Phosphorus Losses in Simulated Rainfall Runoff from Manured Land

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2006

Albert Soil Phosphorus Limits Project

Citation
Ontkean, G.R, Volf, C.A., Bennett, D.R., Nolan, S.C., Chanasyk, D.S., and Miller, J.J. 2006. Phosphorus losses in simulated rainfall runoff from manured land. 71 pp. ***In*** Alberta Soil Phosphorus Limits Project. Volume 3: Soil sampling, manure application, and sorption characteristics. Alberta Agriculture, Food and Rural Development, Lethbridge, Alberta, Canada.

Published by
Irrigation Branch
Alberta Agriculture, Food and Rural Development
Lethbridge, Alberta, Canada

Printed in Canada

Copies of this report are available from
Irrigation Branch
Alberta Agriculture, Food and Rural Development
Agriculture Centre
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Lethbridge, Alberta
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ABSTRACT

Manure applied to agricultural land in excess of annual crop nutrient requirements can be a source of phosphorus in runoff to surface waters. Manure incorporation is often recommended to reduce phosphorus losses in runoff from cultivated soils. A plot-scale rainfall simulation study was conducted at three field sites in Alberta to evaluate the effects of manure rate and incorporation on phosphorus losses in runoff. Simulated rain was applied at an intensity of 70 mm h^{-1} to soils with freshly applied and residual (1 yr after application) solid cattle manure to produce 30 min of runoff from a 1.5 m by 2 m area within each plot. Treatments consisted of three manure application rates (50, 100, and 200 mg kg^{-1} total phosphorus) and a control (unmanured), as well as two incorporation methods (non-incorporated and incorporated with one pass of a double disk). Actual manure total phosphorus (TP) application rates were half of the target rates at the Beaverlodge site and double the target rates at the Wilson site. Soil samples from the 0- to 2.5-cm depth were analyzed for soil-test phosphorus (STP). Manure samples were analyzed for TP and water-extractable phosphorus (WEP). Runoff water samples were analyzed for TP and dissolved reactive phosphorus (DRP). Immediately after manure application, STP values ranged from 40 to 147 mg kg^{-1} at the Beaverlodge site, 88 to 576 mg kg^{-1} at the Lacombe site, and 35 to 2408 mg kg^{-1} at the Wilson site. One year after manure application, STP values were 35 to 111 mg kg^{-1} at the Beaverlodge site, 80 to 513 mg kg^{-1} at the Lacombe site, and 39 to 1242 mg kg^{-1} at the Wilson site. For fresh manure, and at a lower rate for residual manure, phosphorus concentration in runoff increased with manure rate at all sites. Runoff volumes did not change significantly ($P<0.05$) with manure rate. Runoff volumes and phosphorus concentrations did not change significantly with one-pass manure incorporation, except at the Beaverlodge site where they both decreased with incorporation of fresh manure. Incorporation of manure had no significant effect on phosphorus losses at any of the sites 1 yr later. Manure TP and STP generally had strong relationships with TP and DRP concentrations in runoff, but WEP in fresh manure had a weak relationship with DRP in runoff at all sites. Extraction coefficients (slopes) of the relationships between STP and TP in runoff ranged from 0.024 to 0.11 for freshly manured soil and from 0.0067 to 0.015 for residual manured soil. The residual manure extraction coefficients for the STP and TP relationships from the Lacombe and Wilson sites were similar to the coefficient observed in an Alberta microwatershed study. Extraction coefficients for the relationships between STP and DRP concentrations in runoff ranged from 0.013 to 0.032 for freshly manured soil and decreased to 0.0065 to 0.013 for residual manured soil. Relationships between STP and TP or DRP in runoff from the unmanured treatments at all of the sites combined had extraction coefficients that were similar to the residual manured soil. The extraction coefficients for the relationships between STP in residual manured soil and DRP concentrations in runoff were greater than the extraction coefficients in the majority of studies conducted elsewhere in North America and the United Kingdom.

ACKNOWLEDGEMENTS

Special thanks to the many individuals who helped carry out this project. This includes Ki Au, Linda Broderson, Carolin Cattoi-Demkiw, Gyan Mankee, Fawzi Bichai, Janna Casson, Paul Graveland, Ward Henry, Mark Kadijk, Andrea Kalischuk, Heather Kolberg, Jonathan Peters, Murray Peters, Jim Parker, and Janelle Villeneuve from Alberta Agriculture, Food and Rural Development (AAFRD) Irrigation Branch; Syd Abday, Wiebe Buruma, and Mark Nelson from AAFRD Conservation and Development Branch; Kristian Stephens from AAFRD Environmental Practices and Livestock Welfare Branch; and Deirdre Earl, Triston Hampton, and Tasha Kirkeby from 5th on 5th Youth Services, Lethbridge, Alberta. Many thanks to Dennis Mikalson (Irrigation Branch), Toby Entz (Agriculture and Agri-Food Canada, Lethbridge, Alberta) and Phil Gibbs (SAS Institute, Cary, North Carolina, United States) for their statistical wisdom and hard work during the data analysis stage. Thanks also to Brent Paterson, Barry Olson, and Joanne Little (Irrigation Branch), whose experience provided excellent input while developing this project. Partial funding for this study was provided by the Agricultural Funding Consortium, which included contributions from the Alberta Livestock Industry Development Fund, the Alberta Crop Industry Development Fund, and the Alberta Agricultural Research Institute.

We are much indebted to the generous nature of Ray Taylor of Darray Farms, as well as Raman Azooz and Dave Young and their staff from the Agriculture and Agri-Food Canada research centres at Beaverlodge and Lacombe, for sharing their time, equipment, land, and historical records.

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INTRODUCTION

Phosphorus is an essential nutrient for agricultural crop and livestock production. However, excessive amounts of phosphorus in agricultural soils can contribute to eutrophication of surface waters when transported by runoff. Livestock production trends in Alberta show a movement toward larger operations that are concentrated in certain areas of the province. The increased amount of manure in these areas can result in application of manure to surrounding agricultural land at rates that exceed crop nutrient requirements. This leads to a build-up of phosphorus in soil and a greater risk of impairment to surrounding surface waters.

Recent studies have linked increasing soil-test phosphorus (STP) with increasing phosphorus concentrations in runoff (Pote et al. 1996; Pote et al. 1999; Schroeder et al. 2004b; Turner et al. 2004; Vadas et al. 2005a). Similarly, other studies have found a positive relationship between manure application rate and phosphorus in runoff (Edwards and Daniel 1993; Kleinman and Sharpley 2003; Tarkalson and Mikkelsen 2004). Additionally, Kleinman and Sharpley (2003) reported that phosphorus concentrations in runoff decreased with repeated rainfall events during the month following manure application. Schroeder et al. (2004a) observed a similar trend with exponential decline during a period of 5 mo following manure application.

Manure application methods can affect the relationship between phosphorus in soil and in runoff. Relative to surface applied manure, incorporation of manure has been associated with decreased dissolved reactive phosphorus (DRP) concentrations in runoff (Mueller et al. 1984a; Eghball and Gilley 1999; Bundy et al. 2001; Kleinman et al. 2002a; Little et al. 2005). Incorporation in most cases increased particulate phosphorus and consequently total phosphorus (TP) concentrations in runoff due to increased soil erosion (Mueller et al. 1984a; Eghball and Gilley 1999; Bundy et al. 2001; Kleinman et al. 2002a;). Kleinman et al. (2002a) attributed this decline in DRP with manure incorporation to a decrease of phosphorus concentrations at the soil surface and greater sorption of phosphorus in manure to soil.

Sampling depth can also affect the relationship between phosphorus in soil and runoff. For agronomic purposes, a sampling interval of 0 to 15 cm is commonly used for estimating soil nutrient requirements. However, from an environmental perspective, runoff interacts with a much shallower layer of soil. Sharpley (1985) concluded that the effective depth of interaction (EDI) between soil and runoff can vary from 0.13 to 3.74 cm, depending on rainfall intensity and slope. Phosphorus concentrations tend to be relatively uniform in the upper 15-cm layer of tilled soil. However, phosphorus in a no-till soil tends to be stratified, decreasing with depth (Andraski et al. 2003). Recent studies conducted in pastured fields have determined that STP values from various depths within the crop root zone are suitable for estimating phosphorus concentrations in runoff, although the extraction coefficients (slopes of the regression lines) vary due to the effects of phosphorus stratification (Torbert et al. 2002; Schroeder et al. 2004b).

Crop residue is another potential source of phosphorus available for transport in runoff from agricultural land. While residue, either as a source or sink for phosphorus, may potentially have an influence on concentrations of phosphorus in runoff from cropped land (Cermak et al. 2004), the extent of this influence is not largely understood. Grande et al. (2005) found DRP and TP concentrations in runoff to be unaffected by increasing amounts of corn residue in a field rainfall simulation study. Bechmann et al. (2005) also reported little difference in DRP concentrations in runoff from lab simulations on bare soil and soil with ryegrass growth. However, Bechmann et al. (2005) reported increased DRP concentrations in runoff and water-extractable phosphorus (WEP) concentrations in the plant material after soil was exposed to a series of freeze-thaw cycles.

The primary objective of this study was to determine the effects of manure application rate and incorporation on phosphorus concentrations in runoff from cropped agricultural land. These effects were studied immediately after manure application and incorporation treatments were applied as well as 1 yr later, allowing phosphorus from the manure to equilibrate with the soil. Additionally, various measures of phosphorus in manure and soil were evaluated regarding their relationship with phosphorus in runoff. Secondary objectives included determining the effects of crop residue and manure incorporation on measured values of STP, and the effect of soil sampling depth on the relationship between STP and phosphorus in runoff.

MATERIALS AND METHODS

Study Sites

Two study sites were selected in 2003 on Agriculture and Agri-Food Canada research centres near Lacombe and Beaverlodge, Alberta. A third site was selected in 2004 on private land near Wilson Siding (referred to in this report as the Wilson site), approximately 16 km southeast of Lethbridge, Alberta. The three sites represented a range of soils and were in different natural regions of the province associated with agriculture (Table 1). A randomized block design was used with four replicates of eight treatments (four manure levels and two tillage levels). The treatments were re-randomized at each site. Each treatment plot measured 7 by 10 m. A 5-m buffer was left between each replicate and a minimum 3-m buffer was provided around the plot area. Replicates were oriented across the slope at the Beaverlodge and Wilson sites, with Replicate 1 in the upper slope position and Replicate 4 in the lower slope position. Due to space restrictions at the Lacombe site, the replicates were oriented with Replicates 3 and 4 beside Replicates 1 and 2. A 5-m space was provided between the replicates across the slope. During the study, land managers were asked to continue with their management practices as previously planned.

Table 1. Physical characteristics and management history of the three study sites.

	Site		
Characteristic	Beaverlodge	Lacombe	Wilson
Natural region[z]	Boreal Forest	Parkland	Grassland
Soil subgroup[y]	D.GL	O.BLC	O.DBC
Surface soil texture[x]	CL	L to SCL	CL to C
Slope/aspect	5% East	10% West	6% South
Cultivation history	Conventional tillage	Conventional tillage	No-till
Year 1			
Previous crop	Oats	Barley	Wheat
Year 2			
Previous crop	Oats	Barley	Wheat
Nutrient additions	None	May 2004: 168 kg ha^{-1} of 35-14-0	None

[z] ANHIC (2005).
[y] D.GL = Dark Gray Luvisol; O.BLC = Orthic Black Chernozem; O.DBC = Orthic Dark Brown Chernozem.
[x] C = clay; CL = clay loam; L = loam; SCL = sandy clay loam.

Treatments

Solid cattle manure was applied to all manure-amended plots in the first year of the study. Plots at the Lacombe and Wilson sites received one of four manure rates: 0 (unmanured), 50, 100, and 200 kg ha^{-1} TP based on the nutrient content of 10 samples collected from the manure source before transport. Manure rates were reduced to half the above values at the Beaverlodge site due to low phosphorus content of the manure. The volume of manure required to achieve the original phosphorus targets at the Beaverlodge site would have substantially exceeded typical application rates used by producers. Analysis of the manure sampled at the Wilson site during application indicated a moisture content notably lower than previously measured. Because the application rates were based on the moisture content of samples collected prior to transport, approximately twice the target rate of total phosphorus was actually applied at the Wilson site.

Manure was applied to the plots by hand, spread as uniformly as possible using rakes, and was either immediately incorporated with one pass of a double disk or not incorporated. A 3.7-m wide double disk was used for incorporation at the Lacombe and Wilson sites, while a 1.8-m wide disk was used at the Beaverlodge site. Direction of tillage was parallel to the slope. No additional manure application or tillage operations were carried out prior to the second rainfall simulations 1 yr later.

Manure Analysis

Total phosphorus was analyzed (Peters 2003) on 10 samples of fresh manure from the manure source for each site. Manure rates (wet-weight equivalent) applied to the plots were determined according to the TP content of the manure using Equation 1.

$$\text{Wet mass of manure required (kg plot}^{-1}\text{)} = \frac{\text{Target TP rate (kg ha}^{-1}\text{)} \times 0.007\text{ (ha plot}^{-1}\text{)} \times 1000\text{ kg Mg}^{-1}}{\text{TP content of wet manure (kg Mg}^{-1}\text{)}} \qquad (1)$$

Manure samples were also collected at the time of application and analyzed for WEP and TP (Kleinman et al. 2002b; Peters 2003). From this analysis, actual rates of manure TP applied to the plots were calculated for each plot using Equation 2. A similar equation was used to determine rates of manure WEP applied.

$$\text{Actual TP rate (kg ha}^{-1}\text{)} = \frac{\text{TP content of manure (kg Mg}^{-1}\text{)} \times \text{Wet mass of manure applied (kg plot}^{-1}\text{)}}{0.007\text{ (ha plot}^{-1}\text{)} \times 1000\text{ kg Mg}^{-1}} \qquad (2)$$

Soil Sampling and Analysis

Prior to manure application in the initial year of the study, baseline soil samples were collected to a depth of 2.5 cm from the 32 plots at each study site using a frame-excavation method. A 50-cm long by 19-cm wide by 2.5-cm deep metal frame was inserted level with the soil surface. A 2.5-cm deep scoop was used to remove the soil from within the frame to the 2.5-cm depth (Fig. 1). All above-ground crop residue material was removed prior to collection. The analyzed sample was a composite of two sampling sites taken from each plot.

Fig. 1. Frame-excavation method of soil sampling.

Following manure application and incorporation, a post-treatment sample was collected from each treatment plot using the frame-excavation method described above, except the post-treatment sample included all incorporated and above-ground crop residue. One year after manure application, soil samples were collected prior to the second rainfall simulations using the same procedure as for the post-treatment samples of the initial rainfall simulations. From these composite samples, two subsamples were collected for analysis. One of the subsamples was screened to remove the above-ground plant material, primarily crop stubble, prior to analysis, while the other was analyzed with the above-ground material included.

Selected treatments were sampled from 0 to 2.5 cm, 2.5 to 5 cm, and 5 to 15 cm to determine whether STP values from different soil layers affected the relationships with TP in runoff at each of the three sites. Treatments selected included the incorporated treatments of the unmanured and the two greatest manure rates from each site, with samples collected from all four replicates (a total of 12 plots per site). The frame-excavation method was used to collect these soil samples during the second rainfall simulations (i.e., 1 yr after manure application). Soil-test phosphorus results were expressed on a 0- to 2.5-cm, 0- to 5-cm, and 0- to 15-cm basis. Soil-test phosphorus results for the 0- to 5-cm layer was calculated as a mean of the top two layers, and STP results for the 0- to 15-cm layer were calculated as a weighted mean of all three layers.

All soil samples were air-dried, ground (2-mm sieve), and analyzed for STP content using the modified Kelowna extraction method (Qian et al. 1991). Additional soil samples collected from each plot at the time of the simulations were used to determine gravimetric soil moisture content.

Soils were classified at each of the study sites according to the Canadian System of Soil Classification (Soil Classification Working Group 1998). Five soil cores were classified at the Beaverlodge site in 2003 (Appendix Tables A1.1 and A1.2). Four soil cores were classified at each of the Lacombe and Wilson sites in 2004 (Appendix Tables A1.3 to A1.6). Soils were sampled by horizon. Samples were air-dried, ground (< 2 mm), and analyzed from a saturated paste extract for percent saturation moisture content, pH, electrical conductivity, and soluble cations (Rhoades 1982). Sodium adsorption ratios were calculated from these chemistry results. Samples were also analyzed for STP content (Qian et al. 1991) and particle size distribution (Gee and Bauder 1986).

Rainfall Simulations

The initial rainfall simulations were conducted at the Beaverlodge and Lacombe sites in the fall of 2003 after harvest of the annual cereal crops and at the Wilson site in the spring of 2004 prior to seeding. The initial simulations were carried out within 24 h of manure application and incorporation without pre-wetting. The second rainfall simulations were carried out without pre-wetting at the Lacombe and Beaverlodge sites after crop removal in the fall of 2004 and at the Wilson site before seeding in the spring of 2005, 1 yr after manure application and incorporation.

