Degree of Phosphorus Saturation Thresholds in Alberta soils

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ABSTRACT

The risk of phosphorus losses from agricultural land to surface and ground water generally increases as the degree of soil phosphorus saturation (DPS) increases. A single-point soil phosphorus sorption index (PSI) was validated with adsorption isotherm data for determination of the phosphorus sorption status of Alberta soils. Soil phosphorus thresholds (change points) were then examined for two agricultural soils after eight annual applications of different rates of cattle manure, for three agricultural soils after one application of different rates of cattle manure with and without tillage, and for eight microwatershed soils with different land use histories. Soil-test phosphorus (STP), PSI, DPS, desorbed water-extractable phosphorus (WEP), and desorbed calcium chloride-extractable phosphorus ($CaCl_2$-P) were determined for the 13 soils. The WEP and the $CaCl_2$-P parameters served as proxies for phosphorus that could be lost in runoff from these soils. Desorbed phosphorus concentrations (WEP or $CaCl_2$-P) determined in the laboratory were generally higher, in relation to STP or DPS, than runoff DRP concentrations measured in the field. However, the relative amounts of runoff DRP that could be lost from these soils were similar to the desorbed phosphorus values, suggesting that WEP and $CaCl_2$-P may be good indicators of the relative amounts of DRP that can be lost from agricultural soils. Linear relationships were found between STP levels up to 1000 mg kg^{-1} and desorbed phosphorus in the 13 Alberta soils. Weak linear relationships were found between STP and runoff dissolved reactive phosphorus (DRP) measured in simulated rainfall runoff from the three manure rate and tillage soils. A strong linear relationship was found between STP and runoff DRP measured predominantly in snowmelt runoff from the eight microwatershed soils. Change points for DPS ranged from 3 to 47% for WEP and from 11 to 59% for $CaCl_2$-P, but no change points were found between DPS and runoff DRP. Overall DPS thresholds for the 13 soils combined were 35% for WEP and 54% for $CaCl_2$-P at a critical desorbed phosphorus value of 1 mg L^{-1}. These critical DPS thresholds corresponded to modified Kelowna STP levels of approximately 51 mg kg^{-1} for WEP and 86 mg kg^{-1} for $CaCl_2$-P, and these were close to agronomic thresholds of crops grown on Alberta soils. Soluble phosphorus losses in overland flow and leaching may be greater in soils with DPS values that exceed these thresholds than in soils with lower DPS values.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

INTRODUCTION

Repeated applications of high rates of livestock manure result in phosphorus accumulation in soils (Whalen and Chang 2001; Qian et al. 2004). This accumulation may partially or completely saturate soil phosphorus sorption sites, leading to an increase in phosphorus leaching into subsurface soil layers (Eghball et al. 1996) and an increase in phosphorus transported into surface waters via runoff (Schroeder et al. 2004; Vadas et al. 2005). Losses of phosphorus from agricultural land may result in accelerated eutrophication of surface waters (Campbell and Edwards 2001).

The phosphorus sorption capacity (PSC) of soils is a finite characteristic that varies widely according to clay content, clay mineralogy, organic matter content, exchangeable aluminum, iron, and calcium concentrations, and pH (Tisdale et al. 1993). Soil processes that affect adsorption of applied phosphorus to soil are influenced by current sorption status and the phosphorus sorption capacity (Hansen et al. 2002). This will also affect how much phosphorus is available for crop uptake or susceptible to loss in runoff or leachate (Hansen et al. 2002). The degree of phosphorus saturation (DPS) of soils has been identified as a potential phosphorus loss risk indicator because it has a strong relationship with runoff phosphorus concentrations (Sharpley 1995; Sims et al. 2002). Transport of phosphorus from soil to water at a given level of soil-test phosphorus (STP) or DPS is also influenced by the cation status and ionic strength of the aqueous phase (Beauchemin et al. 1996). The DPS is a function of the portion of soil exchange sites that are bound with phosphorus (sorbed phosphorus) in relation to the number of sites available for phosphorus binding (phosphorus sorption capacity, PSC). The DPS is generally defined as

$$\text{DPS (\%)} = [\text{Sorbed phosphorus (mg kg}^{-1}\text{)} / \text{PSC (mg kg}^{-1}\text{)}] \times 100 \qquad (1)$$

Phosphorus sorption capacity of soils may be determined from the sorption maxima of adsorption isotherms using different concentrations of phosphorus solutions and measurements of the quantity of phosphorus sorbed from solution to solid phase at equilibrium (Sharpley 1995). A single-point phosphorus sorption index (PSI) has also been developed to replace the time-consuming adsorption isotherms (Bache and Williams 1971; Mozaffari and Sims 1994).

As a soil becomes enriched or depleted in phosphorus, changes in the concentration in solution (I) and the supporting pool of labile phosphorus (Q) occur (Bache and Williams 1971). The manner in which Q and I change depends on the slope of the sorption isotherm, which expresses the buffering capacity of the soil with respect to phosphorus (Mattingly 1965). Kleinman et al. (2000) proposed a soil chemical approach for determination of soil phosphorus sorption thresholds (i.e., change points) related to soil phosphorus transfer to waterways. These thresholds are based on phosphorus sorption saturation levels in the soil and they delineate a critical soil phosphorus loading level above which any added phosphorus may be lost more readily via surface runoff or leaching. Extractions of surface soils with water and 0.01 *M* $CaCl_2$ have been used for estimation of phosphorus losses in overland flow or leaching (McDowell and Sharpley 2001). McDowell et al. (2001b) found that water-extractable phosphorus (WEP) had the strongest relationship with phosphorus lost via overland flow and calcium chloride extractable phosphorus ($CaCl_2$-P) had the strongest relationship with phosphorus lost via leaching. Split-line models have been used to determine thresholds where the STP or DPS and dissolved reactive phosphorus (DRP) in runoff or drainage relationships are split into two sections, one with greater phosphorus loss per unit soil phosphorus 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,b; Indiati and Sequi 2004; Nair et al. 2004).

Soil DPS values from 25 to 40% are generally associated with greater risk of phosphorus losses in leaching or overland flow (Pautler and Sims 2000). In the Netherlands, DPS is determined from the content of oxalate-extractable phosphorus, aluminum, and iron in soil (Breeuwsma et al. 1995). A DPS of 25% or more has been established as a critical value, above which the potential for phosphorus losses through runoff and leaching become unacceptable (Breeuwsma et al. 1995). Hooda et al. (2000) studied the relationship between DPS and phosphorus release to solution on a number of soils in the United Kingdom. They discovered that little phosphorus desorption occurred below a DPS of 20% (by the Dutch method) and phosphorus leachate losses increased linearly above this value. In Quebec, DPS is determined from the content of Mehlich 3-extractable phosphorus and aluminum in the soil (Giroux and Tran 1996). The surface water quality objective for phosphorus in Quebec (0.03 mg L^{-1} TP) is lower than the water quality objective in the Netherlands (0.15 mg L^{-1} TP), thus a DPS value of 9% has been proposed as a standard to represent the DPS limit in the A horizon of agricultural soils in Quebec (Sims et al. 1998). In Delaware, DPS is determined from the content of Mehlich 3-extractable phosphorus, aluminum, and iron in soil, and soils above 11% are considered to have above optimal phosphorus levels, while soils above 15% DPS may require remedial action to minimize the risk of non-point source phosphorus pollution by runoff and leaching (Sims et al. 2002).

Determination of the phosphorus sorption status of soils is dependant on the methods used to measure STP and PSC, and on the equation used to calculate DPS. Acid oxalate extraction is not considered suitable for alkaline or calcareous soils, which occur widely in the Canadian prairie region, because oxalic acid precipitates calcium during the oxalate extraction and changes the pH of the acid buffer when it reacts with carbonate (Loeppert and Inskeep 1996). Mehlich-3 extractions may also not be appropriate for calcareous soils because NH_4F reacts with $CaCO_3$ and forms CaF_2, which may precipitate soluble phosphorus (Kleinman and Sharpley 2002), and the amount of dissolved phosphorus that might potentially be lost in overland flow from heavily-manured soils may be overestimated (Sharpley et al. 2004).

The objectives of this study were to validate and adapt a single-point PSI method for Alberta soils, to examine the phosphorus sorption characteristics of 13 Alberta agricultural soils, to determine if WEP and $CaCl_2$-P are good proxies for runoff phosphorus in these soils, and to determine the site-specific environmental thresholds of soil phosphorus (change points) in these soils.

MATERIALS AND METHODS

Phosphorus Sorption Index Validation and Adaptation

Forty-seven archived soil samples from a previous study (Wright et al. 2003) were used to compare single-point PSI methods to PSC values determined using adsorption isotherms. These were surface soils (0 to 10 cm) collected throughout Alberta with STP ranging from 15 to 628 mg kg^{-1}. Wright et al. (2003) fitted a number of isotherm equations to their data, including Langmuir and Freundlich equations, but the best fit was an equation referred to as the Alberta Model (Equation 2).

$$PSC = (a \times Peq) - (b \times Peq^{0.95}) \qquad (2)$$

where:
PSC = maximum amount of phosphorus sorbed by soil (mg kg^{-1})
Peq = phosphorus concentration at equilibrium (mg L^{-1})
a, b = constants

A single-point PSI was determined by two methods: a potassium chloride PSI (KCl-PSI) method and a calcium chloride PSI ($CaCl_2$-PSI) method. The Bache and Williams (1971) method was used to determine the KCl-PSI of the soils. Two grams of each soil were shaken with 40 mL of 0.01 *M* KCl containing 75 mg L^{-1} inorganic phosphorus (KH_2PO_4) and two drops of chloroform (to inhibit microbial activity) for 18 h on an end-over-end shaker at 20^{o}C. Two grams of each soil were also shaken with 40 mL of 0.01 *M* $CaCl_2$ containing 75 mg L^{-1} inorganic phosphorus (KH_2PO_4) and two drops of chloroform for 16 h on an end-over-end shaker at 20^{o}C. The $CaCl_2$-PSI method extraction ratio (1:20 soil to solution) and time of shaking (16 h) were the same as used in the phosphorus sorption capacity determinations by Wright et al. (2003). All samples were centrifuged at 27,000 *g* for 10 min at 4^{o}C, filtered (0.45 µm), and aliquots of the filtrate were analyzed for orthophosphate-phosphorus (ortho-phosphorus) by the ammonium molybdate-ascorbic acid method (Murphy and Riley 1962). The PSI was determined using Equation 3.

$$PSI = XV/S \qquad (3)$$

where:
PSI = phosphorus sorption index (mg kg^{-1})
X = initial solution phosphorus – final solution phosphorus (mg L^{-1})
V = solution volume (L)
S = soil weight (kg)

Degree of Soil Phosphorus Saturation

The DPS of 13 Alberta soils (Appendix 1) was assessed using archived soil samples obtained from three field studies: a manure rate study where solid cattle manure had been applied annually to irrigated soils for 8 yr (1993 to 2000) at two sites near Picture Butte, approximately 25 km northeast of Lethbridge, Alberta (Olson et al. 2003); a manure rate and tillage rainfall simulation study where solid cattle manure was applied once at various rates of total phosphorus (TP) at three sites (Ontkean et al. 2006); and a microwatershed study at eight sites that were part of a 3-yr study to determine the relationship between STP and phosphorus in runoff (Little et al. 2006).

Soils at the 8-yr manure rate study sites consisted of neutral to slightly alkaline Orthic Dark Brown Chernozems, with one site predominantly coarse-textured soils and the other site mainly medium-textured soils (Table 1; Fig. 1). The study included five rates of manure (0, 20, 40, 60, and 120 Mg ha^{-1} yr^{-1}; wet weight) arranged in a randomized complete block design with five replicates. Fresh cattle manure supplied by three local feedlot operations was weighed in the field and applied to 8- by 16-m plots using a tractor-pulled, rear-delivery manure spreader. Manure was incorporated on the day of application with two perpendicular tillage passes with a double disk. Five samples of manure collected annually during field applications were analyzed for moisture content, total and extractable phosphorus, and total nitrogen, ammonium nitrogen, and nitrate nitrogen (Table 2). Nitrate nitrogen and extractable phosphorus was determined using a 5:1 solution:soil Miller-Axley extractant followed by colorimetric analysis (Miller and Axley 1956; Technicon Industrial Systems 1978), and ammonium nitrogen was determined using a 5:1 2 *M* KCl extractant-to-soil ratio and colorimetric analysis (Maynard and Kalra 1993). Total phosphorus was measured using a nitric acid-perchloric acid digest and inductively coupled plasma spectrometric analysis (Jones et al. 1991), and total nitrogen was determined by the Kjeldahl digestion method (McGill and Fiqueiredo 1993). Soils at each site were cropped to silage barley (*Hordeum vulgare* L.) from 1994 to 1998 and in 2000, and to silage triticale (*Triticosecale rimpaui* L.) in 1999 and 2001 (Olson et al. 2003). Each site was irrigated as required using a solid-set irrigation system. Soil samples were collected annually from each plot in September or October before manure was applied. A composite sample was obtained from two 75-mm diameter soil cores collected from each plot at increments of 0 to 0.15, 0.15 to 0.3, 0.3 to 0.6, 0.6 to 0.9, 0.9 to 1.2, and 1.2 to 1.5 m. Samples were placed in coolers with ice packs for transportation to the laboratory.

The manure rate and tillage study was conducted at Agriculture and Agri-Food Canada research centres at Beaverlodge and Lacombe, Alberta, and on privately-owned land near Wilson Siding, which was approximately 16 km southeast of Lethbridge, Alberta (Fig. 1). Rainfall simulation tests were completed at these three sites immediately after manure application and tillage and again about 1 yr later. The three study sites were cropped with an annual cereal crop under rainfed conditions between the rainfall simulation tests. The study included four rates of manure (0, 50, 100, and 200 kg ha^{-1} of manure TP) and two manure tillage treatments (not tilled or tilled) arranged in a randomized complete block design with four replicates. Soils were acidic, fine-textured Orthic Dark Gray Luvisols; slightly acidic, coarse-textured Orthic and Eluviated Black Chernozems; and neutral, medium-textured Orthic Dark Brown Chernozems (Table 1). Solid cattle manure, supplied by local feedlot operations, was weighed in the field in garbage cans and was applied by hand to 7- by 10-m plots (Ontkean et al. 2006). Samples of manure collected from each plot during field applications were analyzed for moisture content, TP (AOAC 2003), total nitrogen (AOAC 1995), water-extractable phosphorus (Kleinman et al. 2002), ammonium nitrogen, and nitrate nitrogen. Manure was spread as uniformly as possible on the plots using garden rakes and was either incorporated on the day of application with one pass of a double disk or was not incorporated. Moisture and nutrient content were extremely variable in the three different manure sources (Table 2). Treatments for all manure-amended plots were

Table 1. Soil classification and mean surface soil characteristics before manure application.

