB site, which resulted in lower STP values from these sites as the manure was incorporated into the soil by tillage and manure phosphorus became equilibrated with the soil. Additional data from summer runoff events that corresponded with increased STP levels at the non-manured sites helped to improve the distribution of points. However, there were no observations within the STP range of 75 to 150 mg kg^{-1}, as even a single manure application can rapidly increase the STP levels in soil (Volf et al., 2007). Corresponding changes in STP and the DRP and TP FWMCs at the manured sites support that the relationship is linear and other studies in Alberta have also found a linear relationship within this range (Volf et al., 2007; Wright et al., 2006).

Analysis of the residuals for the 0- to 2.5-cm STP versus TP equation indicated that four of the residuals were outside the 95% confidence intervals of the regression (data not shown). Similar results were observed for the 0- to 5-cm and 0- to 15-cm equations. The regression equation underestimated runoff TP FWMCs at the LLB, PON, and THC sites in the summer of 2005, and overestimated the snowmelt runoff TP FWMC at the PON site in 2005. The summer event at the THC site in 2005 had a very high proportion of particulate phosphorus and therefore, a high TP FWMC. This finding suggests that high-intensity, short-duration summer events may not be well predicted by the model. However, average residual distances were similar between rainfall and snowmelt events, suggesting that the equation can be applied to both types of runoff events. Furthermore, given that spring runoff accounts for the majority of runoff in Alberta, the relationship between TP and STP is likely adequate for predicting phosphorus losses during most runoff events. To ensure that the events with large residual distances were not unduly influencing the relationships, the regressions were also run without the events with the two largest residual distances (from the PON site in 2005). Removal of the two events had only a minor effect on the regression equations, which were not statistically different from the regression with all points. Since there was limited data from manured sites, these points were kept in the dataset.

Many studies have reported strong linear relationships between STP and DRP in simulated runoff at lab and field scales (Wright et al., 2003; Vadas et al., 2005a). However, very few have developed relationships with TP (Schroeder et al., 2004), which combines dissolved and particulate fractions. Particulate phosphorus (PP) concentrations can be impacted by several additional factors related to erosion including tillage (Zhao et al., 2001), event size (Quinton et al., 2001), crop cover, and clay content of the soils (Calhoun et al., 2002). These factors are often difficult to evaluate under lab- or plot-scale rainfall simulations because erosion processes operate differently at larger scales. However, incorporation of an erosion factor to account for PP was not necessary in our study, since 90% of the runoff was generated by spring snowmelt from frozen soils and PP was only a minor component in summer runoff from manured sites (Little et al., 2006).

Although previous studies have found that surface runoff interacts with only a very shallow depth of soil (Sharpley et al., 1978; Sharpley, 1985), the relationships with spring and summer runoff had similar predictive power among all three depth layers. Statistical comparisons of the relationships indicated that the slopes and intercepts of the relationships for all three layers were not significantly different, although slopes and intercepts tended to increase with increasing depth. It was anticipated that STP from shallower sampling depths may have a stronger relationship with runoff phosphorus because the majority of runoff occurred during spring snowmelt when frozen soil restricts infiltration and minimizes the interaction between runoff and soils. However, given that STP results among all three layers were highly correlated in our study (r^2 = 0.99, df = 26), it was not surprising they predicted runoff phosphorus equally well. Andraski and Bundy (2003) also reported increased slopes for the relationship between DRP in simulated rainfall runoff and STP in the 0- to 15-cm soil layer compared with the 0- to 2-cm soil layer, but concluded that taking account of increased STP levels in the shallow layers did not improve relationships with DRP compared to those measured in the 0- to 15-cm layer. Vadas et al. (2005b) combined data from rainfall simulator studies representing 30 soil types throughout the United States at 0 to 5 cm, 0 to 15 cm, and 0 to 20 cm and found that STP measured from shallow samples in phosphorus-stratified soils gave a similar assessment of STP available to DRP in runoff as deeper samples in well-tilled soils.

Extraction coefficients for DRP and TP at the microwatershed scale were greater than those reported from laboratory rainfall simulations in Alberta (Wright et al., 2003). The strength of the TP relationship was much greater at the microwatershed scale (Wright et al., 2003). The DRP fraction was also a very small proportion of TP (0.08) for the laboratory rainfall simulations compared to the DRP/TP ratio of 0.55 for the microwatershed results (Wright et al., 2003). The bare and re-packed soil conditions of the laboratory simulations may have contributed to the large proportion of PP. Andraski and Bundy (2003) also reported low DRP/TP ratios in field-plot-scale rainfall simulations. Conversely, Volf et al. (2007) reported average DRP/TP ratios of 0.70 from field-plot-scale rainfall simulations, with greater ratios from manured sites compared to non-manured sites and lower ratios immediately following manure application compared to 1 yr later.

Possible explanations for the higher proportion of DRP measured at the microwatershed scale relative to the laboratory and small plot scales include the longer time that runoff is in contact with soil at the field scale, which may increase concentrations of dissolved phosphorus in runoff water compared to the plot scale (Nash et al., 2002). The PP fraction of TP tends to be favored in small plot-scale and lab-scale studies, due to the comparatively high kinetic energy of overland flow that increases the detachment of soil particles (Nash et al., 2002). Variations in topography at field scales also offer greater opportunities for the deposition of PP than at plot scales. Manure application and incorporation may have increased infiltration and reduced detachment in the field-plot-scale simulations of Volf et al. (2007), resulting in higher DRP/TP ratios than other small plot-scale studies. In addition, snowmelt runoff, which accounted for the majority of runoff in the microwatershed study, was not measured at the plot or lab scale. Snowmelt tends to have higher proportions of DRP than rainfall-generated runoff since frozen soils reduce the detachment of soil particles (Hansen et al., 2000). Higher ratios of DRP to TP in snowmelt were observed at the non-manured sites, but not at the manured sites (Little et al., 2006).