The treatment plots were divided down the center so that test plot frames and rainfall simulators could be set up on one half for the initial simulations and on the other half for the second simulations, determined randomly for each site. Runoff frame borders for the sides of the test plots were constructed from galvanized steel, while the top and front plates were constructed from steel and painted. The top and side plates were driven into the soil to a depth of approximately 10 cm, while the front plate was driven into the ground so that the top was level with the soil surface. The framed area measured 1.5 m across by 2 m parallel to the slope.

The rainfall simulators were constructed using the specifications defined for rain simulation experiments of the United States National Phosphorus Project (Humphry et al. 2002). Four rainfall simulators were used simultaneously on four adjacent plots (Fig. 2). Each simulator was fitted with a single Fulljet ½HH-SS50WSQ nozzle centered over the runoff frame, 3 m above the soil surface. The simulators were operated at a nozzle pressure of approximately 28 kPa to generate continuous flow at an intensity of 70 mm h^{-1} on the framed area (Fig. 3).

Source water used for application was stored on-site in a 3640-L water truck and a 5460-L fiberglass tank mounted on the deck of the water truck (Fig. 4). Additional water, as required, was transported using two fiberglass tanks (2275 L and 1138 L) mounted on a flatbed trailer. Water was pumped from the water truck and through a header system to each simulator using an electric pump (Fig. 4 inset) powered by a gas generator.

Runoff water was collected from a triangular metal tray attached to the front plate of the runoff frame (Fig. 3, Fig. 5 and Fig. 6). The collection end of the tray was positioned lower than the soil surface above a 30-cm deep hole to allow collection of the runoff water. The collection tray was covered with a 1.2- by 1.8-m sheet of clear plexiglass, which prevented simulated rain from falling directly onto the collection tray.

Fig. 2. Three of the four rainfall simulators used simultaneously.

Fig. 3. Rainfall simulator, runoff frame, and collection tray.

Fig. 4. Water truck, pump, and header system.

Water Sampling and Analysis

Composite samples of runoff water were collected during consecutive intervals ending 5, 10, 20, and 30 min after the commencement of runoff (Fig. 6). Runoff was considered to have commenced when 200 mL min^{-1} of water was measured. The total volume of water collected during each timed interval was recorded. A 1-L sample of water from the total volume collected from each time interval was transported to the lab in a cooler with ice packs. After agitation, approximately 200 mL of unfiltered water was poured from the 1-L bottles and refrigerated. An additional 200 mL was collected after filtration using either a Nalgene membrane 0.45-µm filter unit or a Gelman 0.45-µm high-capacity filter within 24 h of sampling. Samples were preserved with 5% sulphuric acid. Filtered water samples were analyzed for DRP. Unfiltered water samples were analyzed for TP and total suspended solids (TSS) (Greenberg et al. 1995).

Fig. 5. (above) Runoff frame, collection tray, and plexiglass cover during rainfall simulation.

Fig. 6. (right) Runoff sample collection.

Treated water from the municipal supplies of Beaverlodge, Lacombe, and Raymond was used for this study. In 2003, a 1-L sample of source water was collected from the header outlet once per day during rainfall simulations, and filtered and unfiltered samples were analyzed as for the runoff water. In 2004 and 2005, 1-L samples were collected at the municipal outlet and at the simulator header during each set of four simulations. The source water analytical values were generally low (Appendix 2). Sample contamination during filtration may have caused higher DRP values than TP values in some samples.

Data Analysis

The DRP and TP flow-weighted mean concentration (FWMC) values were determined by dividing the total DRP or TP mass load for the 30-min interval by total flow volume for the same period. Total DRP and TP mass loads for the 30-min runoff period were the sum of the mass loads for the four runoff intervals, and these load values were calculated by multiplying the DRP or TP concentration and the runoff volume for the specified interval.

A select few of the 32 plots at each study site in each year were excluded from analysis due to hydrologic or chemical inconsistencies among replicates. Some of these inconsistencies were attributed to field factors such as tire compaction and notably long times required to produce runoff. Other inconsistencies included lower phosphorus concentrations in runoff from heavily manured plots than from the unmanured controls and unusually greater concentrations in runoff from lightly manured plots than from heavily manured plots. In addition, 12 plots at the Wilson site received approximately 17 mm of precipitation between the time manure was applied and initial simulations were carried out. These plots generated notably lower concentrations of phosphorus than plots receiving no rain after manure application.

Significant differences were determined at $P < 0.05$. Analytical results reported as below detection limits were adjusted to zero. Significant differences among pre- and post-treatment STP values for different manure TP rate and incorporation treatments were determined using the Tukey adjustment for multiple comparisons. A paired t-test was used to determine significant differences between STP values of screened and unscreened soil samples collected prior to the second set of rainfall simulations.

Analysis of covariance (ANCOVA), using the Mixed Procedure in SAS (Littell et al. 1996; SAS Institute Inc. 2000), was applied to comparisons of manure TP rate and runoff volume, TP FWMC, and DRP FWMC measured immediately after manure application and incorporation. Comparisons were also analyzed for STP and runoff volume, TP FWMC, and DRP FWMC measured 1 yr later. Additionally, the mixed-model ANCOVA method was used to assess the relationship between pre- and post-treatment STP, total and water-extractable phosphorus in manure, and combinations of pre-treatment STP and manure parameters in predicting DRP and TP FWMC measured immediately after manure application and incorporation. Incorporated and non-incorporated data were combined or analyzed separately, depending on results of the mixed-model analysis. A paired t-test was used to compare mean runoff volumes from incorporated and unincorporated treatments after ANCOVA results indicated no manure rate effect or treatment interaction. Comparisons were also made between STP measurements at varying depths and TP FWMC in runoff. Regression analyses were also performed to obtain the r^2 values of significant relationships determined from the mixed-model analysis. Mixed-model analysis, using the Mixed Procedure in SAS, was chosen because it accounts for the random variation among replicates.

RESULTS AND DISCUSSION

Initial Rainfall Simulations – Fresh Manure and Incorporation

Soil and manure characteristics. Pre-treatment STP values at all sites were relatively uniform (Appendix Table A3.1), with no significant differences among treatments within sites (Table 2). Mean pre-treatment STP values ranged from 33.1 to 37.7 mg kg^{-1} at the Beaverlodge site, 91.7 to 107.6 mg kg^{-1} at the Lacombe site, and 39.6 to 60.4 mg kg^{-1} at the Wilson site. Pre-treatment STP values at the Beaverlodge and Wilson sites were consistent with values reported by Wright et al. (2003) for non-manured soils found elsewhere in Alberta, while the Lacombe site STP values ranged from slightly above to double the values reported by Wright et al. (2003).

Post-treatment STP values for all three sites were analyzed from samples collected immediately after manure application and incorporation (Appendix Table A3.2). Mean post-treatment STP values had a positive relationship with target manure rate (Table 3), but no significant differences were found between the incorporated and non-incorporated treatments at a given rate. This suggests that the majority of phosphorus applied with manure remained in the upper 2.5 cm of the soil profile after incorporation.

The Beaverlodge manure samples collected from each plot at the time of application had a mean moisture content of 65% and TP content of 2.8 g kg^{-1} (dry basis). Eighteen percent of TP in the manure was water-extractable. The Lacombe manure samples had a mean moisture content of 69% and TP content of 4.7 g kg^{-1} (dry basis). Of the TP in the manure, 23% was water-extractable. The Wilson manure samples had a mean moisture content of 45% and TP content of 7.1 g kg^{-1} (dry basis). Twenty-five percent of TP in the manure was water-extractable.

Actual rates of phosphorus applied were calculated from TP and WEP content of manure samples collected from each plot at the time of application (Table 3 and Appendix Tables A3.3 and A3.4). Despite the variable nature of nutrients in manure (Dou et al. 2001) and differences in moisture content with time, the actual rates of TP applied to the plots were close to the target values at the Beaverlodge and Lacombe sites. At the Beaverlodge site, the actual rates tended to be slightly greater than target rates, whereas the opposite occurred at the Lacombe site. At the Wilson site, rates calculated from the source manure samples resulted in over-application of TP on the plots by approximately two times target rates due to changes in moisture content between sampling events.

Runoff volume. Mean runoff volumes were calculated for each treatment at each site for the initial rainfall simulations (Table 4 and Appendix Tables A4.1, A4.2, and A4.3). Because a significant relationship was not observed between runoff volume and manure TP rate, mean runoff volumes were also calculated for each incorporation treatment at each site (Table 4). Lack of a significant relationship between injected liquid swine manure rate and runoff volume was also reported by Daverede et al. (2004).

Table 2. Mean pre-treatment soil-test phosphorus (STP) at the three study sites.

Site	Incorporation method	Target TP rate[z] (kg ha^{-1})	n	Pre-treatment STP Mean[y] (mg kg^{-1})	SE[x] (mg kg^{-1})
Beaverlodge	Non-incorporated	0	3	36 a	3.5
		25	2	37 a	1.7
		50	3	36 a	2.2
		100	3	33 a	0.8
	Incorporated	0	4	37 a	1.6
		25	3	36 a	0.8
		50	3	37 a	0.3
		100	4	38 a	1.2
Lacombe	Non-incorporated	0	4	98 h	4.5
		50	3	108 h	8.5
		100	3	92 h	3.3
		200	4	99 h	10.7
	Incorporated	0	4	94 h	7.3
		50	3	92 h	4.1
		100	4	93 h	8.5
		200	3	95 h	4.2
Wilson	Non-incorporated	0	3	45 q	4.5
		50	3	54 q	8.7
		100	2	40 q	4.9
		200	2	50 q	0.1
	Incorporated	0	2	59 q	10.7
		50	2	47 q	6.8
		100	3	60 q	2.0
		200	2	51 q	6.2

[z] TP = total phosphorus.
[y] Mean values within each site followed by the same letter are not significantly different at $P < 0.05$.
[x] SE = standard error.

Table 3. Mean post-treatment soil-test phosphorus (STP), manure total phosphorus (TP) and manure water-extractable phosphorus (WEP) of samples collected during initial runoff simulations.

Site	Incorporation method	Target TP rate (kg ha^{-1})	n	Post-treatment STP Mean[z]	Post-treatment STP SE[y]	Manure TP rate Mean	Manure TP rate SE[y]	Manure WEP rate Mean	Manure WEP rate SE[y]	Manure WEP:TP (%)
				--- (mg kg^{-1}) ---		--------------- (kg ha^{-1})	---------------			
Beaverlodge	Non-incorporated	0	3	45 b	4	0	0	0	0	-
		25	2	85 a	12	26	3	4	2	15
		50	3	96 a	19	53	3	8	3	15
		100	3	108 a	25	100	11	15	7	15
	Incorporated	0	4	48 b	2	0	0	0	0	-
		25	3	60 a	4	30	3	5	2	16
		50	3	83 a	10	50	5	10	3	20
		100	4	113 a	19	111	6	18	4	16
Lacombe	Non-incorporated	0	4	127 j	10	0	0	0	0	-
		50	3	169 j	7	45	5	9	4	21
		100	3	220 ij	17	101	26	18	2	18
		200	4	341 hi	39	168	13	47	12	28
	Incorporated	0	4	107 j	10	0	0	0	0	-
		50	3	144 j	8	37	2	9	3	25
		100	4	165 j	11	100	8	20	3	19
		200	3	395 h	90	188	12	68	20	36
Wilson	Non-incorporated	0	3	43 s	5	0	0	0	0	-
		50	3	160 s	16	132	10	33	10	22
		100	2	518 qrs	268	179	40	47	22	26
		200	2	2048 q	360	369	20	82	19	26
	Incorporated	0	2	61 s	17	0	0	0	0	-
		50	2	144 s	57	91	7	36	6	31
		100	3	366 rs	169	170	25	43	11	25
		200	2	625 qr	229	369	20	41	33	18

[z] Mean values within each site followed by the same letter are not significantly different at $P < 0.05$.
[y] SE = standard error.

Table 4. Mean runoff volume, total phosphorus (TP) flow-weighted mean concentration (FWMC) and dissolved reactive phosphorus (DRP) FWMC values for 30 min of runoff from the initial rainfall simulations.

Site	Incorporation method	Target TP rate (kg ha^{-1})	n	Runoff volume Mean[z]	Runoff volume SE[y]	TP FWMC Mean	TP FWMC SE[y]	DRP FWMC Mean	DRP FWMC SE[y]	DTP:TP FWMC
				----- (L) -----		---- (mg L^{-1}) ----		---- (mg L^{-1}) ----		(%)
Beaverlodge	Non-incorporated	0	3	37.6	7.5	0.89	0.17	0.09	0.03	10
		25	2	44.4	2.6	3.96	1.21	1.58	0.43	40
		50	3	54.1	1.7	4.49	0.52	1.88	0.32	42
		100	3	40.2	4.3	12.17	2.42	3.51	0.42	29
		Mean	*11*	*44.0 b*	-	-	-	-	-	-
	Incorporated	0	4	27.5	2.4	1.02	0.12	0.12	0.06	12
		25	3	18.5	1.4	1.30	0.29	0.17	0.04	13
		50	3	14.0	2.1	1.67	0.14	0.56	0.09	34
		100	4	19.3	3.2	3.20	0.53	0.97	0.40	30
		Mean	*14*	*20.3 a*	-	-	-	-	-	-
		Site Mean	*25*	*30.8*	-	-	-	-	-	-
Lacombe	Non-incorporated	0	4	15.3	1.7	2.16	0.14	1.52	0.14	70
		50	3	11.0	0.7	4.32	0.55	3.49	0.54	81
		100	3	28.7	6.7	9.87	0.89	8.79	0.59	89
		200	4	24.5	6.9	11.66	1.18	8.96	0.73	77
		Mean	*14*	*19.9 h*	-	-	-	-	-	-
	Incorporated	0	4	34.1	4.9	2.17	0.19	1.70	0.22	78
		50	3	17.4	2.0	5.54	0.46	3.77	0.45	68
		100	4	22.1	4.7	6.55	0.61	5.19	0.49	79
		200	3	35.5	6.5	12.08	1.81	10.90	2.40	90
		Mean	*14*	*27.4 h*	-	-	-	-	-	-
		Site Mean	*28*	*23.6*	-	-	-	-	-	-
Wilson	Non-incorporated	0	3	11.9	3.0	0.61	0.16	0.32	0.11	52
		50	3	20.0	1.6	5.89	0.20	4.72	0.32	80
		100	2	9.3	0.3	16.58	2.93	12.75	1.50	77
		200	2	11.5	2.2	23.86	0.14	19.02	0.02	80
		Mean	*10*	*13.2 q*	-	-	-	-	-	-
	Incorporated	0	2	15.8	3.4	1.44	0.16	0.49	0.23	34
		50	2	19.4	0.5	6.57	1.24	4.94	1.04	75
		100	3	14.7	3.6	9.09	2.96	7.17	2.28	79
		200	2	16.8	7.3	20.77	0.63	14.98	1.70	72
		Mean	*9*	*16.7 q*	-	-	-	-	-	-
		Site Mean	*19*	*14.9*	-	-	-	-	-	-

[z] Mean values within each site followed by the same letter are not significantly different at $P < 0.05$.
[y] SE = standard error.

The Beaverlodge mean runoff volume from the non-incorporated treatment was significantly greater than the mean volume from the incorporated treatment. A similar observation was reported by Daverede et al. (2003), who found that tilling with a chisel plow increased surface retention and infiltration rate of water in soils containing 25% clay on slopes of 6%. Soil textures at the Beaverlodge site were finer, ranging from clay loam to clay at the surface and clay to heavy clay below the A horizon (Appendix Table A1.1), with a similar hill slope of 5%. Other studies reporting greater runoff from untilled treatments compared to various types of tilled treatments include Mueller et al. (1984b), Freese et al. (1993), Myers and Wagger (1996), Gupta et al. (1997), and Little et al. (2005).

Mean runoff volumes at the Lacombe and Wilson sites were not significantly different between incorporated and non-incorporated treatments. The lack of an incorporation effect at the Lacombe site may have been due to soils with a higher infiltration rate caused by coarser textures. Particle-size analysis of Lacombe soil samples indicated loam to sandy clay loam textures (Appendix Table A1.3). A steeper hill slope (10%) at the Lacombe site may also have masked incorporation effects. Textures of the Wilson surface soils were clay loam to clay (Appendix Table A1.5), similar to the Beaverlodge site. However, Wilson soils below the A horizon were clay loam to clay, slightly coarser than Beaverlodge subsoils. Additionally, the Wilson site had a history of no-till management practices, known to increase infiltration rate (Seybold et al. 2002; Shaver et al. 2002). Hill slope at the Wilson site was approximately 6%, similar to the Beaverlodge site.