Parameter[z]	Manure rate study[y]		Manure rate and tillage study[x]		
	Picture Butte - Coarse	Picture Butte - Medium	Beaverlodge	Lacombe	Wilson Siding
Soil classification	Orthic Dark Brown Chernozemic	Orthic Dark Brown Chernozemic	Orthic Dark Gray Luvisolic	Orthic – Eluviated Black Chernozemic	Orthic Dark Brown Chernozemic
Soil series	Kessler-Lethbridge	Lethbridge	Berwyn-Esher	Cygnet-Lonepine	Readymade-Whitney
pH	7.2	7.7	4.0	6.3	7.1
EC (dS m^{-1})	0.89	0.76	1.24	0.88	0.80
Sand (g kg^{-1})	780	310	290	480	280
Clay (g kg^{-1})	80	260	380	230	400
$CaCO_3$ (g kg^{-1})	19.0	64.1	14.4	17.6	17.7

[z]Electrical conductivity (EC) and pH, saturated paste method (Rhoades 1982); sand and clay method (Gee and Bauder 1986); $CaCO_3$ method (Nelson 1982).
[y]Selected soil properties as determined by Olson et al. (2003).
[x]Selected soil properties as determined by Ontkean et al. (2006).

Table 2. Mean characteristics of the solid cattle manure applied.

Parameter[z]	Manure rate study[y]		Manure rate and tillage study[x]		
	Picture Butte - Coarse	Picture Butte - Medium	Beaverlodge	Lacombe	Wilson Siding
Moisture (g kg^{-1})	898	1020	1857	2226	818
Total phosphorus (kg Mg^{-1})	7.3	7.8	2.8	4.7	7.1
Extractable phosphorus (kg Mg^{-1})	2.7	2.9	1.3	2.3	no data
Total nitrogen (kg Mg^{-1})	21.2	25.5	15.9	24.0	20.0
NH_4-N (kg Mg^{-1})	2.6	2.8	1.6	1.5	2.9
NO_3-N (kg Mg^{-1})	0.02	0.02	0.02	0.8	0.0

[z]All parameters are expressed on a dry-weight basis.
[y]Selected manure characteristics as determined by Olson et al. (2003).
[x]Selected manure characteristics as determined by Ontkean et al. (2006).

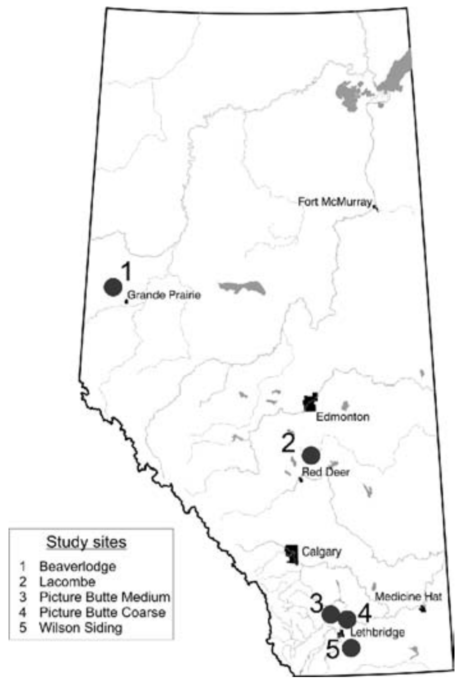

Fig. 1. Sites of the manure rate studies in Alberta.

based on the TP content of each manure source measured about 1 wk before land application. Plots at the Lacombe site received approximately 0 (control), 50, 100, and 200 kg ha^{-1} TP. Manure rates at the Beaverlodge site were reduced to about half these values due to extremely low phosphorus content of the manure source. The manure TP actually applied at the Wilson Siding site was approximately twice the target rates due to a reduction in the moisture content of the manure between the time of analysis of the manure source and land application of the manure. A composite soil sample was collected with a 19-cm-wide by 50-cm-long metal frame and a 2.5-cm-deep scoop (Nolan et al. 2006) from two sampling sites in each plot before each rainfall simulation test. Soil samples used in this study were collected before the second rainfall simulation tests (1 yr after manure application) and were screened to remove aboveground plant material.

The microwatershed soils consisted of one native grassland soil near Stavely (STV); two manured cultivated soils: one near Lower Little Bow (LLB) that was moderately manured every 2 to 3 yr and one near Ponoka (PON) that was heavily manured two times per year; and five cultivated soils that received phosphorus additions in the form of inorganic fertilizer: Crowfoot Creek (CFT), Grand Prairie Creek (GPC), Renwick Creek (REN), Three Hills Creek (THC), and Wabash Creek (WAB) (Fig. 2). All of the soils were medium textured and clay content in the midslope positions ranged from 120 g kg^{-1} at the PON site to 290 g kg^{-1} at the GPC site (Little et al. 2006, Table 3). Organic matter in the midslopes ranged from 140 g kg^{-1} at the STV site to 43 g kg^{-1} at the WAB site. The pH in the midslopes was within the optimum range of nutrient availability at the non-manured sites, but was slightly alkaline at the manured LLB site. Electrical conductivity in the midslopes at the non-manured sites was less than 0.30 dS m^{-1} at the non-manured sites and increased to 0.50 dS m^{-1} at the PON site and to 1.00 dS m^{-1} at the LLB site. Further details of the site locations and characteristics are described by Little et al. (2006). To characterize the phosphorus sorption and STP characteristics within each site, soils were sampled in the fall of 2003 using a 19-cm-wide by 50-cm-long metal frame and a 2.5-cm-deep scoop in six transects representing upper, mid, and lower landform positions (Little et al. 2006). To determine if there were changes in the PSI and STP with time, additional subsamples were taken at six points from the two manured sites in the fall of 2002 and fall of 2004. Soils were sampled after all fall farm management operations were complete (i.e., tillage, fertilization). The soil that was removed was well mixed in the field and about 500 g was randomly removed and placed in coolers with ice packs for transportation to the laboratory for analyses.

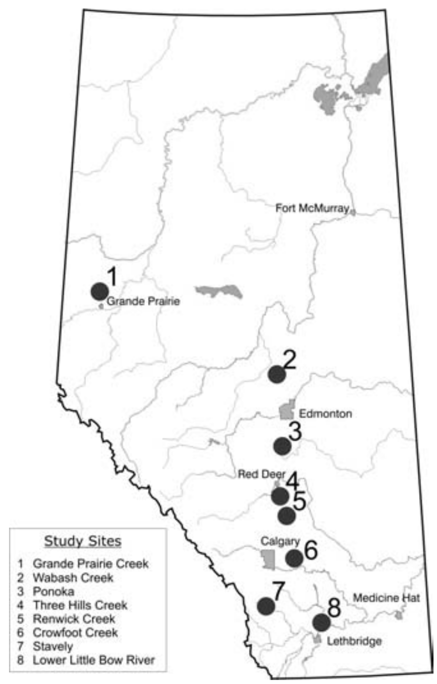

Fig. 2. Microwatershed study sites in Alberta.

Selected soil samples in 2001 from the 0- to 15-cm layer were used for DPS analysis in the 8-yr manure rate study. Soils from the 0- to 2.5-cm layer from the manure rate and tillage study and the microwatershed study were used in the DPS analysis. Samples were air dried, sieved (2-mm), and analyzed for STP (Appendix 1) using the modified Kelowna method (Qian et al. 1991). Phosphorus sorption indices were measured using the $CaCl_2$-PSI method described above. The DPS was determined from the ratio of STP to PSI plus STP using Equation 4 (adapted from Pautler and Sims 2000; Indiati and Sequi 2004).

$$DPS (\%) = [STP / (STP + PSI)] \times 100 \quad (4)$$

Table 3. Site characteristics and selected soil properties in midslope polsitions at the microwatershed study sites[z].

Site	Location	Area (ha)	n	Management[y]	Classification[x]	Added P (kg ha^{-1} yr^{-1})	Slope (%)	Texture[w]	Clay (g kg^{-1})	Organic matter (g kg^{-1})	pH	EC (dS m^{-1})
					Ungrazed grassland site							
STV	Stavely	2	3	Grassland	O.BL	na	6-20	L / CL	140	140	6.5	0.21
					Non-manured sites							
CFT[v]	Strathmore	248	18	NT	O.DB	17-22	1-4	L / SiL	210	53	6.4	0.20
GPC	Grande Prairie	62	17	CT	SZ.DG	10-21	1-4	CL / C	290	75	6.0	0.30
REN	Three Hills	26	18	RT	O.BL	28	1-8	L / SL	150	66	5.7	0.10
THC	Innisfail	51	20	NT	O.BL	15-25	0-6	L / L	230	100	6.0	0.10
WAB	Westlock	33	19	CT	O.DG	15-17	1-4	L / CL	200	43	5.9	0.20
					Manured sites							
LLB[u]	Iron Springs	88	31	CT	O.DB	Modr[t]	1-2	L / CL	260	45	7.7	1.00
PON	Ponoka	30	30	CT	E.BL	High[s]	0-5	L / CL	120	96	6.5	0.50

[z]Site characteristics and soil properties as determined by Little et al. (2006).
[y]CT = conventional tillage, RT = reduced tillage, NT = no tillage before seeding.
[x]Symbols follow Canadian System of Soil Classification: O = Orthic; SZ = Solonetzic; E = Eluviated; DB = Dark Brown; BL = Black; DG = Dark Gray.
[w]Surface/subsurface.
[v]Some grazing.
[u]Irrigated.
[t]Moderate - manured once every 3 yr.
[s]High - manured one to two times per year (manured in 2002, but not in 2003 and 2004).

Phosphorus Desorption and Runoff Phosphorus

Calcium chloride-extractable phosphorus in soils from the 13 sites was determined by shaking 4 g of each soil sample with 20 mL of 0.01 *M* $CaCl_2$ for 1 h on an end-over-end shaker at 20^oC (Appendix 1). Water-extractable phosphorus in soils from the 13 sites was determined by shaking 2 g of each soil with 20 mL of deionized water for 1 h on an end-over-end shaker at 20^oC (Appendix 1). All samples were centrifuged at 27,000 *g* for 10 min at 4^oC, filtered (0.45 µm), and aliquots of the filtrate were analyzed for ortho-phosphorus by the ammonium molybdate-ascorbic acid method (Murphy and Riley 1962). The $CaCl_2$-P and WEP values were used as proxies for phosphorus that could be lost in runoff from these 13 soils.

Rainfall simulation tests were conducted on each plot of the manure rate and tillage study after harvest of an annual cereal crop in the fall of 2003 at the Beaverlodge and Lacombe sites, and before seeding in the spring of 2004 at the Wilson Siding site (Ontkean et al. 2006). Results from rainfall simulation tests conducted again 1 yr after manure applications were used for this study. Four rainfall simulators (Wright et al. 2003) were operated simultaneously on four adjacent plots. Each simulator was fitted with a single Fulljet ½ SS HH WSQ nozzle centered 3.05 m above the soil surface over a 1.5- by 2.0-m runoff frame. The simulators were operated at a pressure of approximately 28 kPa and generated continuous flow at an intensity of 70 mm h^{-1}. Frame borders were constructed of galvanized or painted steel, with top and side plates driven into the soil to a depth of about 10 cm and the front plate was level with the soil surface. Runoff water was collected with a triangular metal tray attached to the front plate and samples were collected within a 0.3-m deep hole excavated at the lower end of the tray. The collection tray was covered with a 1.2 by 1.8-m sheet of clear plexiglass, which prevented water from spraying directly onto the tray. Source water used from treated municipal supplies near each site contained negligible concentrations of nutrients (Ontkean et al. 2006). Composite runoff water samples were collected during consecutive intervals at 5, 10, 20, and 30 min after commencement of continuous runoff. The total volume of water collected during each time interval was also recorded and a 1-L sample from each time interval was transported to the laboratory in a cooler with ice packs. A 200-mL subsample was obtained within 24 h with a 0.45-µm membrane filter unit or a 0.45-µm high-capacity filter, and the filtered sample was analyzed for DRP by the ammonium molybdate-ascorbic acid method (Murphy and Riley 1962). The DRP mass load was calculated by multiplying the DRP concentration by the runoff volume for each interval and by summing the mass loads for the four intervals. The runoff DRP flow-weighted mean concentrations (runoff DRP) were computed by dividing the total DRP mass load for the 30-min interval by the total volume of flow for the same period.

Each microwatershed site was equipped with a flume, an ISCO 6700 water sampling device, a float potentiometer, a ROM Communications Microcom datalogger (except at the STV site where a technician was permanently on-site), and a staff gauge to collect edge-of-field natural snowmelt, rainfall, or irrigation runoff (Little et al. 2006). The microwatershed runoff samples were taken by ISCO samplers, equipped with 24, 1-L ProPaks™ and disposable polyethylene inserts. The ISCO samplers were programmed to take a 150-mL sample every 15 min for a total volume of 900 mL or six samples per bottle. Changes in head were used to trigger the ISCO via the ROM Communications Microcom unit whenever flow volumes reached the minimum criteria set for each microwatershed. Samples were collected daily during runoff events and then immediately transported in coolers to the nearest Envirotest Laboratory in Calgary, Edmonton, or Grande Prairie. Water samples were subsampled and filtered upon arrival and analyzed within 48 h for DRP (method; Murphy and Riley 1962). Blanks filled with deionized water, as well as prepared standards of known phosphorus concentration, were submitted to the lab with each batch of samples as part of a quality assurance/quality control program. To calculate the flow weighted mean concentrations, water chemistry data were linearly interpolated to 1-min intervals using Proc Expand in SAS (SAS Institute Inc. 2000). The expanded 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 runoff DRP values were then calculated by dividing the total load for all events by the total flow volume.

No field runoff data were collected from the 8-yr manure rate study.