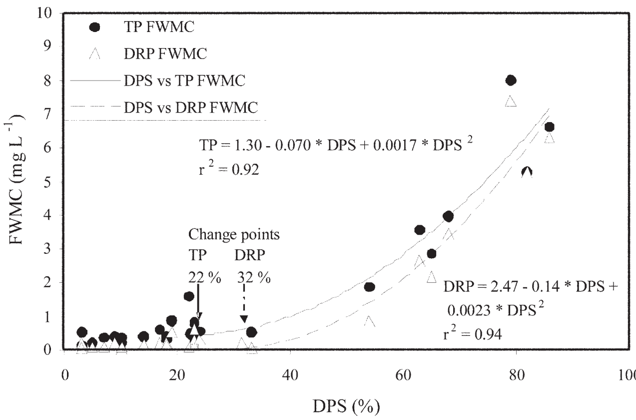

Fig. 4. Relationship between the degree of phosphorus saturation (DPS) in the 0- to 2.5-cm soil layer and the flow-weighted mean concentration (FWMC) of dissolved reactive phosphorus (DRP) and total phosphorus (TP). The equations and r^2 values refer to the curvilinear relationships, which includes DPS values equal to and greater than the change points.

Degree of Phosphorus Saturation and Runoff Phosphorus Relationships

The DPS in the 0- to 2.5-cm layer showed a split line relationship to runoff phosphorus concentrations (Fig. 4). The relationships were described by split line model equations, and explained similar amounts of variation as the STP equations (Fig. 3). Change points could not be determined between DPS and DRP and TP without inclusion of the manured sites. Change points were determined for all sites at a DPS value of 32% for DRP and 22% for TP (Fig. 4). These change point values corresponded to STP values of 37 and 34 mg kg^{-1}, which are approximately half the agronomic threshold of 60 mg kg^{-1}. The agronomic threshold is the level at which crops in most Alberta soils will not respond to the addition of phosphorus (Howard, 2006). There were slightly higher r^2 values for DPS and runoff P relationships (Fig. 4) compared with the STP and runoff P relationships (Fig. 3a and 3b). However, the soils used for DPS relationships were a subset of the soils used for STP relationships. Andraski and Bundy (2003) reported that phosphorus saturation explained similar amounts of variability in runoff phosphorus concentrations at one site, but explained less variability than STP at two other sites. Vadas et al. (2005a) and Andraski and Bundy (2003) reported that the relationship between STP and DRP concentrations in runoff was not improved using alternative STP extraction methods compared with the agronomic sampling methods currently in use. Our results suggest that this may also be true for TP concentrations in runoff.

Conclusions

Strong linear relationships between STP and phosphorus in runoff from eight field-scale microwatershed sites in Alberta were determined in this study. Relationships were developed for FWMCs of DRP and TP. Reduced levels of STP following the cessation of manure application corresponded directly with reductions in runoff phosphorus.

Although a number of different STP sampling strategies were examined, a simple average of all soil sampling points was as good a predictor of runoff phosphorus concentrations as a landform area-weighted mean representation and a subsample of points within the runoff contributing area. A random subset of samples and representative random samples also produced similar results. There were no significant differences in the slopes or intercepts in any of the relationships using different STP sampling strategies.

There were no significant differences among the relationships using different soil sampling depths of 0 to 2.5 cm, 0 to 5 cm, and 0 to 15 cm. Therefore, it is likely that an agronomic soil sampling depth of 0 to 15 cm can be used to predict phosphorus in runoff from agricultural land in Alberta.

Snowmelt runoff accounted for 90% of the runoff volume from the eight sites during the 3-yr study. Although large residual distances were observed for some summer events, the relationship between TP and STP is likely adequate for predicting phosphorus concentrations in most runoff events, given that the vast majority of runoff occurs during spring snowmelt.

Strong relationships were found between DPS and the FWMCs of DRP and TP; however, the relationships were not linear. Predictive abilities were similar to those observed for STP. Change point values corresponded to STP values that were half the agronomic threshold of 60 mg kg^{-1}. Although the DPS holds promise for predicting runoff and leaching losses of phosphorus, modified Kelowna STP is the standard for agronomic sampling in Alberta and our results suggest that there is no strong reason to move toward another soil test.

While several studies have examined the relationship between STP and DRP, few have reported relationships between STP and TP. In comparison with other Alberta studies, extraction coefficients for DRP were greater than lab-derived values. Since our study was based on field-scale results from Alberta, these relationships should provide the basis for phosphorus modeling in Alberta.

Acknowledgments

We wish to thank the staff of Alberta Agriculture and Food Irrigation Branch and Conservation and Development Branch for assistance with soil and runoff sampling. Thanks also to Keith Toogood, Toby Entz, Rong-Cai Yang, and Dennis Mikalson for assistance with data analysis. In addition, this project would not be possible without the cooperation of the producers, landowners, and municipalities. Partial funding for this study came from the Agricultural Funding Consortium, with contributions from the Alberta Livestock Industry Development Fund, the Alberta Crop Industry Development Fund, and the Alberta Agricultural Research Institute.

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