Similar to the Lacombe and Wilson sites, Gilley and Eghball (1998) reported no change in runoff volume between tilled and untilled treatments with recent manure application from a site with a long-term, no-till management history. Alternately, Seta et al. (1993), Kleinman et al. (2002a), and Michaud and Laverdière (2004) reported less runoff collected from untilled than tilled treatments conducted on soils with a variety of soil textures. While tillage may affect volume of runoff, pre-existing soil conditions tend to dictate the degree and nature of these effects relative to untilled soil.

Phosphorus in runoff. A positive relationship was observed between manure TP application rate and TP or DRP FWMC for incorporated and non-incorporated treatments at the three study sites (Table 4 and Appendix Tables A5.1 to A5.3 and A5.7 to A5.9). Several other studies have also observed increased phosphorus in runoff with increasing manure application rates, including various tillage practices and manure sources (Edwards and Daniel 1993; Eghball and Gilley 1999; Pote et al. 2001; Kleinman and Sharpley 2003; Tabbara 2003; Schroeder et al. 2004a; Tarkelson and Mikkelsen 2004).

Results of the mixed-model analysis indicate no significant differences in TP and DRP FWMC values between incorporated and non-incorporated unmanured treatments at the three sites (Figs. 7, 8, and 9). Concentrations of TP and DRP reported by Daverede et al. (2003) at comparable soil phosphorus levels also differed very little between chisel plow and no-till treatments. Total phosphorus and DRP FWMC significantly decreased with incorporation for the Beaverlodge manured treatments (Fig. 7), but showed no change for the Lacombe and Wilson manured treatments (Figs. 8 and 9). The Beaverlodge non-incorporated TP FWMC values increased with manure TP at a rate about six times greater than the incorporated TP FWMC values. The Beaverlodge non-incorporated DRP FWMC values increased with manure TP at a rate about four times greater than the incorporated TP FWMC values.

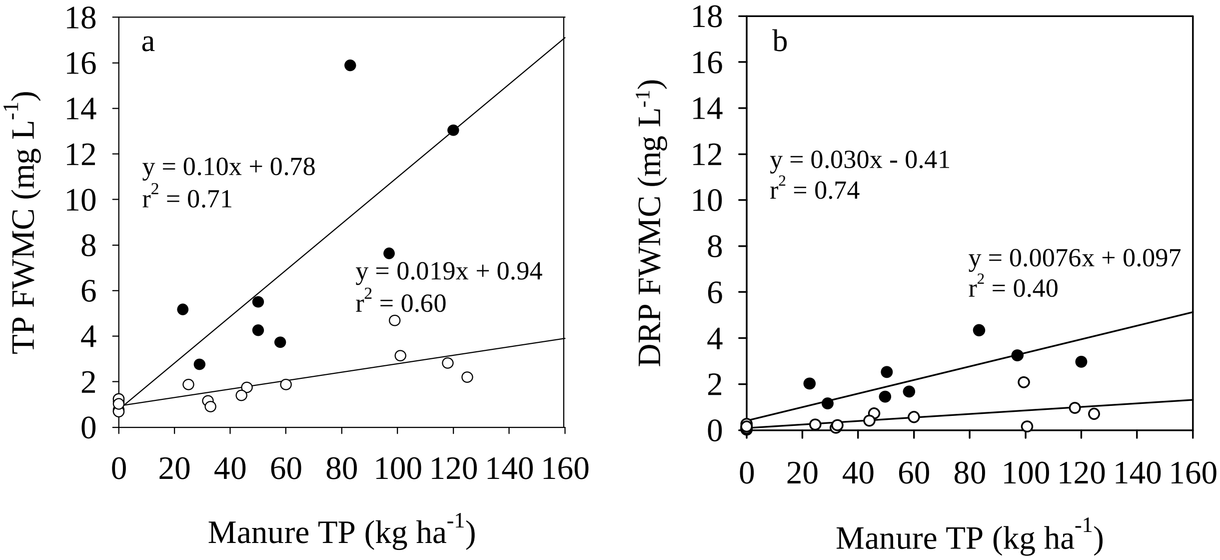

Fig. 7. Relationships between manure total phosphorus (TP) and (a) TP flow-weighted mean concentration (FWMC) and (b) dissolved reactive phosphorus (DRP) FWMC for non-incorporated (black dots) and incorporated (white dots) treatments from the initial rainfall simulations at the Beaverlodge site.

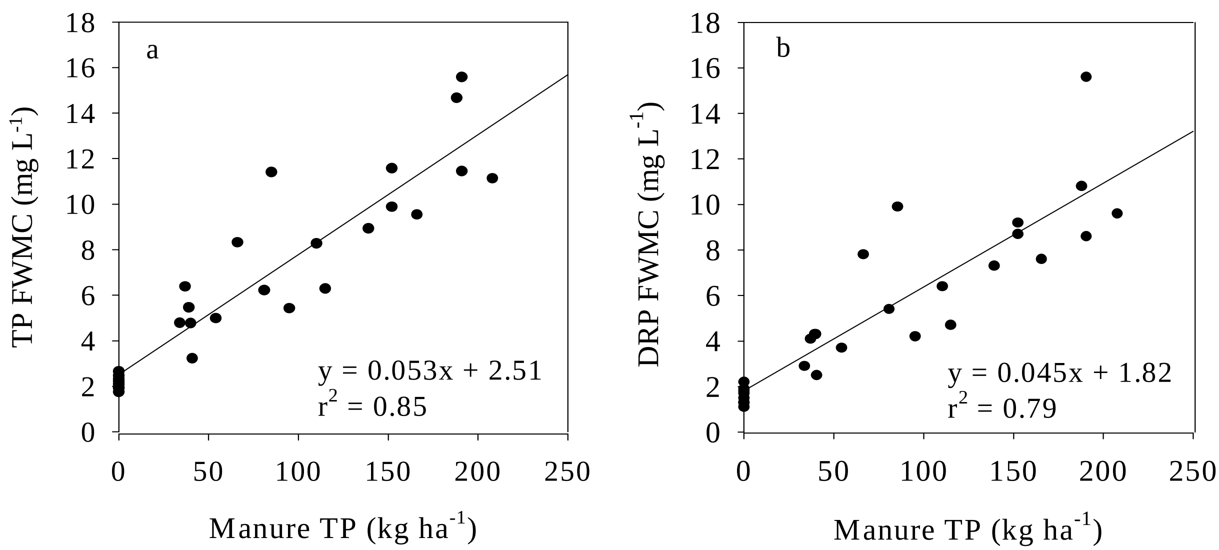

Fig. 8. Relationships between manure total phosphorus (TP) and (a) TP flow-weighted mean concentration (FWMC) and (b) dissolved reactive phosphorus (DRP) FWMC for non-incorporated and incorporated treatments from the initial rainfall simulations at the Lacombe site.

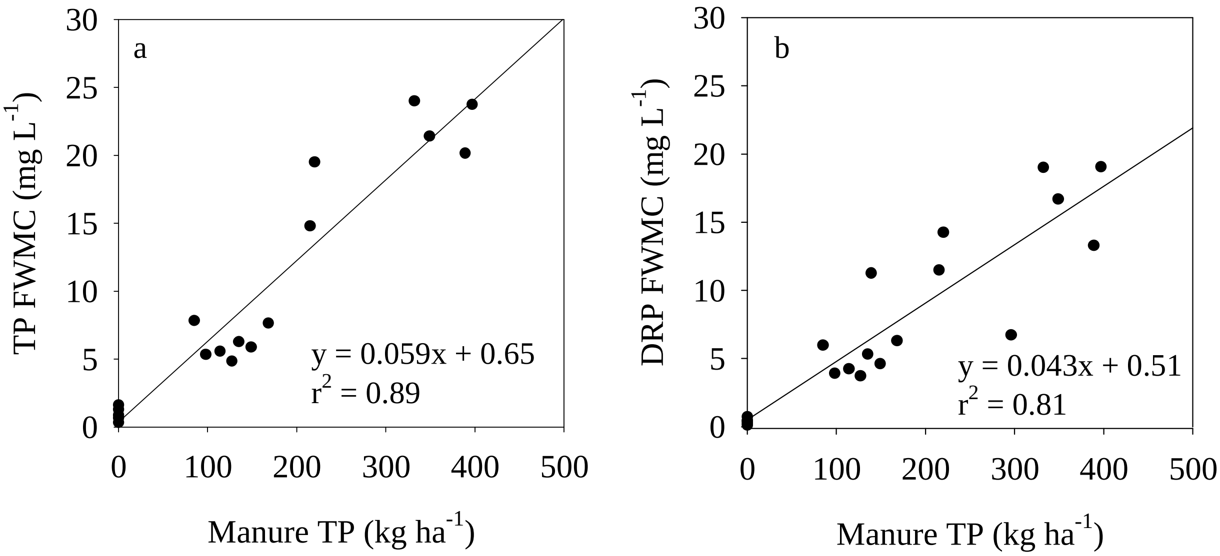

Fig. 9. Relationships between manure total phosphorus (TP) and (a) TP flow-weighted mean concentration (FWMC) and (b) dissolved reactive phosphorus (DRP) FWMC for non-incorporated and incorporated treatments from the initial rainfall simulations at the Wilson site.

Similar studies have reported a variety of runoff phosphorus responses to manure incorporation. Withers et al. (2001), Kleinman et al. (2002a), Tabbara (2003), and Daverede et al. (2004) observed decreased runoff TP and DRP concentrations with manure incorporation. Tarkalson and Mikkelsen (2004) also reported this difference in TP, but did not measure DRP concentrations. Mueller et al. (1984a) and Eghball and Gilley (1999) found decreases in DRP with incorporation, but increases in TP due to greater erosion.

Kleinman et al. (2002a) and Tabbara (2003) cite removal of phosphorus from the effective depth of interaction by incorporation as the primary cause of decreasing phosphorus in runoff. However, no significant STP differences in the upper 2.5-cm depth of the Beaverlodge soil profile were observed between incorporated and non-incorporated treatments. Therefore, factors such as soil infiltration rate or time required to induce runoff may have contributed to the reduction of DRP concentrations with incorporation rather than manure burial.

Concentrations of TP and DRP from the Beaverlodge non-incorporated treatments were similar to concentrations from the Lacombe and Wilson sites, while concentrations from the Beaverlodge incorporated treatments were considerably lower. Dissolved reactive phosphorus concentrations accounted for a large portion of TP in runoff from the Lacombe and Wilson sites, but accounted for less than half the TP concentrations from the Beaverlodge site (Table 4). Runoff from unmanured treatments at the Beaverlodge and Wilson sites had notably lower DRP:TP ratios than from manured treatments. The proportion of DRP in runoff relative to TP concentrations varied little between incorporated and non-incorporated treatments.

Similar experiments involving recently applied manure revealed much variation of DRP:TP ratios in runoff. Schroeder et al. (2004a) reported DRP fractions greater than half of the TP in runoff from broadcast poultry manured soils. Kleinman et al. (2002a) also reported DRP concentrations greater than half TP from broadcast and incorporated dairy, poultry, and swine manured soils, but DRP concentrations less than half of TP from unmanured soils. Kleinman and Sharpley (2003) found DRP concentrations generally greater than half of TP from broadcast dairy, poultry, and swine manured and unmanured soils using one soil type, but found DRP concentrations less than half of TP from another soil type. These variable results were most likely caused by a number of factors influencing erosivity of the soils in each experiment.

The DRP and TP loads at all three sites increased in response to manure application and incorporation, but with greater variability than concentrations due to variable runoff volumes. Similar observations were reported by Pote et al. (1996) and Daverede et al. (2003, 2004). Mueller et al. (1984a) and Schroeder et al. (2004a) also observed phosphorus loads differing from phosphorus concentrations in runoff due to treatment or extraneous effects on runoff volume and rate.

Soil and manure phosphorus as predictors of phosphorus in runoff. A select group of soil and manure phosphorus measurements and calculated parameters were evaluated regarding their ability to predict phosphorus concentration in runoff. These included pre-treatment STP (mg kg^{-1}), post-treatment STP (mg kg^{-1}), applied WEP in manure (kg ha^{-1}), applied TP in manure (kg ha^{-1}), pre-treatment STP plus WEP in manure (kg ha^{-1}), and pre-treatment STP plus TP in manure (kg ha^{-1}). For the comparisons of STP to phosphorus in runoff at the Wilson site, measurements from two non-incorporated plots were removed from the data set because their STP values were two and three times greater than the highest STP values measured from the incorporated plots. The remaining post-treatment STP measurements used to determine the relationship between STP and phosphorus in runoff at the Wilson site were less than 1000 mg kg^{-1}.

Results of mixed-model analysis showed no significant relationship between the pre-treatment STP values and TP or DRP FWMC at any of the three sites. This was expected since the TP and DRP FWMC values were largely influenced by the recently applied manure. Kleinman et al. (2002a) stated that the amendment, rather than the soil, serves as the major source of phosphorus in runoff from soils that received recent surface applications of phosphorus. Bundy et al. (2001) also concluded that recent manure applications tended to mask the relationship between pre-application STP and phosphorus in runoff.

Positive relationships were observed between the remaining five predictors and TP and DRP FWMC for all three sites. Effects of manure rate and incorporation on the relationships involving post-treatment STP, manure WEP, pre-treatment STP plus manure WEP, and pre-treatment STP plus manure TP as independent variables were similar to those discussed with manure TP in the previous section.

When measurements for the two non-incorporated treatments with post-treatment STP values greater than 1000 mg kg^{-1} were included in the STP to TP and DRP FWMC relationships at the Wilson site, there appeared to be a nonlinear relationship (Fig. 10). However, this trend was not supported by the relationships observed for manure TP to phosphorus in runoff. Daverede et al. (2003) noted that many studies have reported linear relationships between lower STP values and

DRP in runoff; however, Daverede et al. (2003) observed a nonlinear (S-curve) relationship involving STP values greater than 1000 mg kg^{-1} on no-till plots.

Of the predictors reviewed, the strongest relationship to TP and DRP FWMC at all three sites was with manure TP, with r^2 values ranging 0.40 to 0.89 (Table 5). Adding the pre-treatment STP values to manure TP did little to improve the strength of the relationship for each site. Relationships using post-treatment STP as the independent variable tended to have slightly lower r^2 values ranging from 0.45 to 0.80 (Table 5). The poorest relationships observed were between manure WEP and DRP FWMC at the Beaverlodge, Lacombe, and Wilson sites, with r^2 values ranging from 0.07 to 0.46 (Table 5). The sum of pre-treatment STP and manure WEP did not improve the relationship with DRP FWMC for any of the three sites. Similar studies have found a strong linear relationship between water-soluble phosphorus concentrations in manure and DRP concentrations in runoff (Kleinman et al. 2002a; DeLaune et al. 2004). DeLaune et al. (2004) observed that this relationship was even stronger than the relationship of TP concentrations in manure to DRP concentrations in runoff. Kleinman and Sharpley (2003) found similar results but noted that DRP concentrations in runoff did not correlate well with application rate of WEP in dairy manure, poultry manure, and swine slurry.

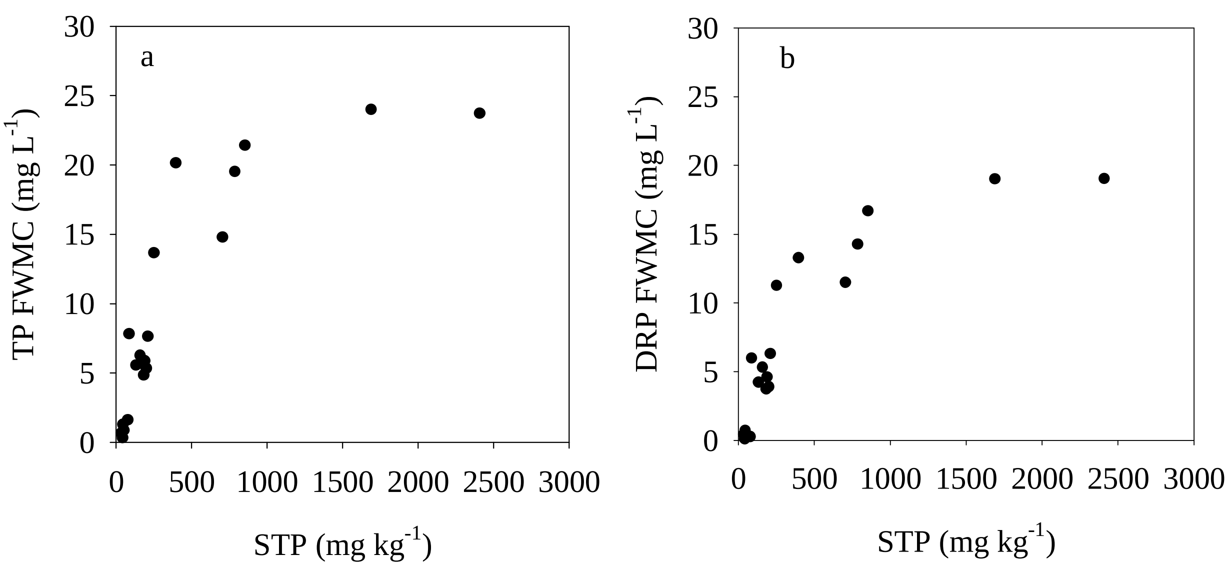

Fig. 10. Relationships between soil-test phosphorus (STP) and (a) total phosphorus (TP) flow-weighted mean concentration (FWMC) and (b) dissolved reactive phosphorus (DRP) FWMC for the non-incorporated treatment including STP values greater than 1000 mg kg^{-1} from the initial rainfall simulations at the Wilson site.