Statistical Analysis

Linear regression analysis was used to evaluate relationships between PSC values determined using the Alberta PSC model developed with adsorption isotherms (Wright et al. 2003) and the single-point KCl-PSI and $CaCl_2$-PSI values measured in this study. Quantity/Intensity relationships were examined between STP or DPS and $CaCl_2$-P or WEP for the 8-yr manure rate study, between STP or DPS and $CaCl_2$-P, WEP, or runoff DRP from the 30-min runoff event for the manure rate and tillage study, and between STP or DPS and $CaCl_2$-P, WEP, runoff DRP from the runoff events that occurred during the microwatershed study. Linear regression analysis was used to evaluate the relationships between $CaCl_2$-P or WEP and runoff DRP. A PROC NLIN split-line model was used to determine the soil phosphorus thresholds (change points) and desorbed phosphorus (WEP, $CaCl_2$-P, or runoff DRP) plateau values. The NLIN procedure required estimation of linear ($d + ex$) and quadratic ($a + bx + cx^2$) parameters, and then solved for the threshold between the linear and quadratic regressions by iterative re-evaluation of the equation. All statistical analyses were performed using SAS 8.1 (SAS Institute 2000). The STP values that corresponded to change points were subsequently determined from the STP-desorbed phosphorus relationships.

RESULTS

Phosphorus Sorption Index Validation

A significant relationship was found between the Alberta Model PSC data (Wright et al. 2003) and the $CaCl_2$-PSI and KCl-PSI measurements for the same soils (Fig. 3). Negative PSI values were detected for some soils with the KCl-PSI method (i.e., the KCl extractant may have removed phosphorus from sorption sites), whereas negative values were not observed for any of the soils with the $CaCl_2$-PSI method. A stronger relationship was also found between the Alberta Model PSC and the $CaCl_2$-PSI method compared to the KCl-PSI method. Therefore, the $CaCl_2$-PSI method was selected for determination of the single-point PSI and the DPS of the soils subsequently examined in the two manure rate studies and in the microwatershed study.

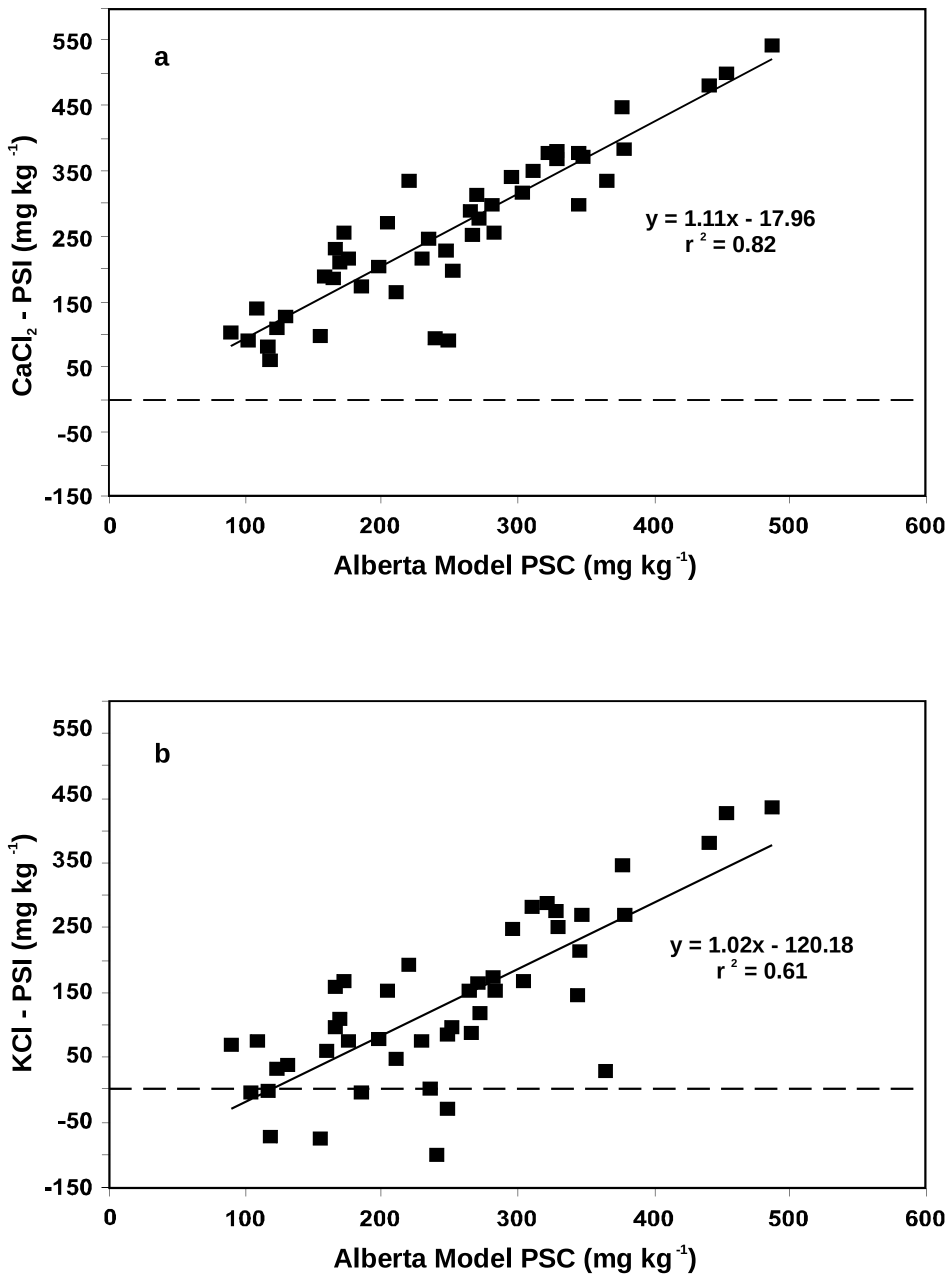

Fig. 3. Relationship between the Alberta Model phosphorus sorption capacity (PSC) and (a) the $CaCl_2$-phosphorus sorption index ($CaCl_2$-PSI) and (b) the KCl-phosphorus sorption index (KCl-PSI).

Eight-year Manure Rate Study

In the coarse- and medium-textured soils at the Picture Butte sites, the PSI decreased and STP increased with increasing rates of manure application (Table 4). Mean PSI values for the highest manure rate were decreased by 95.1 mg kg^{-1} (80%) in the coarse-textured soil and by 254 mg kg^{-1} (56%) in the medium-textured soil compared to the control. The DPS in these soils also increased dramatically as the rate of manure application increased, with DPS values for the highest manure rates greater than 90% in the coarse-textured soil and greater than 70% in the medium-textured soil.

Table 4. Treatment means and standard errors (SE) of soil-test phosphorus (STP), phosphorus sorption index (PSI), and degree of soil phosphorus saturation (DPS) of soils from the 8-yr manure rate study.

	STP[y]		PSI		DPS	
Treatment[z]	Mean	SE	Mean	SE	Mean	SE
	--- (mg kg^{-1}) ---		--- (mg kg^{-1}) ---		----- (%) -----	
Picture Butte - Coarse						
M0	29.3	9.5	118.5	9.9	19.1	6.2
M20	135.3	22.2	71.3	15.2	64.5	8.4
M40	173.6	22.7	64.6	8.0	71.9	4.3
M60	251.0	21.7	60.9	9.8	80.0	3.6
M120	474.8	52.5	23.4	11.1	94.4	2.8
Picture Butte - Medium						
M0	17.9	2.6	450.9	8.7	3.8	0.6
M20	93.4	7.5	367.9	12.4	20.3	1.7
M40	155.4	24.5	324.2	23.7	32.3	4.7
M60	258.9	17.9	270.9	20.8	48.9	3.4
M120	561.9	18.9	196.9	7.6	74.0	1.1

[z]M0 = control, M20 = 20 Mg ha^{-1}, M40 = 40 Mg ha^{-1}, M60 = 60 Mg ha^{-1}, M120 = 120 Mg ha^{-1} of wet cattle manure applied annually for 8 yr.
[y]Soil-test phosphorus means as determined by Olson et al. (2003).

Change points were not detected using the STP-WEP and STP-$CaCl_2$-P relationships because they were linear (Fig. 4a and 4c). However, when DPS was expressed as a function of STP and PSI, the resulting curvilinear relationships with WEP and $CaCl_2$-P (Fig. 4b and 4d) enabled determination of change points where slopes increased with increasing DPS. The DPS and WEP were positively related and change points were identified at a DPS of 44% for the coarse-textured soil (Fig. 4b) and at a DPS of 3% for the medium-textured soil (Fig. 4d). Change points for WEP corresponded to an STP of 46 mg kg^{-1} in the coarse-textured soil and an STP of 48 mg kg^{-1} in the medium-textured soil (Table 5). The DPS and $CaCl_2$-P were also positively related and change points were identified at a DPS of 48% for the coarse-textured soil (Fig. 4b) and a DPS of 11% for the medium-textured soil (Fig. 4d). These change points corresponded to STP values of 44 mg kg^{-1} in the coarse-textured soil and 80 mg kg^{-1} in the medium-textured soil.

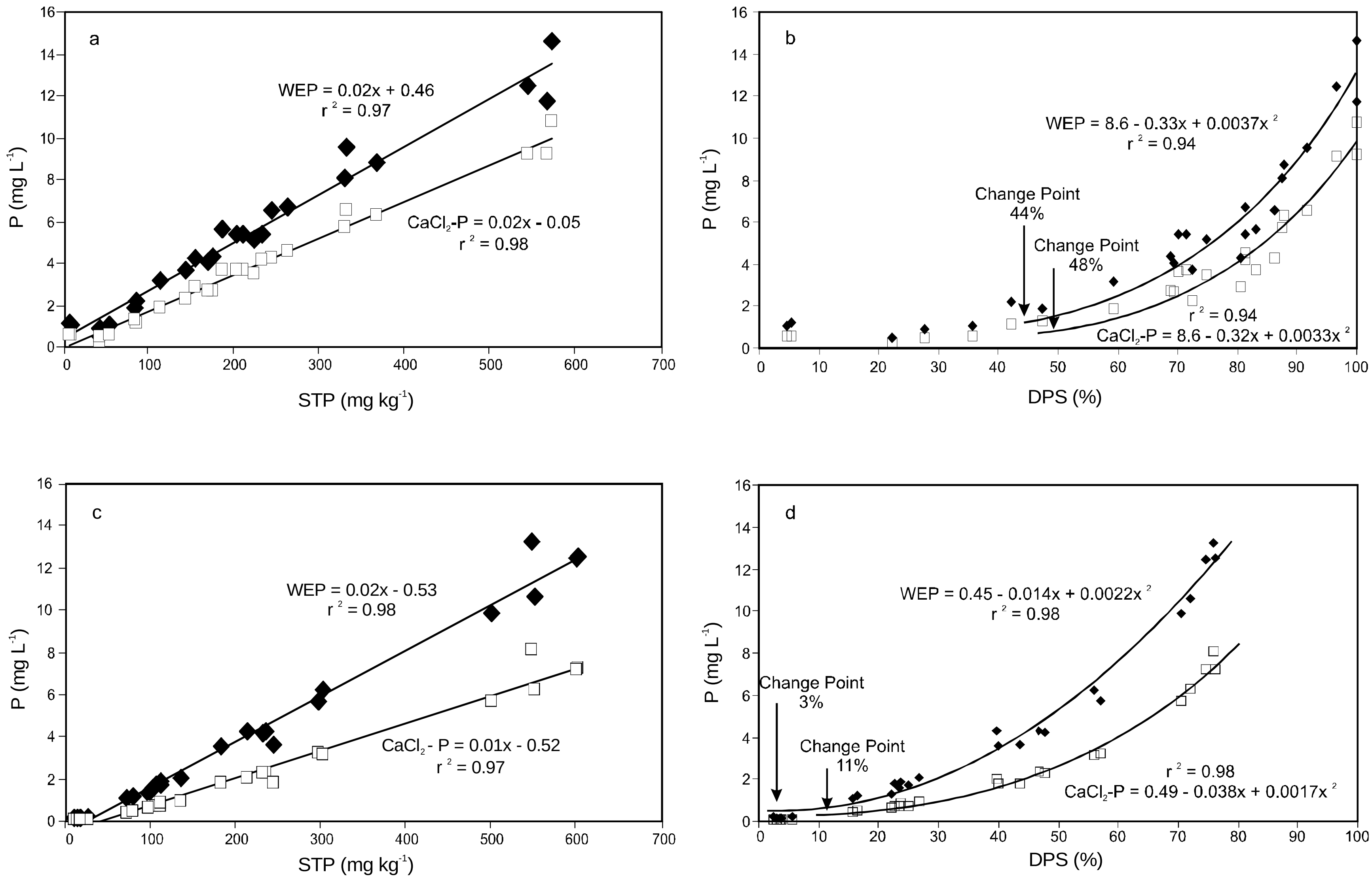

Fig. 4. Relationships between (a) soil-test phosphorus (STP) and water-extractable phosphorus (WEP) or calcium chloride-extractable phosphorus ($CaCl_2$-P) and (b) the degree of phosphorus saturation (DPS) and WEP or $CaCl_2$-P in the Picture Butte coarse-textured soil and between (c) STP and WEP or $CaCl_2$-P and (d) DPS and WEP or $CaCl_2$-P in the Picture Butte medium-textured soil.

Table 5. Degree of phosphorus saturation (DPS) change points, water-extractable phosphorus (WEP) or calcium chloride-extractable phosphorus ($CaCl_2$-P) plateaus, and soil-test phosphorus (STP) values for soils from the three studies.