Table 5. Relationships of post-treatment soil-test phosphorus (STP), manure total phosphorus (TP), pre-treatment STP plus manure TP, manure water-extractable phosphorus (WEP), and pre-treatment STP plus manure WEP to TP and dissolved reactive phosphorus (DRP) flow-weighted mean concentration (FWMC) in runoff from the initial rainfall simulations.

		TP FWMC (mg L^{-1})		DRP FWMC (mg L^{-1})	
Source variable (x)	Site	Equation[z,y]	r^2	Equation[z]	r^2
Post-treatment STP (mg kg^{-1})	Beaverlodge	y_{ni} = 0.1095x - 3.6409	0.64	y_{ni} = 0.0316x - 0.8618	0.66
		y_i = 0.0236x + 0.0328	0.53	y_i = 0.0131x - 0.5391	0.65
	Lacombe	y = 0.0256x + 1.3724	0.50	y = 0.0218x + 0.8853	0.45
	Wilson	y = 0.0238x + 1.9170	0.79	y = 0.0181x + 1.3665	0.80
Manure TP (kg ha^{-1})	Beaverlodge	y_{ni} = 0.1019x + 0.7786	0.71	y_{ni} = 0.0295x - 0.4118	0.74
		y_i = 0.0186x + 0.9351	0.60	y_i = 0.0076x + 0.0968	0.40
	Lacombe	y = 0.0527x + 2.5126	0.85	y = 0.0454x + 1.8222	0.79
	Wilson	y = 0.0593x + 0.6522	0.89	y = 0.0428x + 0.5107	0.81
Pre-treatment STP + manure TP (kg ha^{-1})[x]	Beaverlodge	y_{ni} = 0.1022x - 0.3171	0.71	y_{ni} = 0.0297x + 0.0898	0.74
		y_i = 0.0186x + 0.7280	0.61	y_i = 0.0076x + 0.0102	0.41
	Lacombe	y = 0.0526x + 1.0054	0.84	y = 0.0454x + 0.5127	0.78
	Wilson	y = 0.0590x - 0.2105	0.89	y = 0.0455x - 0.2506	0.87
Manure WEP (kg ha^{-1})	Beaverlodge	nr	nr	y_{ni} = 0.1043x + 1.0482	0.43
		nr	nr	y_i = 0.0164x + 0.3291	0.07
	Lacombe	nr	nr	y = 0.0866x + 3.5716	0.37
	Wilson	nr	nr	y = 0.1408x + 2.3810	0.46
Pre-treatment STP + manure WEP (kg ha^{-1})[x]	Beaverlodge	nr	nr	y_{ni} = 0.1021x - 0.0153	0.41
		nr	nr	y_i = 0.0188x + 0.1016	0.09
	Lacombe	nr	nr	y = 0.0793x + 1.4311	0.33
	Wilson	nr	nr	y = 0.1548x + 0.1872	0.50

[z] ni = non-incorporated; i = incorporated.
[y] nr = comparison not relevant.
[x] STP concentration values in the top 2.5 cm were first converted from mg kg^{-1} to kg ha^{-1} using an assumed soil bulk density of 1.2 Mg m^{-3} and then added to the manure TP and WEP application rates.

Second Rainfall Simulations – One-year Residual Manure

Soil characteristics. Soil-test phosphorus values after 1 yr (Table 6 and Appendix Table A6.1) were generally lower and less variable than STP values immediately after manure application (Table 3). Most STP values decreased, with the reduction ranging from less than 1% to 62%. Gaston et al. (2003) also observed decreased levels of phosphorus in soils 2 yr after the cessation of applying poultry manure, which was applied annually for 1 to more than 20 yr prior to cessation. In our study, five plots, among the three sites, had increased STP values, with the increase ranging from 2 to 21%. As in the initial rainfall simulations, the lowest STP values were observed at the Beaverlodge site and the highest values were observed at the Wilson site. There

Table 6. Mean post-treatment soil-test phosphorus (STP), runoff volume, total phosphorus (TP) flow-weighted mean concentration (FWMC), and dissolved reactive phosphorus (DRP) FWMC values 1 yr after manure application.

Site	Incorporation method	Target TP rate (kg ha^{-1})	n	Post-treatment STP Mean[y] (mg kg^{-1})		Post-treatment STP SE[x]	Runoff volume[z] Mean[y] (L)	Runoff volume SE[x]	TP FWMC[z] Mean (mg kg^{-1})	TP FWMC SE[x]	DRP FWMC[z] Mean (mg kg^{-1})	DRP FWMC SE[x]	DRP:TP FWMC (%)
Beaverlodge	Non-Incorporated	0	3	42	c	2.3	41.5	9.9	0.77	0.08	0.41	0.09	50
		25	4	51	bc	4.2	44.2	7.0	0.88	0.13	0.6	0.1	67
		50	4	73	ab	10.0	34.5	7.7	1.10	0.09	0.8	0.1	73
		100	3	95	a	7.4	44.3	4.0	1.28	0.07	0.94	0.18	69
		Mean	*14*	-		-	*41.1 a*	-	-	-	-	-	-
	Incorporated	0	4	45	bc	5.2	33.9	5.1	0.85	0.08	0.6	0.1	75
		25	4	57	bc	5.7	32.8	6.8	1.08	0.15	0.7	0.2	64
		50	4	71	abc	0.7	47.0	6.4	1.20	0.12	0.9	0.1	75
		100	4	93	a	8.7	36.4	6.1	1.37	0.25	1.0	0.2	71
		Mean	*16*	-		-	*37.5 a*	-	-	-	-	-	-
		Site mean	*30*	-		-	*39.3*	-	-	-	-	-	-
Lacombe	Non-incorporated	0	4	134	ij	10.5	24.3	3.7	1.59	0.20	1.01	0.18	62
		50	4	165	hij	23.4	20.9	7.3	2.80	0.63	1.69	0.15	61
		100	4	219	hij	24.7	21.4	6.0	3.03	0.21	2.43	0.11	80
		200	3	272	h	19.3	24.9	4.9	4.90	0.46	3.74	0.66	76
		Mean	*15*	-		-	*22.9 h*	-	-	-	-	-	-
	Incorporated	0	4	109	j	11.0	22.0	4.3	1.31	0.19	0.80	0.07	62
		50	3	124	ij	10.6	13.3	1.4	1.54	0.16	0.93	0.18	60
		100	2	154	hij	17.3	19.5	4.3	1.94	0.12	1.36	0.30	74
		200	4	243	hi	51.0	12.2	1.7	4.30	0.67	3.19	0.67	74
		Mean	*13*	-		-	*16.8 h*	-	-	-	-	-	-
		Site mean	*28*	-		-	*19.8*	-	-	-	-	-	-
Wilson	Non-incorporated	0	4	45	t	2.5	14.1	3.1	0.67	0.26	0.44	0.20	57
		50	4	194	st	23.6	20.1	3.0	2.43	0.41	2.02	0.37	83
		100	3	348	rs	82.0	20.1	6.7	4.52	1.26	3.93	1.24	87
		200	4	779	qr	175.3	11.1	2.3	4.62	1.02	3.92	0.86	85
		Mean	*15*	-		-	*16.3 q*	-	-	-	-	-	-
	Incorporated	0	4	54	t	5.0	19.8	6.3	0.79	0.27	0.32	0.14	38
		50	4	151	st	26.6	16.3	2.5	1.64	0.27	1.23	0.21	75
		100	4	279	s	27.3	13.1	3.4	1.93	0.77	1.55	0.68	84
		200	4	564	q	75.0	12.0	9.4	7.33	1.71	6.73	1.74	92
		Mean	*16*	-		-	*15.3 q*	-	-	-	-	-	-
		Site mean	*31*	-		-	*15.8*	-	-	-	-	-	-

[z] Mean values are for 30 min of runoff.
[y] Mean values within each site followed by the same letter are not significantly different at $P < 0.05$.
[x] SE = standard error.

were very few differences in STP values from the unmanured treatments at each site during both simulations.

Soil-test phosphorus values for the second rainfall simulations increased with the rate of manure TP originally applied at all three sites, whether or not the manure was incorporated. The overall increase in STP on manured treatments compared to the unmanured treatments was expected since the amount of phosphorus applied was in excess of crop requirement. The STP values in the non-incorporated treatments tended to be greater than the STP values in the incorporated treatments, though the differences were not significant. This supports the observation from the initial rainfall simulations that minimal burial of phosphorus below the 2.5-cm sampling depth occurred with one pass of the double disk.

Crop residue and soil-test phosphorus. Questions arising from modifications between pre- and post-treatment soil sampling methods of this study prompted additional sample collection prior to the second year of rainfall simulations. Differences between STP from screened and unscreened soil samples approximately represented the phosphorus contributions of crop residue to STP measurements. No significant differences were found between mean STP values of unscreened and screened samples calculated for each site (Table 7). Though unscreened STP treatment means from the Lacombe site tended to be greater than screened means, this difference was not statistically significant (Appendix Tables A6.1 and A6.2). As well, STP values of individual soil samples from the Lacombe site, analyzed before and after screening, did not consistently support this trend. Based on these results, the contributions of surface plant material to STP values of the soil samples were considered negligible. The post-treatment STP values of the second rainfall simulations discussed subsequently in this report are from analysis conducted on unscreened soil samples.

Table 7. Mean soil-test phosphorus (STP) values of unscreened and screened samples collected 1 yr after manure application and incorporation from the three study sites.

		Unscreened STP		Screened STP	
		Mean[z]	SE[y]	Mean[z]	SE[y]
Site	n	----------(mg kg^{-1})----------		----------(mg kg^{-1})----------	
Beaverlodge	32	65.6 a	3.8	66.8 a	4.1
Lacombe	31	189.6 h	16.5	178.0 h	15.3
Wilson	32	313.0 q	50.2	316.2 q	44.5

[z] Mean values followed by the same letter are not significantly different at $P < 0.05$.
[y] SE = standard error.

Runoff volume. Mean runoff volumes for the incorporated and non-incorporated treatments, 1 yr after manure application, were not significantly different at any of the three sites (Table 6 and Appendix Tables A4.4 to A4.6). Mean runoff volumes for incorporated and non-incorporated treatments at the Beaverlodge site for 1-yr residual manure were similar to the initial results for the non-incorporated treatments with fresh manure. As the site was not tilled immediately prior to the second simulation tests, all treatments had similar surface conditions, characterized by reduced surface roughness compared to conditions when manure was first applied and incorporated. Reduced surface roughness can result in less surface retention of water (Mohamoud et al. 1990; Daverede et al. 2003).

The greater runoff volumes observed at the Beaverlodge site compared to the other sites also indicate lower soil infiltration rates, likely a result of different soil conditions. Lower infiltration rates were expected from the fine-textured Beaverlodge soils compared to the more coarse-textured Lacombe soils. Though the Beaverlodge and Wilson soil textures were similar in the A horizon, the Beaverlodge site had finer B horizon textures due to translocated clay, which is characteristic of Luvisolic soils. This translocated clay may have impeded infiltration below the A horizon. Additionally, the Beaverlodge site was managed with conventional tillage practices while the Wilson site had a history of no-till management, known to enhance macropore development and thus infiltration. The Lacombe and Wilson soils were also classified as Chernozemic, typically containing greater amounts of organic matter than Luvisolic soils. Organic matter can increase soil structure development, increasing soil infiltration. Finally, greater amounts of sodium in the Beaverlodge soil profile compared to the Lacombe and Wilson sites resulted in a greater potential for soil dispersion, which could reduce infiltration.

Runoff volumes for the non-incorporated treatments at the Lacombe site were generally greater from the second rainfall simulations than from those observed during the initial simulations. The 100 kg ha^{-1} treatment had lower runoff volumes from the second simulations than the initial simulations, and the 200 kg ha^{-1} treatment had a small increase in runoff volume from the initial to the second rainfall simulations. Runoff volumes for the incorporated treatments decreased for all manure treatments from the initial to the second rainfall simulations. The decrease for the incorporated treatments may have been caused by the lack of tillage furrows 1 yr after incorporation. These furrows, created when manure was first applied and incorporated, ran parallel to the 10% slopes and aided in moving water more quickly. Alternately, ridges across the slope on the soil surface can act as sediment traps and natural barriers to surface runoff (Romkens et al. 1973; Mahamoud 1990; Daverede et al. 2003). During the second rainfall simulations, the incorporated treatments reacted in a manner similar to the non-incorporated treatments.

At the Wilson site, runoff volumes from the non-incorporated treatments during the second rainfall simulations were generally greater than those observed in the initial rainfall simulations, while volumes from the incorporated treatments were less than those observed in the initial simulations, though differences were small. Incorporation of manure before the initial rainfall simulations on this no-till managed field likely affected surface structure of the soils and reduced infiltration. One exception was the unmanured incorporated treatments, which showed increased runoff volumes in the second rainfall simulations compared to the initial simulations. For the non-incorporated treatments, the effect of the manure in absorbing water may have resulted in the lower runoff volumes from the initial than the second simulations when the manure was degraded and had been somewhat incorporated through seeding practices. Similar surface conditions for all treatments in the second rainfall simulations resulted in little difference in runoff volume.

Phosphorus in runoff. The TP FWMC and DRP FWMC values at all three sites increased in relation to increased manure TP rate, as observed with fresh manure; however, the increases among rates were not as large as observed with fresh manure (Table 6 and Appendix Tables A5.4 to A5.6 and A5.10 to A5.12). Compared to the initial rainfall simulations, TP FWMC values from the second simulations were generally lower. The non-incorporated unmanured treatments generally showed a small decrease in TP FWMC compared to the initial simulations on fresh manure. The TP FWMC values from the second simulations for the remaining treatments decreased from 1.5 to 9.4 times compared to the initial simulations. The incorporated treatments did not show the same magnitude of decrease, with TP FWMC decreasing from 1.2 to 4.9 times. The unmanured incorporated treatment showed a greater decrease than the unmanured non-incorporated treatment from the initial to the second rainfall simulations.

Dissolved reactive phosphorus concentrations generally accounted for a large portion of TP in runoff from all three sites (Table 6). The proportion of DRP in runoff relative to TP concentrations varied little between incorporated and non-incorporated treatments and with manure application rate. The DRP:TP ratio increased notably at the Beaverlodge site from the initial to the second rainfall simulations; however, little change was observed at the Lacombe and Wilson sites between simulations.

Inasmuch as the surface-applied manure remained in the upper portion of the soil profile, it was readily available for interaction with water. The soil mixing that occurred after the initial manure application and subsequently, due to farming practices, resulted in greater mixing of the manure and soil. In a similar study, Sharpley (2003) observed that the mixing of the soil material served to dilute the manure and potentially reduced the risk of phosphorus enrichment of the runoff. The results of this study were also similar to those of Daverede et al. (2004) who observed a decrease in TP concentration between 1 and 6 mo after application. They also observed a larger decrease in TP concentration in non-incorporated treatments compared to incorporated treatments. Kleinman and Sharpley (2003) found there was a decrease in DRP and TP concentrations with successive rainfall events. They noted that runoff was not the sole cause of the decrease, but that sorption of applied phosphorus by the soil may also have been a factor.

Soil phosphorus as a predictor of phosphorus in runoff. While several predictors of phosphorus in runoff were examined after the initial rainfall simulations (Table 5), only the STP and TP or DRP FWMC relationships were examined with the 1-yr residual manure data. It was thought that the relationship between the other potential indicators and phosphorus concentrations in runoff would not be of consequence given the length of time since the manure had been applied and the field activities that had been carried out.

Positive linear relationships were observed between STP and TP FWMC and STP and DRP FWMC at all three sites. There were no significant differences among the incorporated and non-incorporated treatments imposed the previous year. The TP relationship was weak at the Beaverlodge site (Fig. 11), while the Lacombe site exhibited a stronger relationship, with an r^2 value of 0.59 (Fig. 12). The Wilson site had the strongest relationship between STP values less than 800 mg kg^{-1} and TP FWMC, with an r^2 value of 0.71 (Fig. 13).

As for the comparisons of STP to TP and DRP in runoff from the initial Wilson rainfall simulations, measurements from two non-incorporated plots were removed from the data set because their STP values were much greater than the highest STP values measured from the incorporated plots. The remaining STP measurements were less than 800 mg kg^{-1}. As observed for the initial simulations, when measurements for the two non-incorporated plots were included in the STP to TP and DRP FWMC relationships, there appeared to be a nonlinear relationship.

Daverede et al. (2003) also observed a nonlinear trend with large STP values and suggested that the leveling off of the curve may indicate a point at which the maximum phosphorus able to be placed into solution within the time frame of the rainfall simulation was being approached.

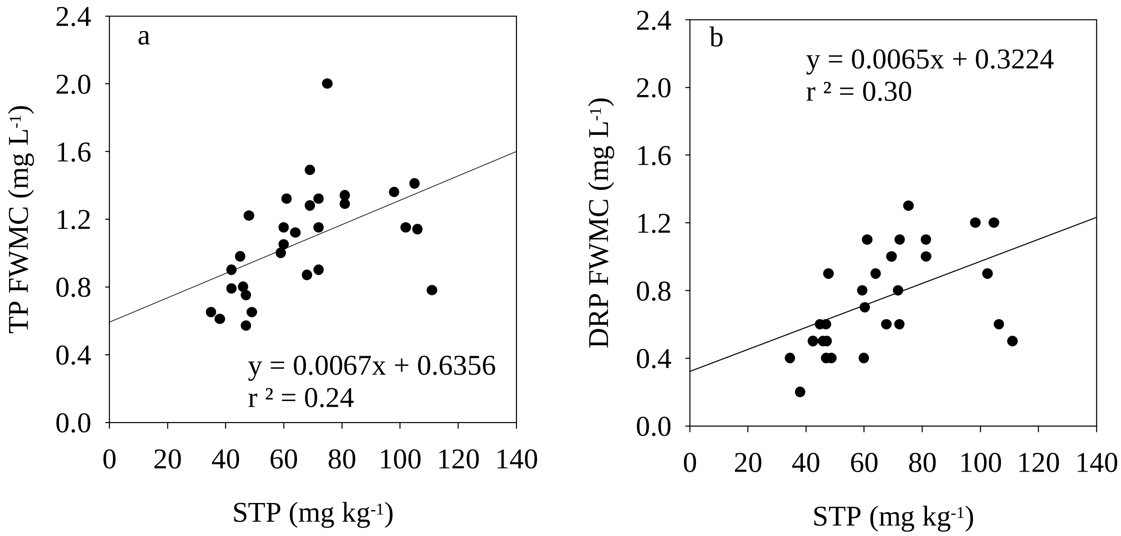

Fig. 11. Relationship between post-treatment soil-test phosphorus (STP) and (a) dissolved reactive phosphorus (DRP) flow-weighted mean concentration (FWMC) and (b) total phosphorus (TP) FWMC for non-incorporated and incorporated treatments from the second rainfall simulations at the Beaverlodge site.

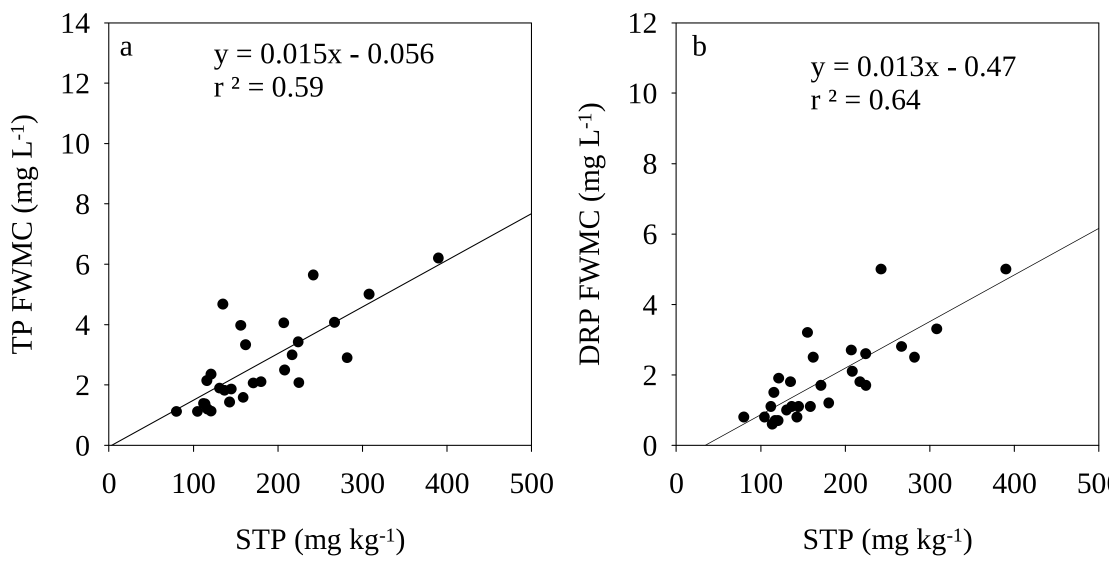

Fig. 12. Relationship between post-treatment soil-test phosphorus (STP) and (a) dissolved reactive phosphorus (DRP) flow-weighted mean concentration (FWMC) and (b) total phosphorus (TP) FWMC for non-incorporated and incorporated treatments from the second rainfall simulations at the Lacombe site.

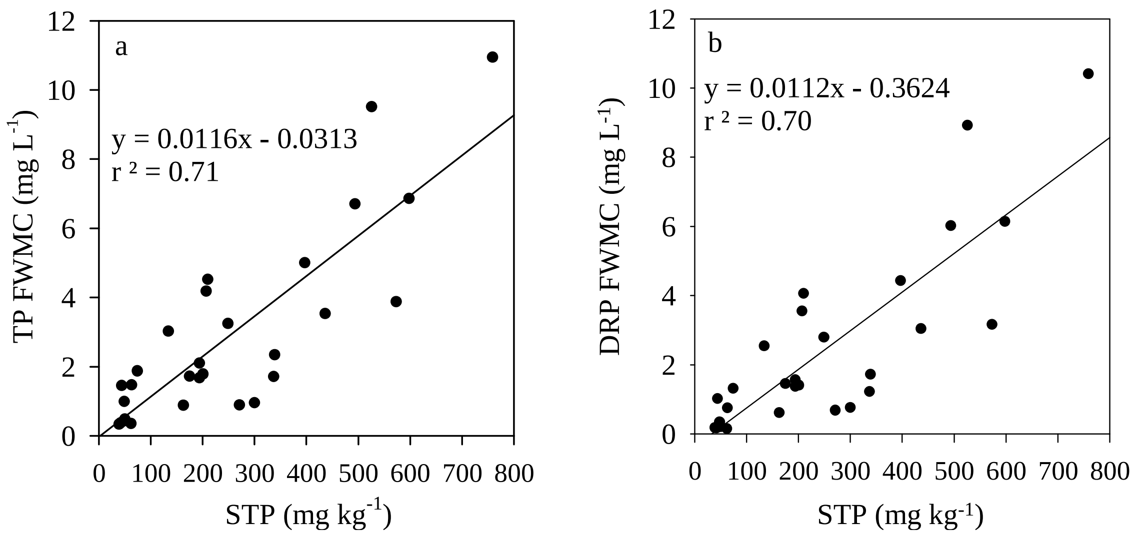

Fig. 13. Relationship between post-treatment soil-test phosphorus (STP) and (a) dissolved reactive phosphorus (DRP) flow-weighted mean concentration (FWMC) and (b) total phosphorus (TP) FWMC for non-incorporated and incorporated treatments from the second rainfall simulations at the Wilson site.

The overall trend observed at all of the sites was a decrease in TP and DRP FWMC in runoff from the initial to the second rainfall simulations. Studies carried out by Pote et al. (1996), Schroeder et al. (2004b), and Vadas et al. (2005a) indicate that there are many variables that can affect the relationship between STP and phosphorus in runoff. These can include variability in soil properties, phosphorus adsorption, calcium carbonate content of the soil, hydrology, antecedent moisture conditions, and management practices (Vadas et al. 2005a). While the recent addition of phosphorus to soils can overshadow the relationship between STP and phosphorus in runoff, the relationship becomes stronger with time as equilibrium is reached (Vadas et al. 2005a).

The lower STP values at the Beaverlodge site, coupled with high soil clay content, may have resulted in the low phosphorus concentrations in the runoff at that site. Cox and Hendricks (2000) found that higher clay content in soil required higher STP levels to achieve a target level of dissolved phosphorus in the runoff water. Soils with a low clay content may adsorb phosphorus more weakly than high clay content soils; therefore, phosphorus may be more readily removed by runoff water (Vadas et al. 2005a). The lower STP values and the time between the simulations would also result in reduced phosphorus being available for removal as phosphorus is taken up by crop as well as removed by snowmelt and rainfall runoff. Kleinman and Sharpley (2003) observed that DRP concentrations decreased with successive rainfall runoff events. While the soils at the Wilson site also had a high percentage of clay in the soil, the STP values were much larger, meaning that more phosphorus was available for removal, which resulted in higher phosphorus concentrations in runoff at the Wilson site compared to the Beaverlodge site.

Additionally, the greatest mean runoff volumes were observed at the Beaverlodge site, which may have resulted in lower phosphorus concentrations due to dilution.

Soil sampling depth and soil phosphorus. Mean STP values from the unmanured treatments (0 rate) were similar among soil layers at the Beaverlodge site, and decreased with depth at the Lacombe and Wilson sites (Table 8 and Appendix 7). Mean STP values within the incorporated manured treatments decreased with depth (Table 8). The STP concentration in the 0- to 2.5-cm layer was 1.3 to 2.9 times higher than in the 0- to 15-cm layer for the manured treatments. A similar increase was reported by Guertal et al. (1991) who measured up to three times greater STP concentrations in the 0- to 2-cm layer than in the 0- to 8-cm layer of soil. Phosphorus tends to be more concentrated near the soil surface since the dilution of STP with lower horizons by tillage has been shown to reduce STP levels with time (Kleinman et al. 2002a) and because of the limited mobility of phosphorus in soil (Sharpley 1985). The variability of STP within the manured treatments at all three sites was generally greatest for the 0- to 2.5-cm layer. The largest decreases in STP with depth were observed at the highest manure rates at all three sites.

Table 8. Mean soil-test phosphorus (STP) for three soil layers from selected target manure total phosphorus (TP) rates of incorporated treatments 1 yr after manure application.

Site	Target TP rate (kg ha^{-1})	n	STP (0 to 2.5 cm) Mean	SE[z]	STP (0 to 5 cm) Mean	SE[z]	STP (0 to 15 cm) Mean	SE[z]
			------------------------------ (mg kg^{-1}) ------------------------------					
Beaverlodge	0	4	40	2	37	3	37	5
	50	4	55	6	47	4	42	3
	100	4	74	13	57	7	44	3
Lacombe	0	4	99	12	90	9	68	8
	100	4	152	28	132	17	91	5
	200	4	233	34	212	28	130	13
Wilson	0	4	47	4	44	5	32	7
	100	4	232	50	198	32	104	10
	200	4	553	241	424	176	192	70

[z] SE = standard error.

Significant relationships were found between STP in the three soil layers and TP concentrations in runoff at the Beaverlodge and Wilson sites (Table 9). Relationships for the individual soil layers at the Lacombe site were not significant (Table 9). Similar coefficients of determination (r^2) were observed for all three layers at the Wilson site. At the Beaverlodge site, the highest r^2 values were observed for the shallowest layers and the lowest r^2 value was observed for the deepest layer. These results indicate that the predictive relationship with TP concentrations did not improve using STP levels from the different soil layers, except for the two surface layers at the Beaverlodge site.

Table 9. Relationships between soil-test phosphorus (mg kg^{-1}) sampled from different depth intervals and total phosphorus (mg L^{-1}) in runoff (n = 24) 1 yr after manure application.

Site	Depth of layer	Slope[z]	SE[y]	Intercept[z]	SE	r^2	Prob > F
Beaverlodge	0 to 2.5 cm	0.02a	0.004	0.32a	0.22	0.66	0.0013
	0 to 5 cm	0.03a	0.006	-0.13a	0.31	0.84	0.0001
	0 to 15 cm	0.03a	0.010	-0.04a	0.42	0.37	0.0365
Lacombe	0 to 2.5 cm	0.01a	0.006	0.74a	1.13	0.26	0.1341
	0 to 5 cm	0.02a	0.007	0.48a	1.15	0.29	0.1062
	0 to 15 cm	0.03a	0.014	-0.44a	1.46	0.30	0.0988
Wilson	0 to 2.5 cm	0.01a	0.002	1.08a	0.93	0.60	0.0033
	0 to 5 cm	0.01a	0.003	0.90a	0.97	0.58	0.0038
	0 to 15 cm	0.03a	0.007	0.38a	1.07	0.58	0.0037

[z] Values within each column per site followed by the same letter are not significantly different at $P < 0.05$.
[y] SE = standard error.

Extraction coefficients (slopes) of the relationships between STP and TP FWMC in runoff increased with the depth of soil layer at all three sites (Table 9). However, results of the test of the homogeneity of the slopes showed that the differences among the three layers were not significant at any of the sites. While not significant ($P = 0.056$), there was a tendency towards an increase in the slope for the 0- to 15-cm soil layer compared with the slopes for the other two layers at the Wilson site, where there was a history of no-till and the highest levels of manure were applied. In addition to the homogenous slopes, no significant differences were detected among y-intercepts, indicating that TP FWMC values were similar at any given STP value, regardless of sampling depth (Table 9). The high variability of STP measurements, particularly in the two surface depths, may have obscured any effects of sampling depth on the STP to TP FWMC relationships.

Andraski and Bundy (2003), as reported in a review by Vadas et al. (2005b), showed greater extraction coefficients for the relationships between STP in the 0- to 15-cm soil layer and DRP concentrations in simulated runoff compared with STP in the 0- to 2.5-cm layer; however, they concluded that higher STP levels in the shallow layers did not improve relationships with DRP compared with those measured in the 0- to 15-cm layer. In a review of rainfall simulation studies on 30 soils with reduced tillage or tilled soils, Vadas et al. (2005a) also found that STP measured from the shallow stratified samples (0 to 5 cm) of the reduced tillage soils gave a similar assessment of STP and DRP in runoff as deeper samples (0 to 15 cm) of the tilled soils. Torbert et al. (2002) reported a greater extraction coefficient for the relationship between STP in the 0- to 15-cm soil layer and DRP in runoff than extraction coefficients for the 0- to 2.5- and 0- to 5-cm layers, but their study was conducted after manure was surface applied with no incorporation.

Soil-test phosphorus in the 0- to 2.5-cm and 0- to 5-cm soil layers was greater than STP in the 0- to 15-cm layer. The STP in the 0- to 2.5-cm layer may have the greater influence on TP

FWMC in runoff because the depth of interaction with runoff water is generally within the top centimeter of soil (Sharpley 1985). However, the relationship between STP in the 0- to 2.5-cm layer and TP FWMC in runoff did not improve compared to the relationship with STP in the 0- to 15-cm layer. The reason for this may have been the high variability of STP in manured conditions, which was increased by the difficulty of obtaining an accurate sample at shallow depths, particularly where soil surfaces were rough due to tillage. This was reflected in the greater variability of STP values in the most heavily manured treatments and shallowest sampling depth (Table 8).

Comparison of Extraction Coefficients from Other Studies

The relationships in this study involving STP as the independent variable in relation to TP and DRP FWMC in runoff were compared to similar published studies (Tables 10 and 11). Few studies have reported STP relationships with TP FWMC. Though more studies have reported STP relationships with DRP FWMC, variations in soil type, analytical and rain simulation methods, and management practices make comparisons difficult.

Extraction coefficients (slopes) of the relationships between STP and TP or DRP FWMC decreased from the fresh to the residual manure rain simulations at all three sites. Sharpley and Tunney (2000) reported that recent applications of manure and fertilizer could temporarily

Table 10. Relationships between soil-test phosphorus (STP) and total phosphorus (TP) concentrations in runoff from similar studies.

Source	Regression equation[z]	r^2	STP method	Management
AAFRD Rain Simulations - Fresh manure				
Beaverlodge (non-incorporated)	TP = 0.11 STP - 3.6	0.64	Modified Kelowna	Field simulations with surface applied and/or incorporated, fresh beef manure on cropped land in Alberta.
Beaverlodge (incorporated)	TP = 0.024 STP + 0.033	0.53		
Lacombe	TP = 0.026 STP + 1.4	0.50		
Wilson	TP = 0.024 STP + 1.9	0.79		
AAFRD Rain Simulations - Residual Manure				
Beaverlodge	TP = 0.0067 STP + 0.64	0.24	Modified Kelowna	Field simulations with residual beef manure on cropped land in Alberta.
Lacombe	TP = 0.015 STP - 0.056	0.59		
Wilson	TP = 0.012 STP - 0.031	0.71		
Little et al. 2006	TP = 0.013 STP + 0.039	0.86	Modified Kelowna	Three-year small catchment study on manured and unmanured, cropped and grassed soils in Alberta.
Schroeder et al. 2004b	TP = 0.0020 STP + 0.43	0.58	Mehlich-3	Field simulations on grassed lands with equilibrated soils in Georgia.