Experiment	Soil	DPS change point (%)	WEP plateau (mg L^{-1})	STP (mg kg^{-1})
8-yr manure rate	Coarse	44	1.37	57
	Medium	3	0.43	44
Manure rate and tillage	Beaverlodge	n/a	n/a	n/a
	Lacombe	44	2.52	96
	Wilson Siding	40	1.57	68
Microwatershed	8 soils	47	1.02	56
All	13 soils	35	1.03	52
Experiment	**Soil**	**DPS change point (%)**	**$CaCl_2$-P plateau (mg L^{-1})**	**STP (mg kg^{-1})**
8-yr manure rate	Coarse	48	0.83	46
	Medium	11	0.28	61
Manure rate and tillage	Beaverlodge	n/a	n/a	n/a
	Lacombe	49	1.74	103
	Wilson Siding	51	0.68	57
Microwatershed	8 soils	59	0.47	64
All	13 soils	54	0.61	65

Manure Rate and Tillage Study

Soil-test phosphorus and DPS generally increased with increasing manure application rates and the PSI decreased with higher manure rates in soils at the Beaverlodge, Lacombe, and Wilson Siding sites (Table 6). Mean PSI values for the highest manure rate were decreased by 15 mg kg^{-1} (8%) at Beaverlodge, by 60.4 mg kg^{-1} (52%) at Lacombe, and by 49.3 mg kg^{-1} (33%) at Wilson Siding compared to the control. Mean DPS values for the highest manure rates were about 25% in soils at Beaverlodge, whereas mean DPS values for the highest manure rates were greater than 80% in soils at Lacombe and Wilson Siding (Table 6).

The relationships between WEP and simulated rainfall runoff DRP and between $CaCl_2$-P and runoff DRP were linear for all three manure rate and tillage study sites combined, although WEP seemed to be a better predictor of runoff DRP (Fig. 5a and 5b). There were strong relationships between individual site WEP and runoff DRP and between $CaCl_2$-P and runoff DRP in the Lacombe soils; however, the relationships between desorbed phosphorus values and runoff DRP values were weak in the Wilson Siding and Beaverlodge soils (Table 7).

Relationships between STP and WEP and between STP and $CaCl_2$-P were linear for all three sites in this study (Figs. 6a, 7a, and 8a). Change-point analysis of soils at the Beaverlodge site was not possible due to the narrow DPS and desorbed phosphorus ranges in these soils (Fig. 6b). Strong curvilinear relationships were found between DPS and WEP, and between DPS and $CaCl_2$-P, in soils at the Lacombe and Wilson Siding sites (Figs. 7b and 8b). Change points for DPS and WEP were detected at DPS values of 44% at Lacombe and 40% at Wilson Siding. These change points correspond to STP values of 96 mg kg^{-1} at Lacombe and 68 mg kg^{-1} at

Wilson Siding (Table 5). Change-point analysis of DPS and $CaCl_2$-P yielded change points of 49% at Lacombe and 51% at Wilson Siding, which correspond to STP values of 103 mg kg^{-1} at Lacombe and 57 mg kg^{-1} at Wilson Siding.

Table 6. Treatment means and standard errors (SE) of soil-test phosphorus (STP), phosphorus sorption index (PSI), and degree of soil phosphorus saturation (DPS) of soils from the manure rate and tillage study.

	STP[y]		PSI		DPS	
Treatment[z]	Mean	SE	Mean	SE	Mean	SE
	--- (mg kg^{-1}) ---		--- (mg kg^{-1}) ---		----- (%) -----	
			Beaverlodge			
M0	44.4	3.2	296.0	12.4	13.2	1.1
M25	55.0	3.5	306.4	6.5	15.2	1.0
M50	72.6	5.7	286.9	5.3	20.2	1.4
M100	95.2	5.2	281.0	6.4	25.3	1.1
			Lacombe			
M0	107.1	6.0	115.2	7.3	48.2	2.3
M50	149.9	16.9	80.9	9.8	64.0	4.7
M100	177.9	16.3	63.5	8.0	72.8	4.1
M200	276.4	32.8	54.8	9.5	81.9	3.9
			Wilson Siding			
M0	49.6	3.4	149.1	5.9	24.9	1.0
M50	221.1	41.2	117.8	8.6	62.2	5.0
M100	369.2	50.0	100.2	9.8	76.7	3.7
M200	624.9	73.1	99.8	10.1	84.8	2.6

[z]M0 = control; M25, M50, M100, M200 = target rates of manure total phosphorus, kg ha^{-1}.
[y]Soil-test phosphorus means as determined by Ontkean et al. (2006).

Weak, but positive, linear relationships were detected between STP and runoff DRP for soils at the Beaverlodge and Wilson Siding sites (Figs. 6c and 8c), but a strong positive relationship was measured at the Lacombe site (Fig. 7c). The slope of the regression equation between STP and runoff DRP was two times greater than the slope for STP and $CaCl_2$-P, but slightly less than the slope for the relationship between STP and WEP for soils at Beaverlodge (Fig. 6a and 6c). Slopes for the relationships between STP and runoff DRP were less than half the slopes for STP and WEP or $CaCl_2$-P for soils at Lacombe (Fig. 7a and 7c) and Wilson Siding (Fig. 8a and 8c). Stronger, curvilinear relationships were found between the DPS and runoff DRP for soils at Lacombe and Wilson Siding (Figs. 7d and 8d); however, change points between DPS and runoff DRP were not found in these soils. The relationship between DPS and runoff DRP was not significant for soils at Beaverlodge (Fig. 6d).

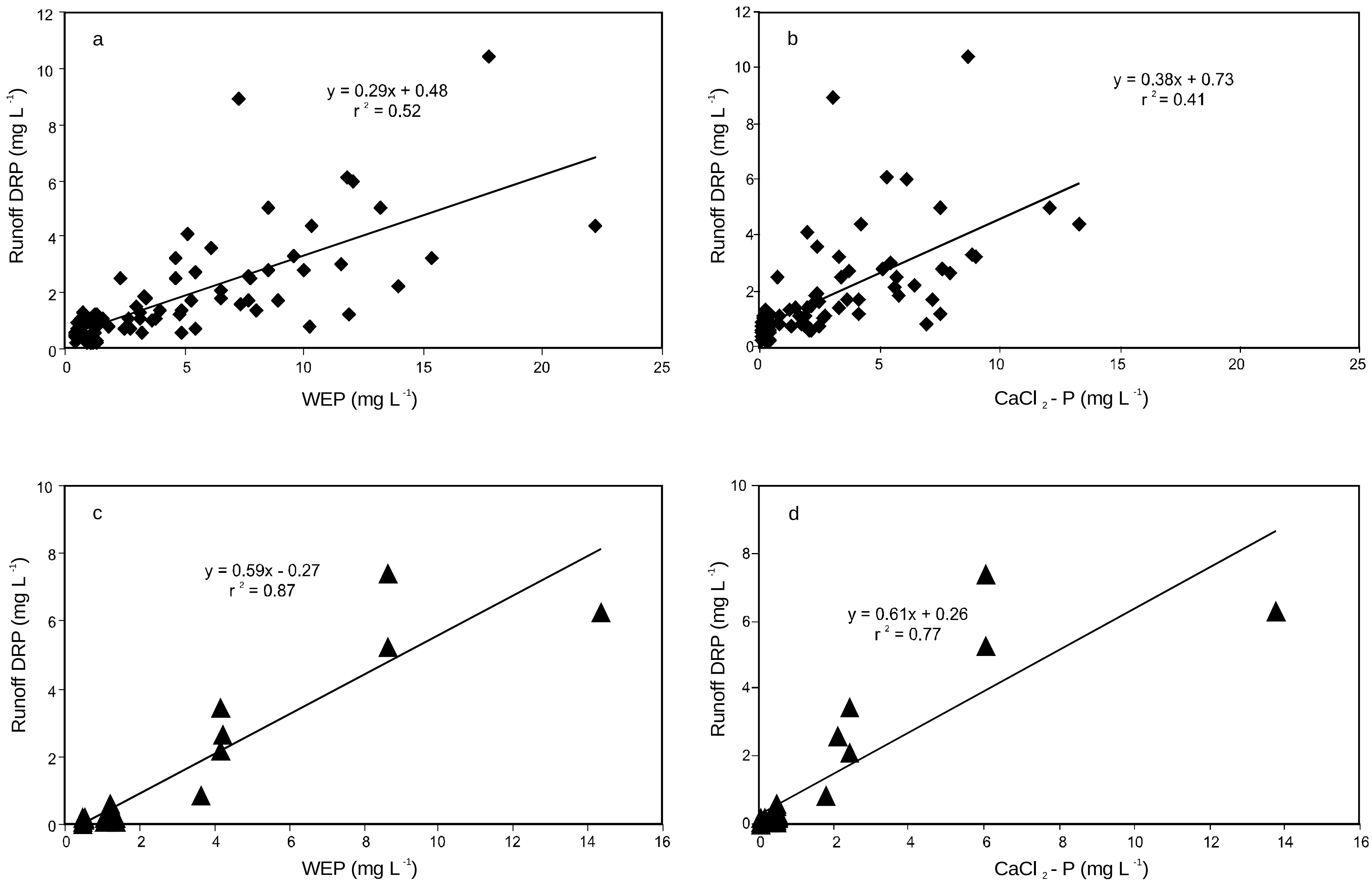

Fig. 5. Relationships between (a) water-extractable phosphorus (WEP) and runoff flow-weighted mean concentrations of dissolved reactive phosphorus (runoff DRP) and (b) calcium chloride-extractable phosphorus ($CaCl_2$-P) and runoff DRP in the manure rate and tillage study soils and between (c) WEP and runoff DRP and (d) $CaCl_2$-P and runoff DRP in the microwatershed study soils.

Table 7. Relationships between water-extractable phosphorus (WEP) or calcium chloride-extractable phosphorus ($CaCl_2$-P) and runoff dissolved reactive phosphorus (runoff DRP) in the manure rate and tillage study.

Site	Regression equations[z]	r^2
Beaverlodge	Runoff DRP = 0.60 (WEP) + 0.33	0.32
Beaverlodge	Runoff DRP = 1.2 ($CaCl_2$-P) + 0.51	0.19
Lacombe	Runoff DRP = 0.36 (WEP) + 0.11	0.70
Lacombe	Runoff DRP = 0.34 ($CaCl_2$-P) + 0.53	0.66
Wilson Siding	Runoff DRP = 0.28 (WEP) + 0.44	0.38
Wilson Siding	Runoff DRP = 0.41 ($CaCl_2$-P) + 1.0	0.27

[z]Where Runoff DRP, WEP, and $CaCl_2$-P are in mg L^{-1}.

Microwatershed Study

Soil-test phosphorus ranged from 10 to 50 times at the PON site and 5 to 26 times higher at the LLB site, compared with the non-manured and ungrazed grassland sites (Table 8). Mean PSI values for the manured PON and LLB sites were lower than the non-manured sites and PSI was highest at the GPC site (Table 8). Mean DPS values were highest at the manured sites compared to the non-manured sites.

Ninety percent of the natural runoff generated from the microwatershed sites during the 3-yr study was generated by snowmelt, and the remainder was generated from a combination of irrigation and rainfall (Little et al. 2006). The spring runoff event from the PON site in 2003 was excluded in the comparisons between desorbed phosphorus and runoff DRP because the STP was overwhelmed by a heavy application of poorly incorporated manure that was applied prior to freezing in the fall of 2002 (Little et al. 2006). Data from the spring runoff event in 2004 at the LLB site were excluded because runoff was generated exclusively from a snowbank at the edge of the field (Little et al. 2006). The runoff events from REN in 2003 and 2004 were also excluded because a private company constructed a natural gas well access road through the microwatershed site, and this affected the runoff for the last 2 yr of the study (Little et al. 2006). Strong linear relationships were determined between WEP and runoff DRP and between $CaCl_2$-P and runoff DRP for all eight microwatershed study sites combined, although WEP seemed to be a better predictor of runoff DRP (Fig. 5c and 5d). Relationships between STP and WEP and between STP and $CaCl_2$-P were linear for all eight sites (Fig. 9a and 9c). Strong curvilinear relationships were found between DPS and WEP, and between DPS and $CaCl_2$-P, in the microwatershed soils (Fig. 9b and 9d). Change points for the relationships between DPS and WEP were detected at a DPS value of 47% and between DPS and $CaCl_2$-P at a DPS value of 59%. These change points correspond to an STP value of 56 mg kg^{-1} for the DPS-WEP relationship and to an STP value of 64 mg kg^{-1} for the DPS-$CaCl_2$-P relationship (Table 5). A change point between DPS and runoff DRP was not determined because of a lack of DPS values between 24 and 61%.

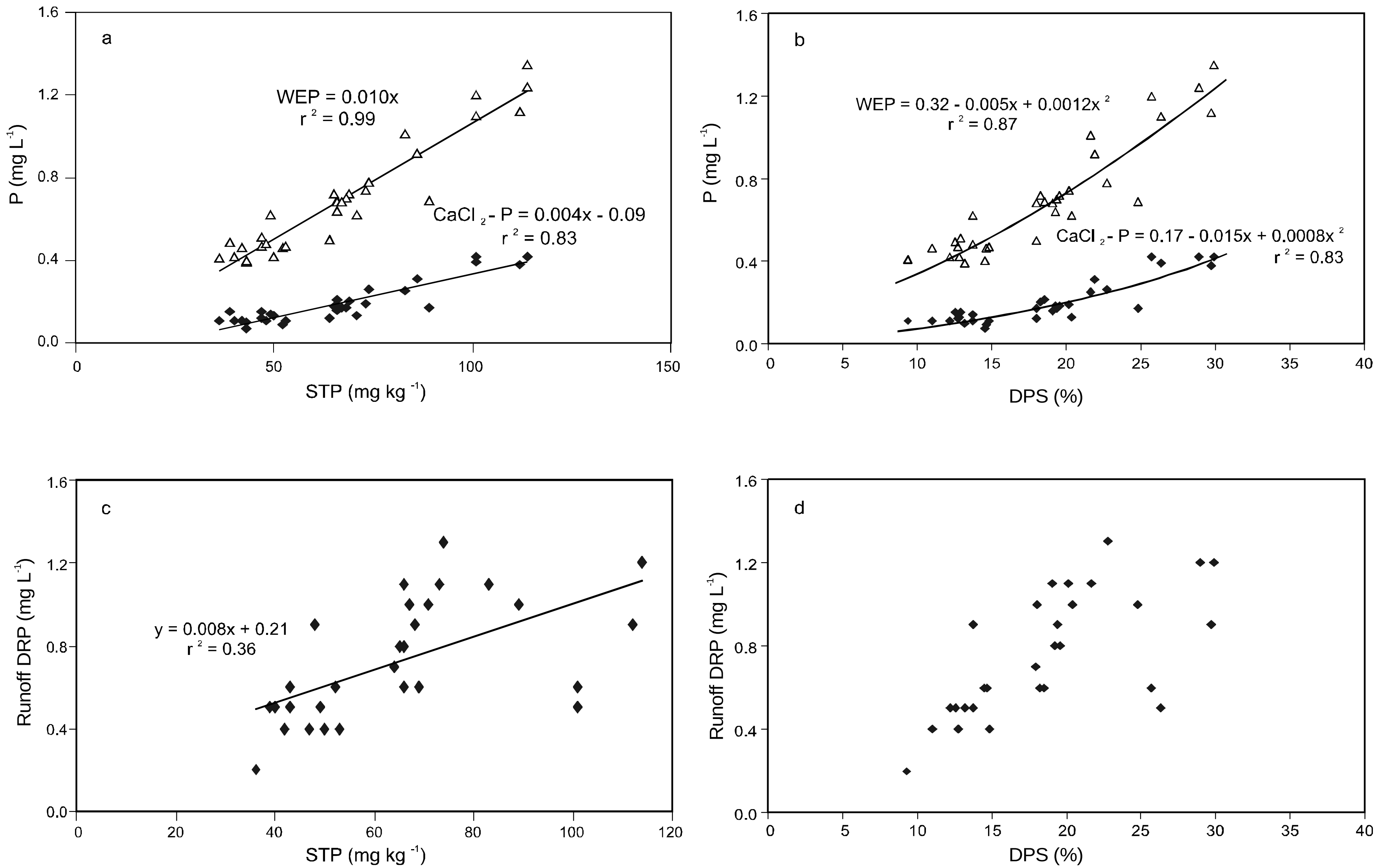

Fig. 6. Relationships between (a) soil-test phosphorus (STP) and water-extractable phosphorus (WEP) or calcium chloride-extractable phosphorus ($CaCl_2$-P), (b) the degree of phosphorus saturation (DPS) and WEP or $CaCl_2$-P, (c) STP and runoff dissolved reactive phosphorus (DRP), and (d) DPS and runoff DRP in soils at the Beaverlodge site.