[z] Where STP is expressed as mg kg^{-1} and TP as mg L^{-1}.

Table 11. Relationships between soil-test phosphorus (STP) and dissolved reactive phosphorus (DRP) concentration in runoff from similar studies.

Source	Regression equation[z]	r^2	STP method	Management
AAFRD rain simulations - fresh manure				
Beaverlodge (non-incorporated)	DRP = 0.032 STP – 0.86	0.66	Modified Kelowna	Field simulations with surface applied and/or incorporated, fresh beef manure on cropped land in Alberta.
Beaverlodge (incorporated)	DRP = 0.013 STP – 0.54	0.65		
Lacombe	DRP = 0.022 STP + 0.89	0.45		
Wilson	DRP = 0.018 STP + 1.37	0.80		
AAFRD rain simulations - residual manure				
Beaverlodge	DRP = 0.0065 STP + 0.32	0.30	Modified Kelowna	Field simulations with residual beef manure on cropped land in Alberta.
Lacombe	DRP = 0.013 STP - 0.47	0.64		
Wilson	DRP = 0.011 STP - 0.36	0.70		
Wright et al. 2006	$DRP_{(T30)}$ = 0.0058 STP – 0.11 $DRP_{(Teq)}$ = 0.0031 STP – 0.04	0.96 0.93	Modified Kelowna	Lab simulations on equilibrated soils in Alberta. Equations derived for the initial 30 min runoff period (T30) and at runoff rate equilibrium (Teq).
	$DRP_{(T30)}$ = 0.0037 STP – 0.05 $DRP_{(Teq)}$ = 0.002 STP – 0.01	0.93 0.93	Mehlich-3	
Little et al. 2006	DRP = 0.014 STP – 0.175	0.89	Modified Kelowna	Three-year small catchment study on manured and unmanured, cropped and grassed soils in Alberta.
Pote et al. 1996	DRP = 0.0026 STP + 0.30	0.72	Mehlich-3	Field simulations on equilibrated soil of fescue pasture in Arkansas.
Pote et al. 1999				
Nella soil	DRP = 0.0036 STP – 0.45	0.82	Mehlich-3	Field simulations on equilibrated soil of fescue pasture in Arkansas.
Linker soil	DRP = 0.0035 STP – 0.38	0.84		
Noark soil	DRP = 0.0016 STP + 0.00	0.87		
Sharpley et al. 2002	DRP = 0.002 STP + 0.08	0.78	Mehlich-3	Lab and field simulations on equilibrated soils from cropped and grassed fields in the U.K. and U.S.
Sharpley et al. 2002	DRP = 0.013 STP + 0.078	0.80	Mehlich-3	Overland flow from cropped watersheds in Oklahoma.
Sharpley et al. 2002	DRP = 0.0027 STP + 0.072	0.81	Mehlich-3	Overland flow from grassed watersheds in Oklahoma.
Schroeder et al. 2004b	DRP = 0.0017 STP + 0.15	0.56	Mehlich-3	Field simulations on hay and pasture fields in Georgia.
Vadas et al. 2005a	DRP = 0.0018 STP + 0.079	0.74	Mehlich-3 or Bray-1	Six lab simulation studies on equilibrated soil from various cropped and hayed fields from the U.K. and U.S.
Vadas et al. 2005a	DRP = 0.0022 STP + 0.0028	0.74	Mehlich-3 or Bray-1	Five field simulation studies on eight tilled and no-till equilibrated soil from cropped and hayed fields in the U.S.

[z] Where STP is expressed as mg kg^{-1} and DRP as mg L^{-1}.

overwhelm relationships between pre-existing phosphorus in soil and the phosphorus in overland flow. This effect diminishes with successive rainfall events (Kleinman and Sharpley 2003), and is affected by the form, method, timing, and rate of phosphorus application (Sharpley et al. 2002).

The STP to TP FWMC relationship extraction coefficients for the Lacombe and Wilson residual manure rainfall simulation equations were similar to the extraction coefficient reported by Little et al. (2006), as derived from field-scale measurements collected from predominantly snowmelt runoff for 3 yr from small catchments of manured and unmanured, cropped, and grassed Alberta soils (Table 10). The extraction coefficient involving Beaverlodge residual manured soils was half as large of the coefficient reported by Little et al. (2006); however, this Beaverlodge equation was based on a relatively narrow range of low STP values, from 35 to 111 mg kg^{-1}. An extraction coefficient of an order of magnitude less, reported by Schroeder et al. (2004b), was derived from measurements collected from field simulations conducted on grassed lands in Georgia. This 10-fold difference is plausible as runoff from grassed land would tend to have a lower erosion risk and less particulate material in the runoff. The Mehlich-3 method of measuring plant-available phosphorus in soil has been shown to extract approximately 20% more phosphorus than the modified Kelowna method based on a study of Alberta soils (Wright et al. 2003). Thus, the Mehlich-3 method would produce an extraction coefficient slightly smaller than the modified Kelowna method for the above-mentioned relationship. The difference between extraction methods cannot account for the 10-fold difference between extraction coefficients derived by Schroeder et al. (2004b) and this study.

The STP to DRP FWMC relationship extraction coefficients for the Beaverlodge, Lacombe, and Wilson residual manure equations were greater than most of the other studies reviewed (Table 11). However, the Lacombe and Wilson equations had similar regression coefficients to those reported by Sharpley et al. (2002), as derived from a combination of lab and field simulations on cropped and grassed soils from the United Kingdom and the United States. The Beaverlodge residual manure equation had a similar extraction coefficient, though slightly greater, than the coefficients reported by Wright et al. (2006), as derived from lab rainfall simulations using equilibrated Alberta soils.

Unmanured Soil Phosphorus and Phosphorus in Runoff

Relationships between STP values of the unmanured treatments and the TP and DRP FWMC values for individual sites were not significant. This was likely due to the large variation of phosphorus concentrations in runoff over the narrow range of STP observed at each site. When data from the three sites were combined, significant relationships were observed (Fig. 14). Combining the sites created a greater range of STP values, primarily as a result of the greater STP values at the Lacombe site than at the Beaverlodge and Wilson sites. While historical records indicate no manure applications at the Lacombe site since 1993, STP values were greater than typical unmanured agricultural soils in Alberta (Wright et al. 2003). The Lacombe results were included in the unmanured data set because any manure additions prior to 1993 would have been well-incorporated and equilibrated with the soil.

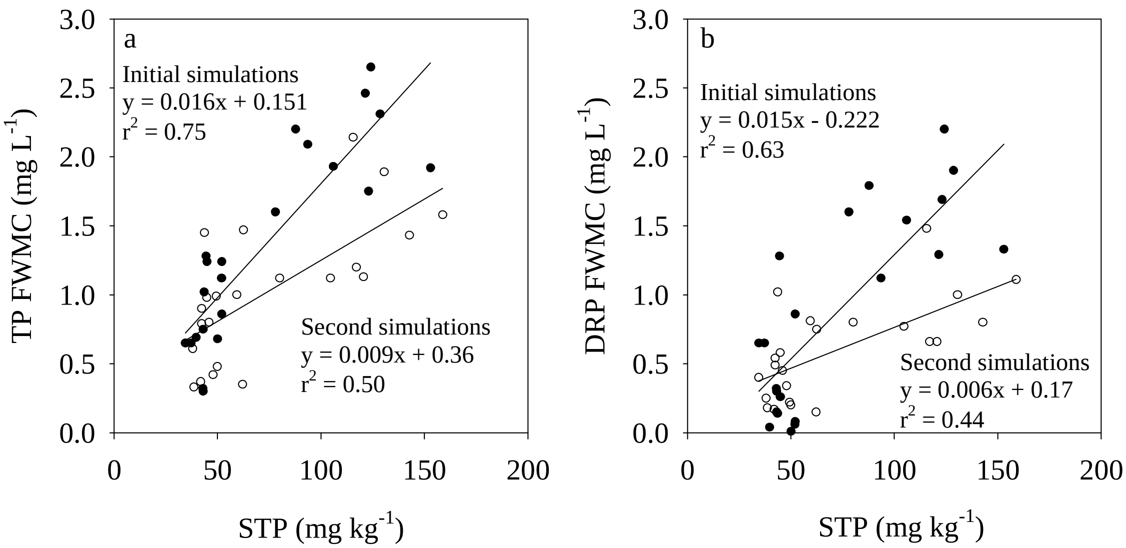

Fig. 14. Relationship between soil-test phosphorus (STP) and (a) total phosphorus (TP) flow-weighted mean concentrations (FWMC) and (b) dissolved reactive phosphorus (DRP) FWMC for unmanured treatments at the three sites for the initial and second rainfall simulations.

Though no difference between incorporation methods was observed, there were notable differences in the relationships between unmanured STP and TP or DRP FWMC in runoff from the second rainfall simulations compared to the initial simulations. Extraction coefficients were significantly greater for the initial rainfall simulations than the second simulations. This was likely caused by different soil conditions at the Lacombe site between simulations that may have impacted infiltration of rainfall. Runoff volumes were greater from both incorporation methods during the second rainfall simulations at the Lacombe site than from initial rainfall simulations on the non-incorporated treatments. Extraction coefficients for both rainfall simulations on the unmanured treatments at all three sites were similar to extraction coefficients observed for the residual manured soils at each site and the extraction coefficients found in the microwatershed study (Little et al. 2006) (Tables 10 and 11). This supports the finding that manured soils may release phosphorus to runoff in a manner similar to unmanured soils after an equilibrium period of at least 6 mo (Vadas et al. 2005a).

Mass Losses of Phosphorus in Runoff

Mean TP and DRP loads from the unmanured treatments were similar between sites and years, although loads from the initial rainfall simulations at the Lacombe site increased notably with tillage (Table 12). Loads generally increased with manure rate for all sites and years (Tables 12 and 13). Total phosphorus and DRP loads from manured treatments at the Beaverlodge site decreased with incorporation immediately after manure application. One year after manure application, TP and DRP loads from the manured treatments of all sites were notably reduced relative to initial loads. Differences between incorporation methods were not observed at the

Beaverlodge site for the second rainfall simulations; however, loads from the incorporated treatment at the Lacombe site were less than half the loads from the non-incorporated treatment.

The portions of TP and DRP removed from plots during the initial rainfall simulations were a relatively small fraction of the phosphorus added to the soil in the manure (Table 13) and were even less the following year (Tables 13). These values indicate that a large portion of the manure-applied phosphorus remained in the soil 1 yr after manure incorporation, and was potentially available for subsequent runoff events. Kleinman and Sharpley (2003) showed similar TP and DRP load to manure TP ratios from lab rainfall simulations of recent surface-applied dairy manure on two different soils.

Table 12. Comparison of total phosphorus (TP) added in fresh manure to TP and dissolved reactive phosphorus (DRP) mass loads removed in 30 min of simulated rainfall runoff immediately after manure application and incorporation.

Site	Incorporation method	Mean manure TP rate (kg ha^{-1})	n	Mean TP mass load in runoff (kg ha^{-1})	Mean DRP mass load in runoff (kg ha^{-1})	Mass Load TP: manure TP (%)	Mass Load DRP: manure TP (%)
Beaverlodge	Non-incorporated	0	3	0.12	0.01	-	-
		25.9	2	0.60	0.24	2.30	0.92
		52.8	3	0.81	0.34	1.54	0.64
		100.2	3	1.56	0.46	1.56	0.46
	Incorporated	0	4	0.09	0.01	-	-
		29.7	3	0.08	0.01	0.27	0.03
		49.9	3	0.08	0.03	0.16	0.05
		110.6	4	0.19	0.05	0.17	0.05
Lacombe	Non-incorporated	0	4	0.11	0.08	-	-
		44.9	3	0.16	0.13	0.36	0.29
		101.4	3	0.97	0.86	0.96	0.85
		167.6	4	0.98	0.76	0.59	0.45
	Incorporated	0	4	0.25	0.19	-	-
		36.7	3	0.32	0.22	0.89	0.59
		100.4	4	0.48	0.39	0.48	0.39
		187.9	3	1.36	1.20	0.72	0.64
Wilson	Non-incorporated	0	3	0.03	0.01	-	-
		133.4	3	0.39	0.32	0.30	0.24
		210.2	2	0.52	0.40	0.25	0.19
		349.7	2	0.92	0.73	0.26	0.21
	Incorporated	0	2	0.08	0.02	-	-
		97	2	0.43	0.32	0.44	0.33
		189.9	3	0.40	0.32	0.21	0.17
		374.4	2	1.15	0.80	0.31	0.21

Table 13. Comparison of total phosphorus (TP) added in fresh manure to TP and dissolved reactive phosphorus (DRP) mass loads removed in 30 min of simulated rainfall runoff 1 yr after manure application and incorporation.

Site	Incorporation method	Mean manure TP rate (kg ha^{-1})	n	Mean TP mass load in runoff (kg ha^{-1})	Mean DRP mass load in runoff (kg ha^{-1})	Mass Load TP: Manure TP (%)	Mass Load DRP: Manure TP (%)
Beaverlodge	Non-incorporated	0	3	0.11	0.06	-	-
		25.9	4	0.13	0.08	0.45	0.28
		52.8	4	0.13	0.10	0.24	0.18
		100.2	3	0.19	0.14	0.18	0.14
	Incorporated	0	4	0.10	0.07	-	-
		29.7	4	0.11	0.07	0.37	0.23
		49.9	4	0.18	0.13	0.35	0.25
		110.6	4	0.17	0.12	0.15	0.11
Lacombe	Non-incorporated	0	4	0.12	0.08	-	-
		44.9	4	0.24	0.12	0.51	0.26
		101.4	4	0.22	0.17	0.22	0.18
		167.6	3	0.42	0.32	0.26	0.20
	Incorporated	0	4	0.09	0.06	-	-
		36.7	3	0.07	0.04	0.17	0.10
		100.4	2	0.12	0.08	0.13	0.09
		187.9	4	0.18	0.14	0.09	0.07
Wilson	Non-incorporated	0	4	0.04	0.02	-	-
		133.4	4	0.17	0.14	0.13	0.11
		210.2	3	0.37	0.33	0.17	0.15
		349.7	4	0.16	0.14	0.05	0.04
	Incorporated	0	4	0.05	0.02	-	-
		97	4	0.09	0.07	0.09	0.07
		189.9	4	0.11	0.09	0.06	0.05
		374.4	4	0.30	0.28	0.08	0.07

CONCLUSIONS

Positive relationships were observed between phosphorus in soil or manure and phosphorus in runoff from incorporated and surface applied freshly manured soil as well as for residual manured soil, 1 yr after application. Soil-test phosphorus measured on fresh and residual manured soils increased with manure rate, but was lower for the residual manured soils at all sites. Similarly, concentrations of TP and DRP in runoff increased with manure rate and STP from freshly manured soil, as well as from residual manured soil, though at a lower rate. Manure rate had no effect on runoff volumes from either fresh or residual manured soils.

Soil-test phosphorus values were similar between incorporated and non-incorporated fresh and residual manured treatments, indicating an insignificant amount of phosphorus burial below the 0- to 2.5-cm depth. Runoff volumes and concentrations of TP and DRP in runoff decreased with manure incorporation for the freshly manured Beaverlodge simulations. However, incorporation did not impact volumes and phosphorus concentrations at the other two sites, nor at the Beaverlodge site 1 yr after manure incorporation. The effects of immediate incorporation at the Beaverlodge site were likely due to impeded infiltration of the non-incorporated treatments caused by soil surface sealing. Concentrations of phosphorus in runoff were lower from the residual manured soils than the freshly manured soils. This decrease with time was likely due to increased soil and manure interaction that enhanced phosphorus sorption to soil. Manure incorporation reduced phosphorus losses from soil to runoff immediately after application at Beaverlodge, but incorporation had no significant effect on phosphorus losses 1 yr year later at any of the sites.

Of the parameters evaluated to predict TP and DRP concentration in runoff from freshly manured soils, the strongest relationships were found with applied manure TP. Strong relationships were also observed with STP after manure application. Manure WEP provided the weakest relationships with DRP concentrations in runoff. The strength of relationships between STP and phosphorus concentrations in runoff were similar from freshly manured and residual manured soils for the Lacombe and Wilson sites, but stronger relationships were found at the Beaverlodge site from the freshly manured than the residual manured soils, possibly a result of high soil clay content and low phosphorus additions. The relationships between STP values in the 0- to 2.5-cm layer and TP in runoff was not improved using STP values in the 0- to 5-cm or 0- to 15-cm layers.

Extraction coefficients (slopes) for the relationships between STP and phosphorus in runoff decreased from simulations conducted on freshly manured soils to those on residual manured soils. However, extraction coefficients 1 yr after manure application were still greater than those found in several other studies. Residual manure extraction coefficients of STP and TP concentrations from the two heavily manured sites were similar to the extraction coefficient found in a small field-scale catchment study under predominantly snowmelt runoff conducted on agricultural soils in Alberta. Relationships between STP and phosphorus in runoff from the unmanured treatments at all of the sites combined had extraction coefficients that were similar to the residual manured soil. Residual manure extraction coefficients for STP and DRP concentrations were greater than the extraction coefficients in the majority of studies conducted elsewhere in North America and the United Kingdom.