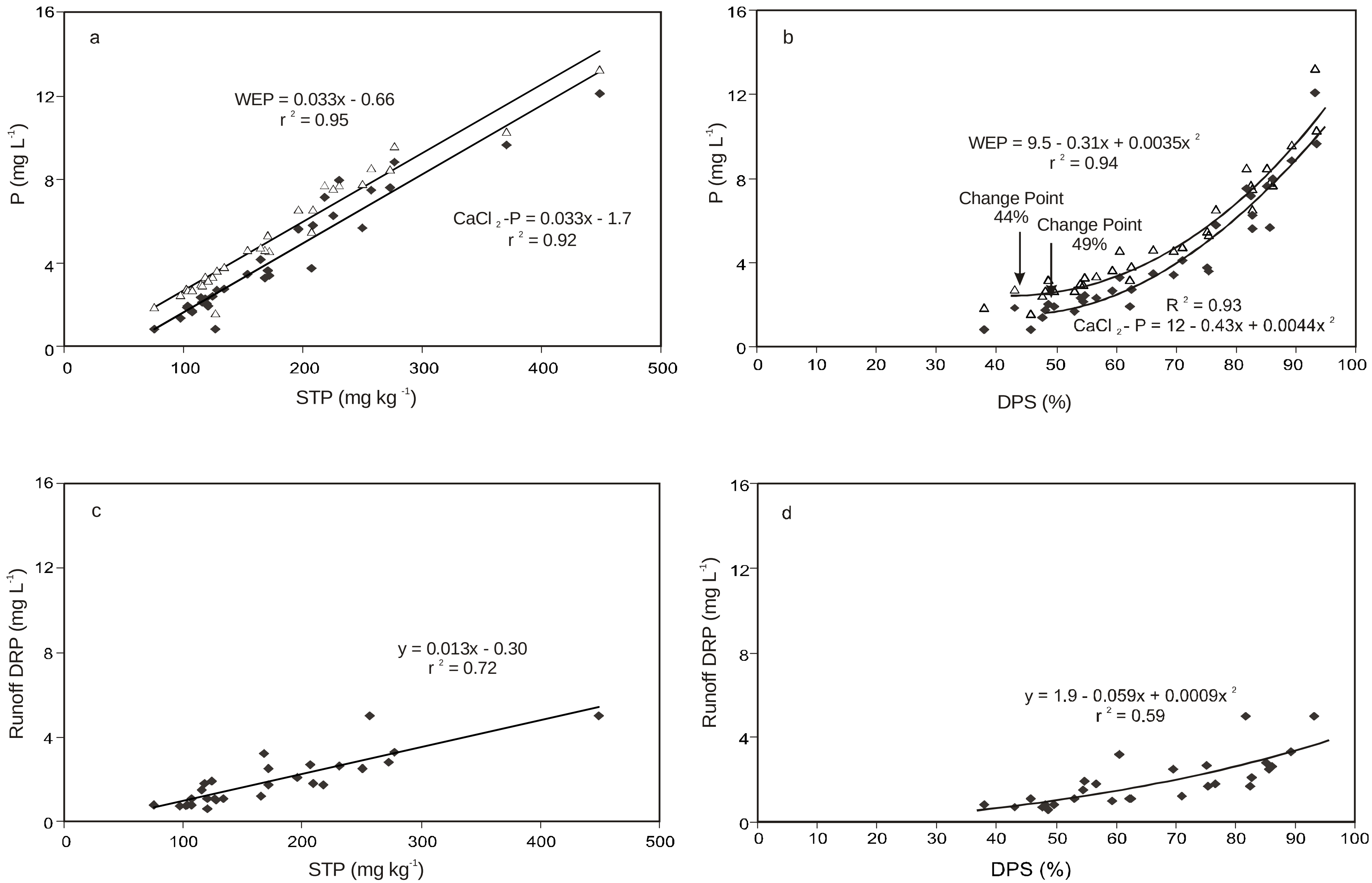

Fig. 7. Relationships between (a) soil-test phosphorus (STP) and water-extractable phosphorus (WEP) or calcium chloride-extractable phosphorus ($CaCl_2$-P), (b) the degree of phosphorus saturation (DPS) and WEP or $CaCl_2$-P, (c) STP and runoff dissolved reactive phosphorus (DRP), and (d) DPS and runoff DRP in soils at the Lacombe site.

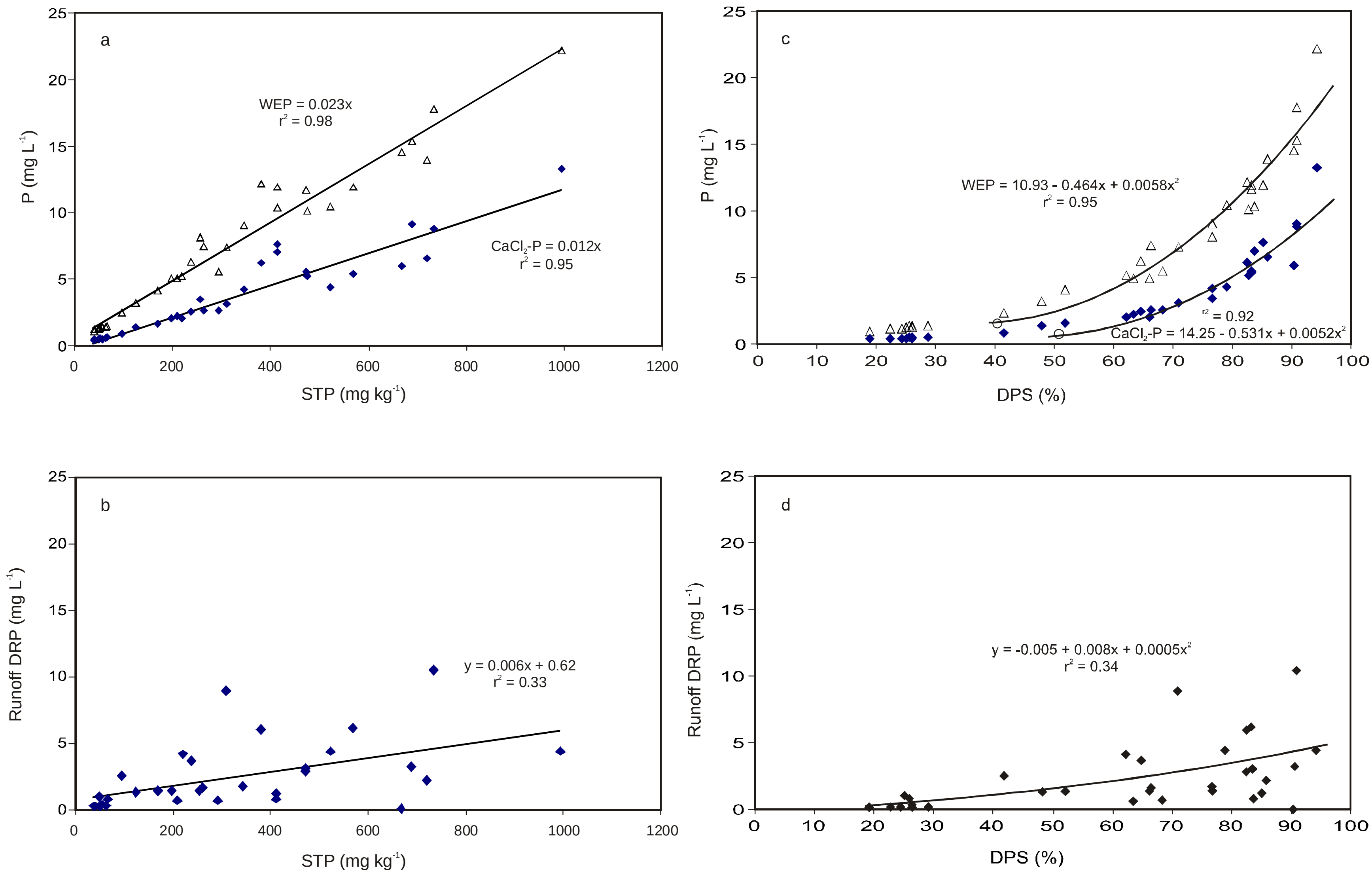

Fig. 8. Relationships between (a) soil-test phosphorus (STP) and water-extractable phosphorus (WEP) or calcium chloride-extractable phosphorus ($CaCl_2$-P), (b) the degree of phosphorus saturation (DPS) and WEP or $CaCl_2$-P, (c) STP and runoff dissolved reactive phosphorus (DRP), and (d) DPS and runoff DRP in soils at the Wilson Siding site.

Table 8. Treatment means and standard errors (SE) of soil-test phosphorus (STP), phosphorus sorption index (PSI), and degree of soil phosphorus saturation (DPS) of soils from the microwatershed study.

		STP[z]		PSI		DPS	
Site	Year	Mean	SE	Mean	SE	Mean	SE
		--- (mg kg^{-1}) ---		--- (mg kg^{-1}) ---		----- (%) -----	
			Ungrazed grassland site				
STV	2003	9.0	1.0	192.7	6.9	4.5	0.4
			Non-manured sites				
CFT	2003	52.5	12.0	146.4	6.2	23.6	2.9
GPC	2003	47.8	2.7	441.5	19.3	9.9	0.6
REN	2003	47.8	2.4	194.2	10.2	20.4	1.5
THC	2003	45.7	4.3	151.0	6.5	22.9	1.6
WAB	2003	38.1	2.9	170.7	4.2	18.0	1.1
			Manured sites				
LLB	2002	265.3	33.0	122.9	21.5	68.3	4.2
	2003	237.0	38.3	31.8	7.2	59.4	3.7
	2004	203.3	25.2	127.4	12.3	60.5	4.1
PON	2002	537.4	86.0	88.4	15.2	84.9	2.6
	2003	532.0	49.2	45.5	9.5	91.1	1.8
	2004	377.3	47.5	99.6	11.9	78.4	2.5

[z]Soil-test phosphorus as determined by Little et al. (2006).

Overall Change-point Analysis

Strong linear relationships were found between STP and WEP and between STP and $CaCl_2$-P (Fig. 10a and 10c), and strong curvilinear relationships were found between DPS and WEP and between DPS and $CaCl_2$-P, when data from all 13 sites were combined (Fig. 10b and 10d). The change point for DPS and WEP was observed at 35%, which is equivalent to an STP level of 52 mg kg^{-1} (Table 5). A change point was also detected at 54% for DPS and $CaCl_2$-P, which equates to an STP level of 65 mg kg^{-1} (Table 5).