Phosphorus loads in runoff from rainfall simulations conducted on fresh and residual manured soils exhibited similar trends to phosphorus concentrations. A relatively small portion of the phosphorus applied with manure was removed by runoff from the freshly manured soils and even less was removed 1 yr after manure application. This indicates a large amount of phosphorus remains in the soil for potential transport during subsequent runoff events.

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APPENDICES

Appendix 1. Soil characterization.

Table A1.1. Physical characteristics, pH, electrical conductivity (EC) and sodium adsorption ratio (SAR) of the Beaverlodge soils.

Borehole number	Depth interval (cm)	Soil horizon[z]	PM[y]	Sand (%)	Clay (%)	Silt (%)	Texture class[x]	Sat.[w] (%)	pH	EC (dS m^{-1})	SAR
1-W-03	0 - 12	Ap	M	24	39	37	CL-C	51.3	4.2	1.71	1.8
	12 - 30	Bt	M	18	63	19	HC	50.0	6.2	0.98	4.0
	30 - 48	BC	M	-	-	-	-	-	-	-	-
	48 - 65	Cca	M	16	80	4	HC	83.3	7.4	5.48	4.8
	65 - 110	Ck	M	33	41	26	CL-C	50.7	7.6	6.42	7.4
2-W-03	0 - 12	Ap	L	28	40	32	CL-C	55.3	4.5	1.33	0.9
	12 - 38	Bt	L	17	61	22	C-HC	50.7	5.7	1.19	3.1
	38 - 58	BC	L	-	-	-	-	-	-	-	-
	58 - 87	Cca	L	15	58	27	C	69.7	7.4	4.66	4.9
	87 - 120	II Ck	M	14	73	13	HC	86.7	7.5	4.52	5.7
3-W-03	0 - 12	Ap	L	30	36	34	CL	86.7	4.9	1.15	1.8
	12 - 43	Bt	L	16	66	18	HC	60.0	6.7	1.79	5.9
	43 - 60	BC	L	15	62	23	HC	60.0	7.3	4.07	8.0
	60 - 85	II Cca	M	14	74	12	HC	86.7	7.6	6.22	7.7
	85 - 120	Ck	M	19	64	17	HC	86.7	7.6	6.18	8.1
4-W-03	0 - 20	Ap	M	32	35	33	CL	48.3	4.5	1.21	0.8
	20 - 30	Ah	M	-	-	-	-	-	-	-	-
	30 - 41	Aej	M	-	-	-	-	-	-	-	-
	41 - 51	Ae	M	-	-	-	-	-	-	-	-
	51 - 90	Bt	M	31	48	21	C	50.0	6.8	5.20	5.6
	90 - 120	Cca	M	20	69	11	HC	75.2	7.5	5.14	6.7
5-W-03	0 - 16	Ap	LM	30	38	32	CL	65.0	4.7	0.79	3.0
	16 - 50	Bt	LM	21	60	19	C-HC	56.7	6.4	1.48	5.9
	50 - 60	BC	LM	-	-	-	-	-	-	-	-
	60 - 85	Cca	M	18	59	23	C-HC	56.7	7.6	6.34	8.0
	85 - 120	Ck	M	14	74	12	HC	68.3	7.6	6.62	9.7

[z] Soil horizons classified according to the Canadian System of Soil Classification (Soil Classification Working Group 1998).

[y] Parent material (PM), lacustrine (L), morainal (M).

[x] Clay (C), clay loam CL), heavy clay (HC).

[w] Saturation (Sat.).

Table A1.2. Nutrients and soluble ions of the Beaverlodge soils.

				-------- Nutrients[x] --------				-------------------- Soluble ions[w] -----------------							
Borehole number	Depth interval (cm)	Soil horizon[z]	PM[y]	NO_3-N	NH_3-N	STP	K	Ca	Mg	Na	K	SO_4	HCO_3	CO_3	Cl
				--------- (mg kg^{-1}) ---------				------------------- (mmolc L^{-1}) -------------------							
1-W-03	0 - 12	Ap	M	68.9	14.2	46.7	5.8	5.9	5.6	4.2	0.19	2.5	-	-	0.7
	12 - 30	Bt	M	3.7	6.4	5.2	5.1	1.8	2.6	6.0	0.04	4.9	-	-	0.3
	30 - 48	BC	M	-	-	-	-	-	-	-	-	-	-	-	-
	48 - 65	Cca	M	2.4	4.1	2.0	5.6	24.2	29.7	25.0	0.31	67.0	3.5	0.0	0.3
	65 - 110	Ck	M	6.1	5.2	1.2	3.3	20.0	32.2	37.9	0.36	78.0	2.8	0.0	1.0
2-W-03	0 - 12	Ap	L	56.9	20.0	53.3	6.2	7.2	4.5	2.1	0.27	0.9	-	-	0.5
	12 - 38	Bt	L	14.6	6.7	4.3	5.5	3.6	2.9	5.6	0.07	5.6	3.4	0.0	0.2
	38 - 58	BC	L	-	-	-	-	-	-	-	-	-	-	-	-
	58 - 87	Cca	L	8.5	4.1	2.0	4.9	25.0	16.7	22.6	0.32	51.0	3.5	0.0	1.0
	87 - 120	II Ck	M	7.1	4.9	1.5	6.0	21.5	14.7	24.4	0.28	49.0	3.2	0.0	0.5
3-W-03	0 - 12	Ap	L	36.4	17.4	41.4	6.9	4.4	2.5	3.4	0.27	2.3	-	-	1.9
	12 - 43	Bt	L	10.1	4.7	2.6	4.9	4.7	4.0	12.3	0.04	7.5	-	-	0.3
	43 - 60	BC	L	18.3	3.9	2.2	4.6	11.4	10.5	26.4	0.13	23.0	4.5	0.0	13.1
	60 - 85	II Cca	M	17.1	5.8	1.9	6.4	25.6	26.2	39.1	0.26	72.0	4.1	0.0	0.8
	85 - 120	Ck	M	13.4	5.8	1.6	5.1	24.0	21.8	38.7	0.24	69.5	3.3	0.0	1.6
4-W-03	0 - 20	Ap	M	48.3	8.9	44.0	5.1	5.6	3.2	1.7	0.16	0.7	1.1	0.0	0.2
	20 - 30	Ah	M	-	-	-	-	-	-	-	-	-	-	-	-
	30 - 41	Aej	M	-	-	-	-	-	-	-	-	-	-	-	-
	41 - 51	Ae	M	-	-	-	-	-	-	-	-	-	-	-	-
	51 - 90	Bt	M	14.7	4.4	2.6	3.5	28.6	18.0	26.9	0.16	56.5	4.6	1.9	0.6
	90 - 120	Cca	M	25.5	2.7	2.1	4.6	23.8	16.0	30.1	0.15	53.5	3.6	0.0	1.3
5-W-03	0 - 16	Ap	LM	24.7	13.0	38.4	5.9	1.6	1.4	3.7	0.11	0.9	-	-	0.3
	16 - 50	Bt	LM	4.9	6.0	9.7	5.6	3.7	2.9	10.8	0.07	10.6	-	-	0.3
	50 - 60	BC	LM	-	-	-	-	-	-	-	-	-	-	-	-
	60 - 85	Cca	M	13.9	4.5	2.5	5.0	25.9	23.5	39.8	0.36	71.3	3.9	0.0	2.6
	85 - 120	Ck	M	15.5	9.8	2.3	5.9	23.0	21.8	45.8	0.33	78.0	4.1	0.0	1.1

[z] Soil horizons classified according to the Canadian System of Soil Classification (Soil Classification Working Group 1998).

[y] Parent material (PM), lacustrine (L), morainal (M).

[x] Nitrate-nitrogen (NO_3-N), ammonia-nitrogen (NH_3-N), soil-test phosphorus (STP) and potassium (K).

[w] Calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), sulphate (SO_4), bicarbonate (HCO_3), carbonate (CO_3), chloride (Cl).

Table A1.3. Physical characteristics, pH, electrical conductivity (EC) and sodium adsorption ratio (SAR) of the Lacombe soils.

Borehole number	Depth interval (cm)	Soil horizon[z]	PM[y]	Sand (%)	Clay (%)	Silt (%)	Texture class[x]	Sat.[w] (%)	pH	EC (dS m^{-1})	SAR
1-W-04	0 - 20	Ap	F	51	22	27	SCL-L	49.5	5.7	0.99	0.9
	25 - 39	Ah	F	-	-	-	-	-	-	-	-
	39 - 80	Bm	F	55	29	16	SCL	41.9	6.8	0.20	0.7
	80 - 155	Bm	F	55	31	14	SCL	39.4	6.0	0.56	0.4
	155 - 210	II Cca	M	53	36	11	SC-SCL	48.0	7.4	0.95	0.3
2-W-04	0 - 13	Ap	F	39	24	37	L	51.9	6.1	1.41	1.9
	13 - 35	Bm	F	45	39	16	CL-C-SC	43.3	6.8	0.54	0.4
	50 - 70	Bm	F	71	18	11	SL	35.6	7.4	0.21	0.8
	70 - 125	II Cca	M	43	37	20	CL	39.4	6.0	0.31	0.6
	125 - 210	III Cca	F	70	12	18	SL	31.3	6.9	1.31	0.3
3-W-04	0 - 20	Ap	F	50	24	26	SCL	52.3	6.2	0.51	0.3
	20 - 50	Bm	F	55	26	19	SCL	47.4	6.9	0.27	0.4
	50 - 120	II Cca	M	60	14	26	SL	44.5	6.5	1.59	0.4
	120 - 160	III Ck1	F	70	14	16	SL	31.3	7.3	0.78	0.3
	160 - 210	III Ck2	F	78	11	11	SL	27.3	7.8	0.83	0.3
4-W-04	0 - 20	Ap	F	53	23	24	SCL	53.7	7.1	0.63	0.4
	20 - 45	Ah	F	46	24	30	L	54.7	7.4	0.48	0.3
	45 - 90	Bm	F	66	22	12	SCL	39.3	7.3	0.58	0.3
	90 - 147	II BC	M	65	26	9	SCL	41.3	6.5	0.95	0.5
	147 - 180	II Cca	M	50	30	20	SCL	40.0	7.0	1.90	0.2
	180 - 210	Ck	M	-	-	-	-	-	-	-	-

[z] Soil horizons classified according to the Canadian System of Soil Classification. (Soil Classification Working Group 1998).

[y] Parent material (PM), fluvial (F), morainal (M).

[x] Clay (C), clay loam CL), loam (L), sandy clay (SC), sandy clay loam (SCL), sandy loam (SL).

[w] Saturation (Sat.).

Table A1.4. Nutrients and soluble ions of the Lacombe soils.

				-------- Nutrients[x] --------				-------------------- Soluble ions[w] -----------------							
Borehole	Depth	Soil		NO_3-N	NH_3-N	STP	K	Ca	Mg	Na	K	SO_4	HCO_3	CO_3	Cl
number	interval (cm)	horizon[z]	PM[y]	--------- (mg kg^{-1}) ---------				------------------- (mmolc L^{-1}) -------------------							
1-W-04	0 - 20	Ap	F	41.0	11.5	51.9	na	5.5	1.6	1.6	0.37	1.1	-	-	2.2
	25 - 39	Ah	F	-	-	-	-	-	-	-	-	-	-	-	-
	39 - 80	Bm	F	3.1	4.0	5.5	na	1.1	0.4	0.6	0.05	0.7	-	-	0.1
	80 - 155	Bm	F	1.4	3.9	2.8	na	3.0	1.1	0.6	0.10	0.5	-	-	3.6
	155 - 210	II Cca	M	1.6	2.0	0.8	na	6.1	1.8	0.5	0.02	0.8	-	-	6.0
2-W-04	0 - 13	Ap	F	50.8	63.8	101.4	na	5.8	1.7	3.7	1.30	2.0	-	-	3.6
	13 - 35	Bm	F	11.7	3.9	18.7	na	3.2	1.0	0.6	0.09	0.5	-	-	1.5
	50 - 70	Bm	F	2.6	2.6	7.8	na	1.1	0.4	0.7	0.06	0.2	-	-	bd
	70 - 125	II Cca	M	1.3	2.2	6.1	na	1.4	0.7	0.6	0.02	0.7	-	-	1.6
	125 - 210	III Cca	F	1.8	2.9	1.3	na	8.0	3.0	0.6	0.06	0.5	-	-	8.6
3-W-04	0 - 20	Ap	F	22.7	7.2	41.1	na	3.6	1.0	0.4	0.09	0.5	-	-	0.2
	20 - 50	Bm	F	8.3	3.3	7.4	na	1.7	0.5	0.4	0.03	0.2	-	-	bd
	50 - 120	II Cca	M	2.2	2.7	2.7	na	9.8	3.2	0.9	0.10	0.2	-	-	12.9
	120 - 160	III Ck1	F	3.3	2.5	0.5	na	5.2	1.5	0.6	0.10	0.5	-	-	3.9
	160 - 210	III Ck2	F	1.4	2.3	0.4	na	5.3	1.7	0.6	0.11	0.4	-	-	5.0
4-W-04	0 - 20	Ap	F	27.9	4.9	90.3	na	5.0	1.4	0.7	0.17	0.7	-	-	0.5
	20 - 45	Ah	F	13.9	3.6	61.5	na	3.9	0.9	0.5	0.04	0.3	-	-	0.2
	45 - 90	Bm	F	1.4	2.9	14.8	na	3.5	1.1	0.5	0.10	0.4	-	-	3.4
	90 - 147	II BC	M	1.2	3.2	2.4	na	4.8	2.2	1.0	0.15	0.4	-	-	7.2
	147 - 180	II Cca	M	1.2	3.1	0.7	na	11.5	4.5	0.7	0.12	0.5	-	-	14.5
	180 - 210	Ck	M	-	-	-	-	-	-	-	-	-	-	-	-

[z] Soil horizons classified according to the Canadian System of Soil Classification (Soil Classification Working Group 1998).

[y] Parent material (PM), fluvial (F), morainal (M).

[x] Nitrate-nitrogen (NO_3-N), ammonia-nitrogen (NH_3-N), soil-test phosphorus (STP) and potassium (K).

[w] Calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), sulphate (SO_4), bicarbonate (HCO_3), carbonate (CO_3), chloride (Cl).

Table A1.5. Physical characteristics, pH, electrical conductivity (EC) and sodium adsorption ratio (SAR) of the Wilson soils.

Borehole number	Depth interval (cm)	Soil horizon[z]	PM[y]	Sand (%)	Clay (%)	Silt (%)	Texture class[x]	Sat.[w] (%)	pH	EC (dS m^{-1})	SAR
9-W-04	0 - 15	Apk	M	30	40	30	CL-C	62.0	7.2	1.08	0.6
	15 - 45	Bmk	M	36	36	28	CL	47.5	8.1	0.57	0.4
	45 - 115	Cca	M	26	55	19	C	59.0	8.9	0.66	2.9
	115 - 210	II Csk	L	13	58	29	C	75.0	8.4	7.69	5.4
10-W-04	0 - 15	Ap	M	29	38	33	CL	60.0	7.7	0.57	0.3
	15 - 27	Bmk	M	32	48	20	C	64.0	7.8	0.59	0.2
	27 - 90	Cca	M	35	48	17	C	52.0	8.4	0.38	0.3
	90 - 160	Ck	M	44	38	18	CL	44.5	8.7	0.68	1.8
	160 - 210	Csk	M	36	50	14	C	66.5	8.0	4.62	2.9
11-W-04	0 - 20	Ap	M	27	38	35	CL	59.5	7.2	0.85	0.6
	20 - 30	Ah	M	-	-	-	-	-	-	-	-
	30 - 45	Bmk	M	26	45	29	C	60.0	8.0	0.69	0.6
	45 - 95	Ccasa	M	21	40	39	SiCL-C	51.0	8.6	5.58	5.4
	95 - 200	Ck	M	25	52	23	C	55.5	8.7	9.33	8.0
	200 - 210	Csk	M	-	-	-	-	-	-	-	-
12-W-04	0 - 20	Ap	L	25	43	32	C	55.0	6.4	0.71	0.6
	20 - 38	Btjk	L	22	53	25	C	62.5	8.2	0.78	0.8
	38 55	BC	L	-	-	-	-	-	-	-	-
	55 - 120	Cca	L	27	41	32	C-CL	48.5	8.8	6.81	7.6
	120 - 210	Ck	L	21	37	42	SiCL-CL	51.5	8.6	2.54	5.9

[z] Soil horizons classified according to the Canadian System of Soil Classification (Soil Classification Working Group 1998).
[y] Parent material (PM), lacustrine (L), morainal (M).
[x] Clay (C), clay loam (CL), silty clay loam (SCL).
[w] Saturation (Sat.).