DISCUSSION

Soil Phosphorus Saturation

The increase in STP and DPS and the decrease in the PSI with increasing rates of manure application in the Alberta soils investigated are consistent with similar studies on alkaline, calcareous soils in Alberta (Whalen and Chang 2002), on neutral soils in the United Kingdom (Siddique and Robinson 2003), and on acidic soils in the United States (Reddy et al. 1980;

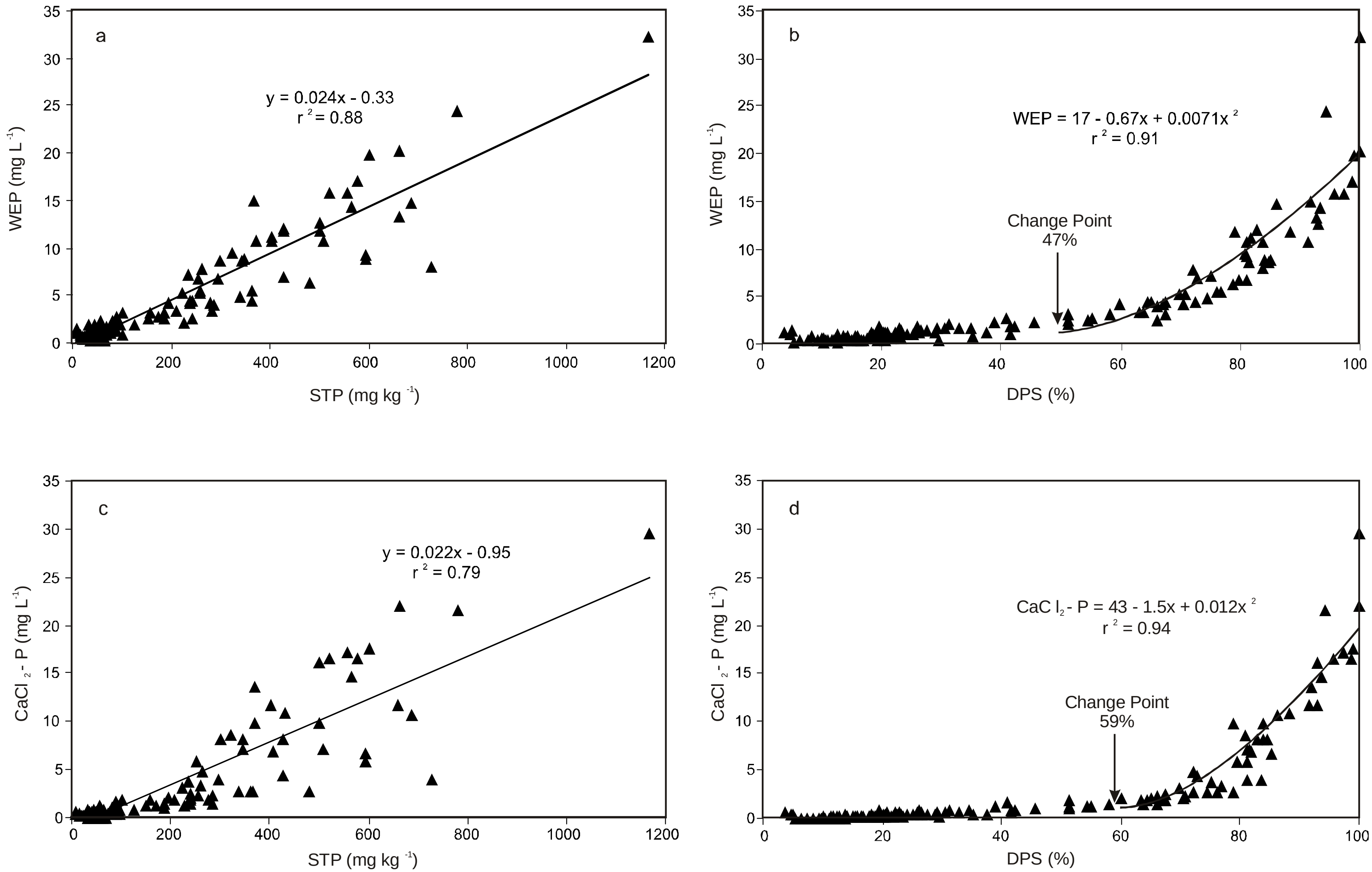

Fig. 9. Relationships between (a) soil-test phosphorus (STP) and water-extractable phosphorus (WEP), (b) the degree of phosphorus saturation (DPS) and WEP, (c) STP and calcium chloride-extractable phosphorus ($CaCl_2$-P), and (d) DPS and $CaCl_2$-P in eight Alberta microwatershed soils.

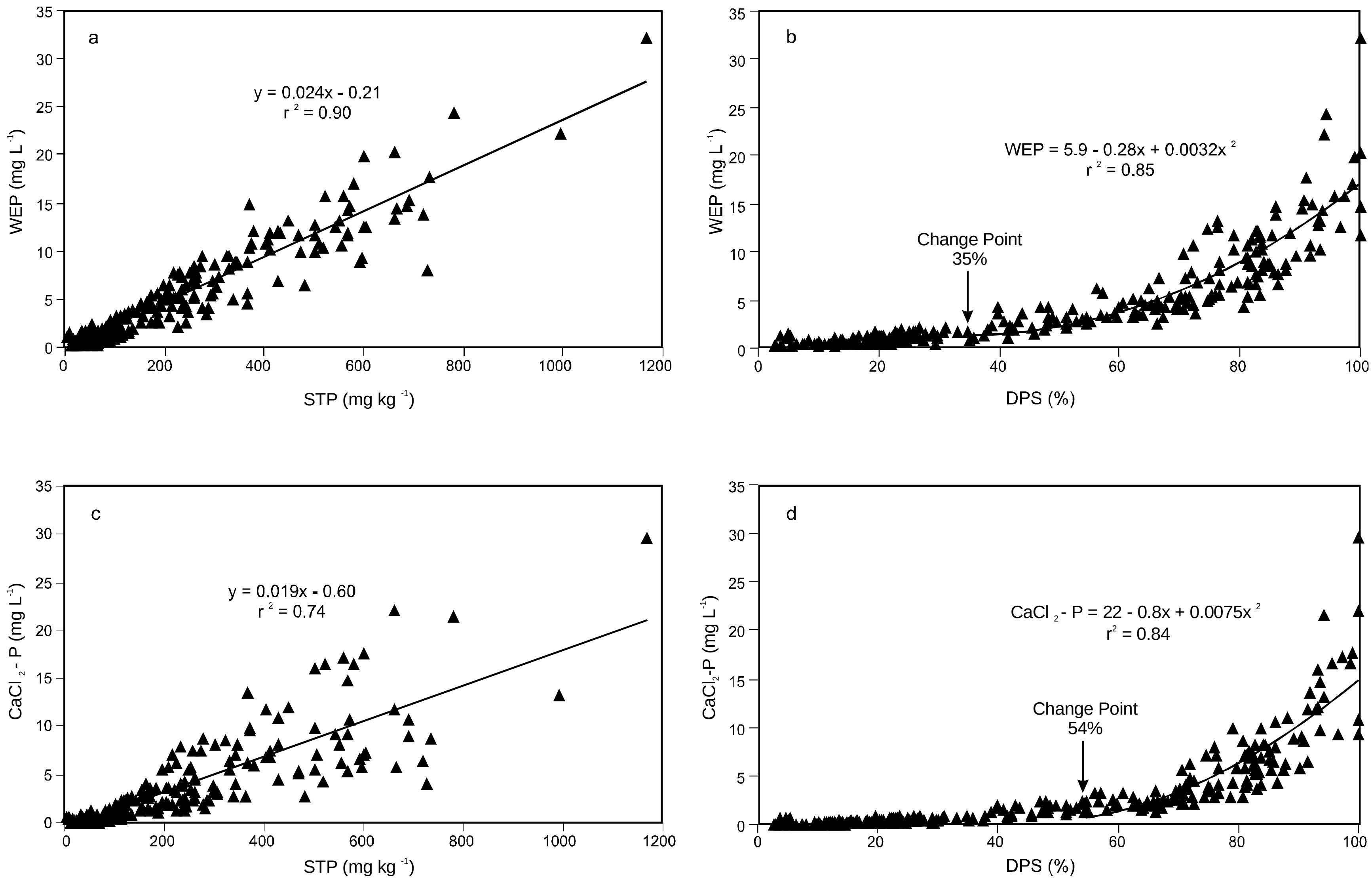

Fig. 10. Relationships between (a) soil-test phosphorus (STP) and water-extractable phosphorus (WEP), (b) the degree of phosphorus saturation (DPS) and WEP, (c) STP and calcium chloride-extractable phosphorus ($CaCl_2$-P), and (d) DPS and $CaCl_2$-P in 13 Alberta soils.

Sharpley et al. 1984; Mozaffari and Sims 1994; Iyamuremye et al. 1996). These changes have been attributed to organic acids produced during the mineralization of added organic matter. These organic acids can compete for phosphorus sorption sites, modify surface charge characteristics, or form complexes with iron, aluminum, or calcium (Reddy et al. 1980; Iyamuremye and Dick 1996; Whalen and Chang 2002). This results in a reduction in the phosphorus binding energy in manure-amended soils, and this increases the susceptibility of these soils to phosphorus losses (Holford et al. 1997; Whalen and Chang 2002). Annual applications of high rates of cattle manure for 20 yr have increased soil labile phosphorus to as much as 61% of total phosphorus in a Lethbridge clay loam (Dark Brown Chernozem) soil (Dormaar and Chang 1995). Sharpley et al. (2004) found that phosphorus was increasingly precipitated in more soluble calcium-phosphorus forms (tricalcium-phosphorus and octocalcium-phosphorus) in manured soils compared with less soluble calcium-phosphorus forms (hydroxapatite) in untreated soils. Runoff DRP concentrations at all levels of STP have been found to be lower in calcareous than in non-calcareous soils (Torbert et al. 2002). They postulated that the presence of free $CaCO_3$ resulted in precipitation of the insoluble minerals hydroxyapatite and fluorapatite, which reduced the soluble phosphorus concentration in calcareous soils. Organic carbon has been shown to inhibit calcium-phosphorus precipitation and amorphous and organically-complexed iron and manganese have been shown to contribute to phosphorus retention in calcareous soils (Leytem and Westermann 2003).

The classical concept of soil saturation is of a fixed capacity (i.e., the bucket) that can range from 0% (completely empty) to 100% (completely full). Since the value of the denominator changes in Equation 4 as phosphorus is added to a given soil, DPS, as defined by Equation 4, is more an index rather than a representation of the percent saturation of a soil's total sorption capacity (occupied plus unoccupied sites). The ability to quantify the portion of sites that are occupied and the portion of sites that are unoccupied is method dependent, thus comparison of our DPS results with other studies must be made with caution since the method of STP analysis and the equation for calculating DPS are different from methods used in most other studies. The modified Kelowna extraction method (Qian et al. 1991) results in slightly lower STP values than the Mehlich-3 method (Wright et al. 2003). Calculation of the DPS by the Pautler and Sims (2000) method ensures that DPS values do not exceed 100% since the current STP status of soils is included in the numerator and denominator of Equation 4. Calculation of the DPS by this method results in an apparent increase in the PSC of our soils (STP + PSI, the denominator in Equation 4) with manure rate (Tables 4, 6, and 7); however, this apparent increase in PSC is related to increased levels of STP with manure rate and not to a dramatic increase in sorption sites. Soluble phosphorus in the soil solution and desorbable phosphorus from the labile fraction of soil phosphorus generally increase with manure rate, even though adsorption sites on the mineral and organic surfaces are satisfied to a greater degree, as indicated by the decreased PSI for the higher manure rates. Relationships between single-point PSI estimates and PSC maxima determined using adsorption isotherms have been improved by taking previously sorbed phosphorus into account (Burkitt et al. 2002; Bolland and Allen 2003). The PSC estimates for the control treatments of each soil in our study were similar to PSC values determined for alkaline soils in Alberta (Whalen and Chang 2002) and in Manitoba (Ige et al. 2005).

Phosphorus Desorption and Runoff Phosphorus

Numerous researchers have found that WEP and $CaCl_2$-P correlate well with phosphorus lost via surface runoff (McDowell and Sharpley 2001; McDowell et al. 2001b). In our study, weak significant relationships were determined between desorbed phosphorus and simulated rainfall runoff DRP values in the three manure rate and tillage soils combined (Fig. 5a and 5b), although good relationships between desorbed phosphorus and runoff DRP values were observed in the Lacombe soils (Table 7). For narrow WEP, $CaCl_2$-P, and runoff phosphorus ranges, as in the Beaverlodge soils (Fig. 6), the relationships between desorbed phosphorus values and runoff phosphorus are weak (Table 7). Compared to phosphorus in runoff, the WEP and $CaCl_2$-P desorption methods overestimated the amount of phosphorus that could be lost in runoff from the Lacombe (Fig. 7) and Wilson Siding soils (Fig. 8), and the $CaCl_2$-P desorption method underestimated the amount of phosphorus that could be lost in runoff from the Beaverlodge soils (Fig. 6).

Strong relationships were found between WEP and runoff DRP and between $CaCl_2$-P and runoff DRP in natural runoff from the eight microwatershed soils, although WEP was a better predictor of runoff DRP (Fig. 5c and 5d). The WEP and $CaCl_2$-P desorption methods overestimated the amount of phosphorus loss in runoff from the microwatershed sites, and this may be related to the differences in runoff event duration and volumes. However, the relative amounts of desorbed phosphorus extracted and runoff DRP lost between microwatershed sites were similar. These data suggest that WEP and $CaCl_2$-P may be good indicators of the relative amounts of DRP that can be lost in natural runoff from agricultural soils for the range of WEP and $CaCl_2$-P values observed.

Soil Phosphorus Thresholds

In our study, soil phosphorus thresholds (change points) for WEP, $CaCl_2$-P, or runoff DRP with increases in STP were not evident for STP values less than 1000 mg kg^{-1} in any of the manure rate soils examined. However, change points were detected at DPS values of 3 to 44% for WEP and at 11 to 51% for $CaCl_2$-P in four of the five manure rate soils investigated. Change points were not determined on the individual microwatershed soils because of the narrow STP ranges at each of the non-manured sites. Therefore, the microwatershed soils were combined to determine change points at a DPS of 47% for WEP and 59% for $CaCl_2$-P in the eight soils investigated. The STP values that corresponded to these change points were similar to the agronomic threshold of 50 to 60 mg kg^{-1} for optimum crop growth in Alberta agricultural soils (Howard 2003), except for WEP and $CaCl_2$-P at the Lacombe site, where STP thresholds were close to 100 mg kg^{-1}. A change point between DPS and runoff DRP was not determined because of the large gap in data between DPS values of 24 and 61% and between STP values of 50 and 200 mg kg^{-1} from the microwatershed sites. Change-point analysis of data from all 13 soils combined resulted in change points that were similar to the agronomic STP threshold for Alberta soils.

Since change point results are highly dependant on measurement and calculation methods, there is a wide range of values for DPS reported in the literature. Pote et al. (1999) used the ammonium oxalate extraction method and detected change points in three acidic Arkansas soils at DPS values from 20 to 30%. They also described the relationship between DPS and runoff DRP using a quadratic equation [Runoff DRP, mg L^{-1} = 0.3083 – 0.0353(DPS, %) + 0.0014$(DPS, \%)^2$, r^2 = 0.87]. Sims et al. (2002) reported a change point of 14% for Mehlich-3 DPS and runoff DRP in northeastern United States soils (Breeuwsma et al. 1995). Vadas et al. (2005) recently compared 10 non-calcareous soils from a number of studies, including the work by Pote et al. (1999), and found that runoff DRP increased rapidly at DPS values greater than 12.5%, as determined by an acid ammonium oxalate extraction. Other studies have found change points between DPS and WEP of 10% (Hooda et al. 2000), and 16 to 20% (Nair et al. 2004). Change points between DPS and $CaCl_2$-P were observed at 18% in an Italian soil (Indiati and Sequi 2004); from 26 to 34% in a wide range of soils from the United Kingdom, New Zealand, and the northeastern United States (McDowell et al. 2001a); and from 26 to 38% in Florida soils (Nair et al. 2004). Borling et al. (2004) found strong linear relationships between the ratio of Olsen STP to PSI and $CaCl_2$-P and between the ratio of ammonium lactate-extractable STP to PSI and $CaCl_2$-P in several Swedish soils; however, change points were not observed within the range of STP values they examined (up to 80 mg kg^{-1} Olsen phosphorus or about 190 mg kg^{-1} ammonium lactate-extractable phosphorus).

Laboski and Lamb (2004) recently determined that a DPS value of about 22% in Minnesota soils corresponded with a critical WEP concentration of 1 mg L^{-1}. Coincidentally, this WEP target value of 1 mg L^{-1} is similar to the WEP plateau of 1.03 mg L^{-1} determined for the 13 Alberta soils and corresponds to a DPS level of 35% (Table 5). This critical DPS value is equivalent to an STP value of 52 mg kg^{-1}. A change point was also detected at a DPS value of 54%, which equates to an STP level of 86 mg kg^{-1} using 1 mg L^{-1} as the critical $CaCl_2$-P value.

CONCLUSIONS

A single-point $CaCl_2$-PSI method was validated using adsorption isotherm data from a wide range of Alberta soils. This method was subsequently used to determine the phosphorus sorption status of five Alberta soils following land application of cattle manure at different rates and of eight microwatershed soils throughout the province, ranging from native grassland to a heavily manured site.

Strong linear relationships were determined between STP and desorbed phosphorus (WEP and $CaCl_2$-P) in 13 Alberta soils. The WEP method generally resulted in higher concentrations of desorbed phosphorus than the $CaCl_2$-P method. Change points for DPS were identified in 12 of the 13 soils at values between 3 to 47% for WEP and 11 to 59% for $CaCl_2$-P using DPS-desorbed phosphorus relationships determined in the laboratory. Weak linear relationships were also found between STP and runoff DRP for the three soils used for the manure rate and tillage study. Change points for DPS and runoff DRP were not evident in the manure rate and tillage and microwatershed study soils.

Desorbed phosphorus concentrations (WEP or $CaCl_2$-P) determined in the laboratory were generally higher, in relation to STP or DPS, than runoff DRP concentrations measured in the three manure rate and tillage soils and eight microwatershed soils. However, the relative amounts of runoff DRP that could be lost from these soils were similar to the desorbed phosphorus values for the range of WEP and $CaCl_2$-P values observed. Both proxies overestimated phosphorus losses in runoff from the microwatershed sites, but relative amounts lost between sites were similar. These results suggest that WEP and $CaCl_2$-P may be good indicators of the relative amounts of DRP that can be lost from agricultural soils.

Analysis of all 13 soils combined resulted in DPS change points that were similar to the agronomic STP threshold of 50 to 60 mg kg^{-1} for crops grown on Alberta soils. The overall DPS threshold for these 13 soils was 35% for WEP and 54% for $CaCl_2$-P. These critical DPS thresholds correspond to modified Kelowna STP values of approximately 51 mg kg^{-1} and 86 mg kg^{-1}, which are close to the agronomic threshold. Soils with DPS values that exceed these thresholds may be more susceptible to soluble phosphorus losses in overland flow and leaching.

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APPENDICES

Appendix 1. Soil phosphorus sorption and desorption results for soils used in the change point analysis.

Table A1.1. Soil phosphorus sorption and desorption results for soils from the 8-yr manure rate study.

Site[z]	Manure rate ($Mg\ ha^{-1}\ yr^{-1}$)	Rep	STP ($mg\ kg^{-1}$)	PSI ($mg\ kg^{-1}$)	DPS (%)	WEP ($mg\ L^{-1}$)	$CaCl_2$-P ($mg\ L^{-1}$)
Coarse	0	1	40.2	140.8	22.2	0.51	0.26
Coarse	0	2	41.2	108.3	27.6	0.87	0.45
Coarse	0	3	52.1	93.6	35.8	1.06	0.56
Coarse	0	4	6.1	107.2	5.4	1.18	0.58
Coarse	0	5	6.9	142.8	4.6	1.05	0.59
Coarse	20	1	83.3	114.5	42.1	2.20	1.12
Coarse	20	2	81.5	90.4	47.4	1.87	1.30
Coarse	20	3	184.8	37.3	83.2	5.61	3.70
Coarse	20	4	173.4	77.5	69.1	4.37	2.71
Coarse	20	5	153.3	36.7	80.7	4.25	2.87
Coarse	40	1	112.3	76.7	59.4	3.16	1.89
Coarse	40	2	141.9	53.8	72.5	3.68	2.26
Coarse	40	3	168.9	73.7	69.6	4.05	2.67
Coarse	40	4	242.2	38.3	86.4	6.54	4.28
Coarse	40	5	202.5	80.3	71.6	5.36	3.68
Coarse	60	1	222.2	74.1	75.0	5.15	3.49
Coarse	60	2	231.9	52.9	81.4	5.39	4.16
Coarse	60	3	261.9	59.5	81.5	6.70	4.54
Coarse	60	4	208.4	88.0	70.3	5.35	3.64
Coarse	60	5	330.5	30.2	91.6	9.57	6.53
Coarse	120	1	366.4	51.2	87.7	8.78	6.25
Coarse	120	2	565.6	0.0	100.0	11.73	9.22
Coarse	120	3	328.9	46.8	87.5	8.10	5.69
Coarse	120	4	542.6	18.7	96.7	12.50	9.19
Coarse	120	5	570.6	0.0	100.0	14.64	10.79
Medium	0	1	26.6	433.4	5.8	0.22	0.08
Medium	0	2	18.6	457.6	3.9	0.13	0.06
Medium	0	3	14.0	454.6	3.0	0.13	0.05
Medium	0	4	18.4	478.1	3.7	0.15	0.06
Medium	0	5	11.7	430.8	2.6	0.19	0.06
Medium	20	1	103.9	341.4	23.3	1.58	0.68
Medium	20	2	98.6	343.9	22.3	1.31	0.66
Medium	20	3	72.4	390.9	15.6	1.08	0.40
Medium	20	4	112.1	360.3	23.7	1.87	0.83
Medium	20	5	79.9	402.7	16.6	1.22	0.48
Medium	40	1	184.5	278.3	39.9	3.57	1.80
Medium	40	2	106.6	320.9	24.9	1.72	0.74
Medium	40	3	236.6	267.1	47.0	4.29	2.32
Medium	40	4	113.6	386.2	22.7	1.76	0.73
Medium	40	5	135.7	368.7	26.9	2.04	0.93
Medium	60	1	297.8	223.6	57.1	5.71	3.23
Medium	60	2	304.4	238.3	56.1	6.19	3.15

Site	Manure rate (Mg ha^{-1} yr^{-1})	Rep	STP (mg kg^{-1})	PSI (mg kg^{-1})	DPS (%)	WEP (mg L^{-1})	$CaCl_2$-P (mg L^{-1})
Medium	60	3	232.5	251.5	48.0	4.20	2.28
Medium	60	4	244.9	316.0	43.7	3.65	1.78
Medium	60	5	215.1	325.2	39.8	4.25	2.02
Medium	120	1	549.3	172.4	76.1	13.25	8.08
Medium	120	2	501.8	207.9	70.7	9.87	5.67
Medium	120	3	553.3	214.2	72.1	10.62	6.24
Medium	120	4	603.8	186.8	76.4	12.50	7.21
Medium	120	5	601.3	203.2	74.7	12.45	7.18

[z]Sample depth was 0 to 15 cm. Samples were collected in 2001 after eight annual applications of cattle manure.

Table A1.2. Soil phosphorus sorption and desorption results for soils from the manure rate and tillage study.

Site[z]	Manure rate (kg TP ha^{-1})	Tillage	Rep	STP (mg kg^{-1})	PSI (mg kg^{-1})	DPS (%)	WEP (mg L^{-1})	$CaCl_2$-P (mg L^{-1})
Beaverlodge	0	no till	1	36.0	350.0	9.3	0.41	0.11
Beaverlodge	0	no till	2	47.0	316.0	12.9	0.51	0.15
Beaverlodge	0	no till	3	39.0	272.0	12.5	0.49	0.15
Beaverlodge	0	no till	4	43.0	283.0	13.2	0.39	0.10
Beaverlodge	0	till	1	42.0	339.0	11.0	0.46	0.11
Beaverlodge	0	till	2	65.0	267.0	19.6	0.72	0.18
Beaverlodge	0	till	3	40.0	288.0	12.2	0.42	0.11
Beaverlodge	0	till	4	43.0	253.0	14.5	0.40	0.07
Beaverlodge	25	no till	1	49.0	308.0	13.7	0.62	0.14
Beaverlodge	25	no till	2	68.0	283.0	19.4	0.70	0.17
Beaverlodge	25	no till	3	47.0	322.0	12.7	0.47	0.12
Beaverlodge	25	no till	4	52.0	303.0	14.6	0.46	0.09
Beaverlodge	25	till	1	50.0	341.0	12.8	0.42	0.13
Beaverlodge	25	till	2	73.0	289.0	20.2	0.74	0.19
Beaverlodge	25	till	3	48.0	301.0	13.8	0.48	0.11
Beaverlodge	25	till	4	53.0	304.0	14.8	0.47	0.11
Beaverlodge	50	no till	1	69.0	309.0	18.3	0.72	0.20
Beaverlodge	50	no till	2	66.0	280.0	19.1	0.68	0.16
Beaverlodge	50	no till	3	112.0	265.0	29.7	1.12	0.38
Beaverlodge	50	no till	4	64.0	292.0	18.0	0.50	0.12
Beaverlodge	50	till	1	66.0	290.0	18.5	0.69	0.21
Beaverlodge	50	till	2	67.0	305.0	18.0	0.68	0.17
Beaverlodge	50	till	3	66.0	277.0	19.2	0.64	0.18
Beaverlodge	50	till	4	71.0	277.0	20.4	0.62	0.13
Beaverlodge	100	no till	1	101.0	292.0	25.7	1.20	0.42
Beaverlodge	100	no till	2	114.0	267.0	29.9	1.35	0.42
Beaverlodge	100	no till	3	86.0	306.0	21.9	0.92	0.31
Beaverlodge	100	no till	4	83.0	300.0	21.7	1.01	0.25
Beaverlodge	100	till	1	101.0	282.0	26.4	1.10	0.39
Beaverlodge	100	till	2	114.0	280.0	28.9	1.24	0.42
Beaverlodge	100	till	3	74.0	251.0	22.8	0.78	0.26
Beaverlodge	100	till	4	89.0	270.0	24.8	0.69	0.17
Lacombe	0	no till	1	102.0	135.0	43.0	2.72	1.87
Lacombe	0	no till	2	107.0	115.0	48.2	2.68	1.71
Lacombe	0	no till	3	116.0	97.0	54.5	2.94	2.13
Lacombe	0	no till	4	127.0	151.0	45.7	1.55	0.82
Lacombe	0	till	1	104.0	106.0	49.5	2.68	1.93
Lacombe	0	till	2	76.0	124.0	38.0	1.85	0.82
Lacombe	0	till	3	128.0	88.0	59.3	3.64	2.68
Lacombe	0	till	4	97.0	106.0	47.8	2.44	1.36
Lacombe	50	no till	1	124.0	103.0	54.6	3.30	2.41
Lacombe	50	no till	2	118.0	90.0	56.7	3.35	2.30
Lacombe	50	no till	3	165.0	67.0	71.1	4.75	4.12
Lacombe	50	no till	4	218.0	46.0	82.6	7.71	7.15
Lacombe	50	till	1	120.0	126.0	48.8	3.18	2.03

Site	Manure rate (kg TP ha^{-1})	Tillage	Rep	STP (mg kg^{-1})	PSI (mg kg^{-1})	DPS (%)	WEP (mg L^{-1})	$CaCl_2$-P (mg L^{-1})
Lacombe	50	till	2	107.0	95.0	53.0	2.68	1.65
Lacombe	50	till	3	226.0	47.0	82.8	7.51	6.25
Lacombe	50	till	4	121.0	73.0	62.4	3.16	1.93
Lacombe	100	no till	1	172.0	75.0	69.6	4.58	3.38
Lacombe	100	no till	2	250.0	42.0	85.6	7.79	5.66
Lacombe	100	no till	3	231.0	37.0	86.2	7.69	7.95
Lacombe	100	no till	4	196.0	41.0	82.7	6.53	5.60
Lacombe	100	till	1	134.0	80.0	62.6	3.82	2.73
Lacombe	100	till	2	115.0	98.0	54.0	3.00	2.31
Lacombe	100	till	3	154.0	79.0	66.1	4.60	3.47
Lacombe	100	till	4	171.0	56.0	75.3	5.31	3.60
Lacombe	200	no till	1	277.0	33.0	89.4	9.58	8.83
Lacombe	200	no till	2	449.0	33.0	93.2	13.23	12.07
Lacombe	200	no till	3	273.0	48.0	85.0	8.48	7.62
Lacombe	200	no till	4	371.0	26.0	93.5	10.27	9.64
Lacombe	200	till	1	168.0	109.0	60.6	4.59	3.28
Lacombe	200	till	2	257.0	57.0	81.8	8.51	7.50
Lacombe	200	till	3	209.0	64.0	76.6	6.54	5.78
Lacombe	200	till	4	207.0	68.0	75.3	5.48	3.73
Wilson Siding	0	no till	1	37.0	156.0	19.2	0.91	0.27
Wilson Siding	0	no till	2	47.0	139.0	25.3	1.20	0.36
Wilson Siding	0	no till	3	48.0	148.0	24.5	1.11	0.31
Wilson Siding	0	no till	4	53.0	148.0	26.4	1.28	0.34
Wilson Siding	0	till	1	64.0	185.0	25.7	1.30	0.46
Wilson Siding	0	till	2	49.0	138.0	26.2	1.19	0.40
Wilson Siding	0	till	3	38.0	130.0	22.6	1.11	0.31
Wilson Siding	0	till	4	61.0	149.0	29.0	1.28	0.44
Wilson Siding	50	no till	1	167.0	153.0	52.2	4.00	1.47
Wilson Siding	50	no till	2	93.0	130.0	41.7	2.31	0.72
Wilson Siding	50	no till	3	253.0	77.0	76.7	8.02	3.33
Wilson Siding	50	no till	4	471.0	99.0	82.6	9.97	5.11
Wilson Siding	50	till	1	261.0	132.0	66.4	7.32	2.48
Wilson Siding	50	till	2	195.0	100.0	66.1	4.88	1.95
Wilson Siding	50	till	3	123.0	132.0	48.2	3.12	1.26
Wilson Siding	50	till	4	206.0	119.0	63.4	4.89	2.12
Wilson Siding	100	no till	1	217.0	131.0	62.4	5.10	1.95
Wilson Siding	100	no till	2	666.0	72.0	90.2	14.53	5.87
Wilson Siding	100	no till	3	342.0	104.0	76.7	8.90	4.10
Wilson Siding	100	no till	4	379.0	80.0	82.6	12.08	6.07
Wilson Siding	100	till	1	291.0	135.0	68.3	5.41	2.46
Wilson Siding	100	till	2	235.0	128.0	64.7	6.14	2.38
Wilson Siding	100	till	3	412.0	80.0	83.7	10.25	6.91
Wilson Siding	100	till	4	412.0	72.0	85.1	11.84	7.49
Wilson Siding	200	no till	1	569.0	115.0	83.2	11.83	5.27
Wilson Siding	200	no till	2	469.0	94.0	83.3	11.56	5.43
Wilson Siding	200	no till	3	719.0	118.0	85.9	13.93	6.45
Wilson Siding	200	no till	4	993.0	62.0	94.1	22.19	13.28
Wilson Siding	200	till	1	308.0	126.0	71.0	7.25	3.04
Wilson Siding	200	till	2	519.0	138.0	79.0	10.30	4.22

Site	Manure rate (kg TP ha^{-1})	Tillage	Rep	STP (mg kg^{-1})	PSI (mg kg^{-1})	DPS (%)	WEP (mg L^{-1})	$CaCl_2$-P (mg L^{-1})
Wilson Siding	200	till	3	689.0	71.0	90.7	15.34	8.99
Wilson Siding	200	till	4	733.0	74.0	90.8	17.73	8.70

[z]Sample depth was 0 to 2.5 cm. Samples were collected 1 yr after one application of cattle manure.

Table A1.3. Soil phosphorus sorption and desorption results for soils from the microwatershed study.

Site[z]	Sample Site No.	Year sampled	STP (mg kg^{-1})	PSI (mg kg^{-1})	DPS (%)	WEP (mg L^{-1})	$CaCl_2$-P (mg L^{-1})
CFT	2	2003	43.0	122.1	26.0	1.79	0.89
CFT	4	2003	50.0	142.6	26.0	1.46	0.62
CFT	5	2004	37.0	147.5	20.1	1.03	0.34
CFT	9	2003	34.0	143.4	19.2	0.80	0.24
CFT	14	2003	22.0	134.6	14.0	0.61	0.21
CFT	15	2003	46.0	159.8	22.3	1.20	0.48
CFT	16	2003	15.0	132.4	10.2	0.66	0.22
CFT	17	2003	49.0	154.1	24.1	0.95	0.40
CFT	18	2003	33.0	142.4	18.8	0.79	0.24
CFT	19	2003	242.0	123.2	66.3	2.60	1.37
CFT	20	2003	75.0	124.7	37.6	1.20	0.50
CFT	25	2003	24.0	152.1	13.6	0.64	0.28
CFT	26	2004	88.0	216.4	28.9	1.32	0.32
CFT	30	2003	44.0	174.3	20.2	0.61	0.24
CFT	31	2003	35.0	123.3	22.1	1.09	0.68
CFT	41	2003	32.0	131.9	19.5	1.79	0.81
CFT	42	2004	18.0	114.4	13.6	0.88	0.44
CFT	43	2003	58.0	195.6	22.9	1.64	0.60
GPC	1	2002	37.0	455.8	7.5	0.33	0.06
GPC	4	2002	31.0	458.2	6.3	0.44	0.08
GPC	7	2002	55.0	442.5	11.1	0.48	0.06
GPC	9	2002	35.0	623.9	5.3	0.25	0.03
GPC	11	2002	45.0	435.7	9.4	0.34	0.03
GPC	12	2002	38.0	323.3	10.5	0.44	0.04
GPC	15	2002	46.0	513.1	8.2	0.75	0.05
GPC	16	2002	68.0	430.6	13.6	0.90	0.07
GPC	17	2002	57.0	428.6	11.7	0.48	0.05
GPC	18	2002	44.0	539.8	7.5	0.38	0.04
GPC	21	2002	53.0	476.0	10.0	0.65	0.05
GPC	22	2002	62.0	423.0	12.8	1.14	0.07
GPC	23	2002	33.0	316.3	9.4	0.45	0.08
GPC	24	2002	44.0	300.9	12.8	0.60	0.10
GPC	34	2002	54.0	475.8	10.2	0.26	0.05
GPC	35	2002	64.0	441.0	12.7	0.21	0.05
GPC	36	2002	46.0	421.8	9.8	0.33	0.04
LLB	1	2003	84.0	190.3	30.6	1.75	0.73
LLB	3	2003	260.0	78.8	76.7	5.45	3.28
LLB	12	2003	727.0	141.6	83.7	8.06	4.07
LLB	15	2003	257.0	105.8	70.8	5.27	2.26
LLB	16	2003	152.0	127.1	54.5	2.63	1.31
LLB	17	2004	239.0	128.1	65.1	4.43	2.02
LLB	18	2003	99.0	182.2	35.2	0.89	0.34
LLB	19	2003	96.0	130.9	42.3	1.86	0.93
LLB	20	2003	76.0	107.0	41.5	1.15	0.71
LLB	21	2003	82.0	97.8	45.6	2.22	1.15
LLB	22	2003	172.0	140.1	55.1	2.67	1.35

Site	Sample Site No.	Year sampled	STP (mg kg^{-1})	PSI (mg kg^{-1})	DPS (%)	WEP (mg L^{-1})	$CaCl_2$-P (mg L^{-1})
LLB	23	2003	242.0	117.0	67.4	4.34	2.60
LLB	27	2003	240.0	100.1	70.6	4.12	2.13
LLB	28	2003	283.0	160.1	63.9	3.39	1.50
LLB	31	2003	482.0	130.5	78.7	6.39	2.79
LLB	32	2003	277.0	136.2	67.0	4.17	1.90
LLB	33	2003	364.0	114.5	76.1	5.58	2.79
LLB	34	2003	186.0	134.7	58.0	3.10	1.49
LLB	35	2003	187.0	177.4	51.3	2.52	1.15
LLB	1	2002	226.0	214.9	51.3	2.09	1.26
LLB	3	2002	296.0	68.7	81.2	6.84	3.91
LLB	16	2002	339.0	116.3	74.5	4.87	2.80
LLB	18	2002	209.0	121.4	63.3	3.31	1.86
LLB	21	2002	157.0	76.3	67.3	3.25	1.82
LLB	22	2002	365.0	139.9	72.3	4.52	2.79
LLB	1	2004	127.0	178.3	41.6	1.83	0.89
LLB	3	2004	235.0	78.1	75.1	7.26	3.84
LLB	16	2004	240.0	133.2	64.3	4.46	1.80
LLB	18	2004	194.0	129.6	60.0	4.25	2.07
LLB	21	2004	102.0	97.2	51.2	3.18	1.95
LLB	22	2004	286.0	147.6	66.0	4.10	2.34
PON	3	2003	508.0	118.2	81.1	10.76	7.09
PON	5	2003	578.0	8.7	98.5	17.03	16.63
PON	6	2003	1166.0	0.0	100.0	32.25	29.55
PON	8	2003	323.0	76.6	80.8	9.45	8.69
PON	9	2003	404.0	37.7	91.5	10.73	11.79
PON	10	2003	600.0	6.8	98.9	19.90	17.66
PON	11	2004	263.0	102.3	72.0	7.79	4.81
PON	12	2003	661.0	51.1	92.8	13.29	11.81
PON	13	2003	346.0	66.1	84.0	8.95	8.22
PON	14	2003	521.0	23.4	95.7	15.82	16.55
PON	15	2003	566.0	39.4	93.5	14.34	14.73
PON	16	2003	663.0	0.0	100.0	20.31	22.07
PON	17	2003	254.0	65.1	79.6	6.83	5.78
PON	18	2003	558.0	14.5	97.5	15.87	17.18
PON	19	2003	369.0	32.8	91.8	14.87	13.62
PON	20	2003	502.0	37.1	93.1	12.72	16.05
PON	21	2003	595.0	138.4	81.1	9.35	5.81
PON	22	2003	430.0	57.1	88.3	11.90	10.94
PON	3	2002	502.0	133.4	79.0	11.72	9.91
PON	10	2002	372.0	72.2	83.7	10.79	9.88
PON	17	2002	344.0	78.6	81.4	8.73	7.05
PON	18	2002	781.0	46.8	94.3	24.36	21.57
PON	21	2002	688.0	111.0	86.1	14.74	10.67
PON	3	2004	427.0	160.0	72.7	6.87	4.46
PON	6	2004	429.0	89.0	82.8	12.11	8.26
PON	10	2004	300.0	54.5	84.6	8.68	8.21
PON	17	2004	224.0	97.0	69.8	5.20	3.16
PON	18	2004	406.0	90.4	81.8	11.27	6.90
PON	21	2004	592.0	103.6	85.1	8.84	6.65

Site	Sample Site No.	Year sampled	STP (mg kg^{-1})	PSI (mg kg^{-1})	DPS (%)	WEP (mg L^{-1})	$CaCl_2$-P (mg L^{-1})
REN	1	2003	52.0	198.0	20.8	1.25	0.36
REN	2	2003	55.0	86.5	38.9	2.36	1.28
REN	3	2004	67.0	192.0	25.9	1.68	0.51
REN	4	2003	55.0	144.3	27.6	1.40	0.45
REN	9	2003	55.0	233.1	19.1	1.11	0.26
REN	10	2004	58.0	229.3	20.2	1.31	0.31
REN	12	2003	38.0	229.6	14.2	0.75	0.21
REN	13	2004	29.0	218.1	11.7	0.50	0.14
REN	14	2003	45.0	178.9	20.1	0.83	0.21
REN	15	2003	53.0	147.7	26.4	1.21	0.37
REN	16	2003	49.0	146.0	25.1	1.03	0.33
REN	19	2003	50.0	229.3	17.9	0.90	0.17
REN	20	2003	47.0	248.5	15.9	0.93	0.15
REN	21	2003	50.0	208.2	19.4	0.86	0.19
REN	22	2003	47.0	217.5	17.8	0.68	0.14
REN	23	2003	44.0	237.5	15.6	0.89	0.20
REN	24	2003	43.0	194.4	18.1	0.78	0.23
REN	27	2003	23.0	157.0	12.8	0.50	0.17
STV	1	2003	10.0	185.4	5.1	1.54	0.43
STV	2	2002	10.0	206.6	4.6	1.08	0.46
STV	3	2003	7.0	186.1	3.6	1.26	0.54
THC	1	2003	90.0	130.3	40.8	2.78	1.59
THC	3	2003	43.0	193.6	18.2	1.21	0.43
THC	6	2003	40.0	152.7	20.8	1.25	0.53
THC	7	2003	91.0	201.9	31.1	2.12	0.92
THC	8	2003	40.0	133.9	23.0	1.28	0.47
THC	9	2003	54.0	109.8	33.0	1.63	0.65
THC	11	2003	33.0	134.0	19.8	0.98	0.37
THC	13	2003	67.0	126.0	34.7	1.70	0.78
THC	14	2003	57.0	157.5	26.6	1.58	0.61
THC	15	2003	43.0	168.7	20.3	1.20	0.38
THC	16	2003	41.0	177.5	18.8	0.99	0.29
THC	17	2003	29.0	110.3	20.8	0.87	0.32
THC	18	2003	32.0	146.7	17.9	0.71	0.29
THC	19	2003	25.0	133.2	15.8	0.62	0.20
THC	20	2003	20.0	112.5	15.1	0.50	0.18
THC	21	2003	45.0	149.1	23.2	1.39	0.46
THC	22	2003	43.0	191.2	18.4	0.87	0.27
THC	23	2003	35.0	196.6	15.1	0.45	0.17
THC	24	2003	29.0	157.8	15.5	0.72	0.22
THC	29	2003	56.0	136.1	29.2	1.75	0.66
WAB	1	2003	20.0	153.2	11.5	0.44	0.17
WAB	5	2003	31.0	156.5	16.5	0.48	0.17
WAB	3	2003	55.0	211.3	20.7	1.14	0.45
WAB	4	2003	52.0	206.1	20.1	0.59	0.26
WAB	8	2003	48.0	175.4	21.5	0.67	0.24
WAB	9	2003	23.0	158.5	12.7	0.33	0.11
WAB	10	2003	34.0	180.2	15.9	0.41	0.12
WAB	13	2003	50.0	178.1	21.9	0.68	0.17

Site	Sample Site No.	Year sampled	STP (mg kg^{-1})	PSI (mg kg^{-1})	DPS (%)	WEP (mg L^{-1})	$CaCl_2$-P (mg L^{-1})
WAB	14	2003	44.0	175.9	20.0	0.54	0.15
WAB	15	2003	36.0	177.6	16.9	0.46	0.16
WAB	16	2003	34.0	142.0	19.3	0.48	0.17
WAB	17	2003	33.0	169.3	16.3	0.40	0.13
WAB	18	2003	31.0	188.1	14.1	0.41	0.11
WAB	19	2003	48.0	157.6	23.3	0.60	0.20
WAB	20	2003	25.0	178.5	12.3	0.68	0.24
WAB	21	2003	41.0	159.3	20.5	0.36	0.12
WAB	22	2003	23.0	171.2	11.8	0.41	0.12
WAB	23	2003	29.0	147.0	16.5	0.36	0.13
WAB	24	2003	66.0	157.6	29.5	0.40	0.12

[z]CFT = Crowfoot Creek, GPC = Grande Prairie Creek, LLB = Lower Little Bow, PON = Ponoka, REN = Renwick Creek, STV = Stavely, THC = Three Hills Creek, and WAB = Wabash Creek. Sample depth was 0 to 2.5 cm.