Table A1.6. Nutrients and soluble ions of the Wilson soils.

				-------- Nutrients[x] --------				-------------------- Soluble ions[w] -----------------							
Borehole number	Depth interval (cm)	Soil horizon[z]	PM[y]	NO_3-N	NH_3-N	STP	K	Ca	Mg	Na	K	SO_4	HCO_3	CO_3	Cl
				--------- (mg kg^{-1}) ---------				------------------- (mmolc L^{-1}) -------------------							
9-W-04	0 - 15	Apk	M	4.4	0.8	69.6	-	7.6	2.5	1.4	0.94		-	-	-
	15 - 45	Bmk	M	1.7	bd	1.6	-	3.3	1.5	0.6	0.03		-	-	-
	45 - 115	Cca	M	1.0	2.9	1.4	-	0.6	2.9	3.8	0.08		-	-	-
	115 - 210	II Csk	L	21.0	0.7	2.0	-	21.9	68.7	36.6	0.23		-	-	-
10-W-04	0 - 15	Ap	M	3.2	0.6	19.7	-	3.8	1.0	0.4	0.57		-	-	-
	15 - 27	Bmk	M	5.2	bd	2.5	-	4.0	1.5	0.4	0.07		-	-	-
	27 - 90	Cca	M	6.4	1.1	1.9	-	1.8	1.8	0.4	0.06		-	-	-
	90 - 160	Ck	M	1.0	1.9	2.0	-	0.7	3.7	2.6	0.17		-	-	-
	160 - 210	Csk	M	3.7	3.1	2.5	-	23.6	33.0	15.6	0.44		-	-	-
11-W-04	0 - 20	Ap	M	9.2	bd	46.6	-	4.8	2.1	1.1	0.92		-	-	-
	20 - 30	Ah	M	-	-	-	-	-	-	-	-		-	-	-
	30 - 45	Bmk	M	3.4	0.7	2.0	-	3.3	2.8	1.0	0.08		-	-	-
	45 - 95	Ccasa	M	1.7	bd	5.4	-	6.5	51.8	29.0	0.11		-	-	-
	95 - 200	Ck	M	3.8	bd	9.7	-	7.0	88.9	55.4	0.25		-	-	-
	200 - 210	Csk	M	-	-	-	-	-	-	-	-		-	-	-
12-W-04	0 - 20	Ap	L	14.5	0.7	43.4	-	2.8	3.2	1.0	0.25		-	-	-
	20 - 38	Btjk	L	11.2	0.8	5.3	-	2.3	4.0	1.4	0.04		-	-	-
	38 55	BC	L	-	-	-	-	-	-	-	-		-	-	-
	55 - 120	Cca	L	40.9	bd	24.7	-	3.2	58.0	42.2	0.05		-	-	-
	120 - 210	Ck	L	15.2	bd	9.3	-	2.3	13.1	16.3	0.06		-	-	-

[z] Soil horizons classified according to the Canadian System of Soil Classification (Soil Classification Working Group 1998).

[y] Parent material (PM), lacustrine (L), morainal (M).

[x] Nitrate-nitrogen (NO_3-N), ammonia-nitrogen (NH_3-N), soil-test phosphorus (STP) and potassium (K), below laboratory detection limit (bd).

[w] Calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), sulphate (SO_4), bicarbonate (HCO_3), carbonate (CO_3), chloride (Cl).

Appendix 2. Source water chemistry.

Year 1[z]						Year 2[z]					
		DRP	TP	TSS	Cl			DRP	TP	TSS	Cl
Site	Date	----------- (mg L^{-1}) -----------				Site	Date	----------- (mg L^{-1}) -----------			
Beaverlodge (on-site)	Oct.19/03	0.014	bd	10	7.09	Beaverlodge (on-site)	Oct.1/04	0.004	0.006	0	17.73
	Oct.20/03	0.010	bd	10	7.44		Oct.1/04	0.004	0.006	0	17.73
	Oct.21/03	0.054	bd	0	9.50		Oct.2/04	0.008	0.010	0	17.73
	Oct.22/03	bd	0.106	0	8.87		Oct.2/04	0.008	0.010	0	17.73
							Oct.3/04	0.010	0.011	0	17.73
							Oct.3/04	0.011	0.012	0	17.73
							Oct.4/04	0.004	0.008	8	17.73
							Oct.4/04	0.005	0.007	0	17.73
						Beaverlodge (purchased)	Oct.1/04	0.002	0.006	0	17.73
							Oct.1/04	0.006	0.007	0	17.73
							Oct.2/04	0.008	0.011	0	17.73
							Oct.3/04	0.003	0.010	0	17.73
							Oct.3/04	0.009	0.009	0	17.73
							Oct.4/04	0.004	0.010	22	17.73
							Oct.4/04	0.005	0.007	0	17.73
Lacombe (on-site)	Oct.2/03	bd	bd	0	15.95	Lacombe (on-site)	Aug.27/04	0.088	0.125	5	17.73
	Oct.3/03	bd	bd	0	13.83		Aug.27/04	0.054	0.096	0	17.73
	Oct.4/03	0.148	0.068	20	15.24		Aug.28/04	0.087	0.101	0	17.73
	Oct.5/03	0.002	0.088	0	16.31		Aug.29/04	0.075	0.126	3	17.73
							Aug.29/04	0.086	0.109	0	17.73
							Aug.30/04	0.089	0.119	0	17.73
							Aug.30/04	0.081	0.099	1	17.73
							Aug.31/04	0.092	0.101	0	17.73
						Lacombe (purchased)	Aug.27/04	0.091	0.110	0	17.73
							Aug.27/04	0.088	0.112	0	17.73
							Aug.29/04	0.091	0.119	0	17.73
							Aug.30/04	0.084	0.133	0	17.73
							Aug.30/04	0.087	0.094	2	17.73
Wilson (on-site)	Apr.27/04	0.006	0.039	0	7.09	Wilson (on-site)	Apr. 12/05	0.002	0.030	0	4.50
	Apr.29/04	0.004	0.012	0	7.09		Apr. 12/05	0.013	0.023	0	4.45
	Apr.30/04	0.012	0.077	1600	7.09		Apr. 13/05	0.005	0.020	0	4.45
	May 3/04	bd	0.027	0	7.09		Apr. 13/05	0.018	0.023	0	4.20
	May 3/04	bd	0.033	0	7.09		Apr. 18/05	0.010	0.020	0	4.02
	May 4/04	bd	0.022	0	7.09		Apr. 20/05	0.011	0.032	0	4.31
	May 4/04	bd	0.042	0	7.09		Apr. 20/05	0.009	0.032	0	4.24
	May 5/04	0.003	0.045	0	7.09		Apr. 21/05	bd	0.002	0	4.18
Wilson (purchased)	Apr.27/04	0.006	0.033	0	7.09	Wilson (purchased)	Apr. 12/05	0.003	0.035	0	4.40
	Apr.30/04	0.015	0.074	2200	7.09		Apr. 12/05	0.006	0.025	0	4.59
	May 3/04	bd	0.033	0	7.09		Apr. 13/05	0.008	0.025	0	4.30
	May 3/04	bd	0.031	0	7.09		Apr. 13/05	0.005	0.021	0	4.40
	May 4/04	bd	0.025	0	7.09		Apr. 18/05	0.013	0.015	0	bd
	May 4/04	bd	0.029	0	7.09		Apr. 20/05	0.012	0.025	0	4.27
							Apr. 20/05	0.010	0.035	0	4.17

[z] Dissolved reactive phosphorus (DRP), total phosphorus (TP), total suspended solids (TSS), chloride (Cl), below laboratory detection limit (bd).

Appendix 3. Phosphorus in soil and manure.

Table A3.1. Pre-treatment soil-test phosphorus (STP) values from samples collected directly before manure application and incorporation.

Site	Incorporation method	Target TP rate[z] (kg ha^{-1})	Pre-treatment STP (mg kg^{-1}) n	Mean	SE[y]	Replicates 1	2	3	4
Beaverlodge	Non-incorporated	0	3	36	4	30	-	42	36
		25	2	37	2	35	38	-	-
		50	3	36	2	39	-	37	32
		100	3	33	1	34	34	32	-
	Incorporated	0	4	37	2	37	40	38	32
		25	3	36	1	-	38	36	35
		50	3	37	0	37	-	37	36
		100	4	38	1	40	35	38	38
Lacombe	Non-incorporated	0	4	98	4	90	92	110	99
		50	3	108	8	116	91	-	116
		100	3	92	3	96	-	95	85
		200	4	99	11	94	85	130	85
	Incorporated	0	4	94	7	113	88	95	79
		50	3	92	4	-	95	84	98
		100	4	93	9	90	78	118	88
		200	3	95	4	88	95	103	-
Wilson	Non-incorporated	0	3	45	4	38	43	-	53
		50	3	54	9	54	39	-	69
		100	2	40	5	45	35	-	-
		200	2	50	0	-	49	-	50
	Incorporated	0	2	59	11	70	48	-	-
		50	2	47	7	54	40	-	-
		100	3	60	2	60	57	-	64
		200	2	51	6	57	45	-	-

[z] Total phosphorus (TP).

[y] Standard error (SE).

Table A3.2. Post-treatment soil-test phosphorus (STP) values from samples collected directly after manure application and incorporation.

Site	Incorporation method	Target TP rate[z] (kg ha^{-1})	-------- STP, fresh manure (mg kg^{-1}) --------						
			n	Mean	SE[y]	------ Replicates ------ 1	2	3	4
Beaverlodge	Non-incorporated	0	3	45	4	40	-	52	43
		25	2	85	12	73	98	-	-
		50	3	96	19	84	-	133	72
		100	3	108	25	61	117	147	-
	Incorporated	0	4	48	2	50	52	45	44
		25	3	60	4	-	68	58	55
		50	3	83	10	64	-	94	92
		100	4	113	19	134	61	146	112
Lacombe	Non-incorporated	0	4	127	10	129	106	153	122
		50	3	169	7	174	155	-	179
		100	3	220	17	210	-	196	253
		200	4	341	39	315	327	451	270
	Incorporated	0	4	107	10	123	88	124	94
		50	3	144	8	-	138	134	160
		100	4	165	11	148	155	163	196
		200	3	395	90	314	296	576	-
Wilson	Non-incorporated	0	3	43	5	35	43	-	52
		50	3	160	16	189	133	-	159
		100	2	518	268	786	251	-	-
		200	2	2048	360	-	2408	-	1689
	Incorporated	0	2	61	17	78	45	-	-
		50	2	144	57	87	201	-	-
		100	3	366	169	705	211	-	184
		200	2	625	229	396	854	-	-

[z] Total phosphorus (TP).

[y] Standard error (SE).

Table A3.3. Manure total phosphorus (TP) application rates calculated from analytical results of samples collected directly after manure application.

Site	Incorporation method	Target TP rate[z] (kg ha^{-1})	n	------ Manure TP (kg ha^{-1}) ------ Mean	SE[y]	--- Replicates --- 1	2	3	4
Beaverlodge	Non-incorporated	25	2	26	3	29	23	-	-
		50	3	53	3	58	-	50	50
		100	3	100	11	97	120	83	-
	Incorporated	25	3	30	3	-	25	32	33
		50	3	50	5	46	-	44	60
		100	4	111	6	99	101	118	125
Lacombe	Non-incorporated	50	3	45	5	40	41	-	54
		100	3	101	26	152	-	66	85
		200	4	168	13	152	188	139	191
	Incorporated	50	3	37	2	-	37	34	39
		100	4	100	8	81	115	95	110
		200	3	188	12	208	191	166	-
Wilson	Non-incorporated	50	3	132	10	149	114	-	135
		100	2	179	40	220	139	-	-
		200	2	365	32	-	397	-	332
	Incorporated	50	2	91	7	85	98	-	-
		100	3	170	25	215	168	-	127
		200	2	369	20	389	349	-	-

[z] Total phosphorus (TP).

[y] Standard error (SE).

Table A3.4. Manure water-extractable phosphorus (WEP) application rates calculated from analytical results of samples collected directly after manure application.

Site	Incorporation method	Target TP rate[z] (kg ha^{-1})	n	---- Manure WEP (kg ha^{-1}) ---- Mean	SE[y]	--- Replicates --- 1	2	3	4
Beaverlodge	Non-incorporated	25	2	4	2	2	6	-	-
		50	3	8	3	3	-	13	7
		100	3	15	7	30	8	8	-
	Incorporated	25	3	5	2	-	4	8	2
		50	3	10	3	7	-	15	8
		100	4	18	4	12	30	11	20
Lacombe	Non-incorporated	50	3	9	4	9	16	-	3
		100	3	18	2	18	-	21	15
		200	4	47	12	33	53	78	25
	Incorporated	50	3	9	3	-	6	7	14
		100	4	20	3	16	29	17	16
		200	3	68	20	69	33	101	-
Wilson	Non-incorporated	50	3	33	10	20	53	-	27
		100	2	47	22	25	69	-	-
		200	2	82	19	-	64	-	101
	Incorporated	50	2	36	6	30	43	-	-
		100	3	43	11	26	65	-	38
		200	2	41	33	8	74	-	-

[z] Total phosphorus (TP).

[y] Standard error (SE).

Appendix 4. Runoff volumes.

Table A4.1. Runoff volumes measured directly after manure application and incorporation at the Beaverlodge site.

Incorporation method	Target TP rate[z] (kg ha^{-1})	Replicate	Volume (mL), fresh manure Total 0-30 min	------- Time intervals (min) ------- 0-5	5-10	10-20	20-30
Non-incorporated	0	1	23460	2800	3010	7890	9760
		2	-	-	-	-	-
		3	49170	8070	8190	16370	16540
		4	40190	3770	4150	15000	17270
	25	1	41750	580	7110	16070	17990
		2	46960	4350	7500	15680	19430
		3	-	-	-	-	-
		4	-	-	-	-	-
	50	1	50600	8140	6720	17540	18200
		2					
		3	56160	7200	8890	19350	20720
		4	55370	8160	8730	19080	19400
	100	1	48640	7500	8500	16170	16470
		2	37490	3870	5270	12810	15540
		3	34540	4510	5300	11600	13130
		4	-	-	-	-	-
Incorporated	0	1	23260	2090	3110	8120	9940
		2	25690	2310	3210	9520	10650
		3	26660	1650	3040	9640	12330
		4	34540	4030	5160	11840	13510
	25	1	-	-	-	-	-
		2	16890	1480	2150	5820	7440
		3	21290	2310	3230	7590	8160
		4	17140	1850	2440	5740	7110
	50	1	10080	1290	1420	3400	3970
		2	-	-	-	-	-
		3	14870	1420	2010	5110	6330
		4	17080	1380	2180	5980	7540
	100	1	10100	1230	1520	3760	3590
		2	20150	2410	2730	6650	8360
		3	22080	1450	1900	7400	11330
		4	24680	2370	3030	8400	10880

[z] Total phosphorus (TP).

Table A4.2. Runoff volumes measured directly after manure application and incorporation at the Lacombe site.							
	Target		Volume (mL), fresh manure				
Incorporation	TP rate[z]		Total	------- Time intervals (min) -------			
method	(kg ha^{-1})	Replicate	0-30 min	0-5	5-10	10-20	20-30
Non-incorporated	0	1	20240	2310	2840	7070	8020
		2	12720	1180	1360	3590	6590
		3	14730	1670	2000	5020	6040
		4	13440	1560	1810	4340	5730
	50	1	10350	1140	1360	3470	4380
		2	10400	1170	1500	3670	4060
		3	-	-	-	-	-
		4	12400	1280	1550	4560	5010
	100	1	19850	1890	2510	6730	8720
		2	-	-	-	-	-
		3	24400	2400	3280	8360	10360
		4	41870	5050	5840	14410	16570
	200	1	43020	4630	6230	15100	17060
		2	26530	2920	2570	10000	11040
		3	12030	1100	1500	4120	5310
		4	16190	2750	3880	3590	5970
Incorporated	0	1	23540	2590	3520	7330	10100
		2	30010	3190	3700	10610	12510
		3	36560	2750	4700	13740	15370
		4	46450	3840	5680	17930	19000
	50	1	-	-	-	-	-
		2	20750	2530	3450	7100	7670
		3	17600	1860	2330	5970	7440
		4	13880	1470	2070	4780	5560
	100	1	34810	4100	5690	11710	13310
		2	12200	1470	1900	4110	4720
		3	21270	2220	3090	7540	8420
		4	19970	2390	2870	6550	8160
	200	1	32940	3730	4510	12100	12600
		2	25620	3670	4880	9560	7510
		3	47860	3340	6750	17420	20350
		4	-	-	-	-	-

[z] Total phosphorus (TP).

Table A4.3. Runoff volumes measured directly after manure application and incorporation at the Wilson site.

Incorporation method	Target TP rate[z] (kg ha^{-1})	Replicate	Volume (mL), fresh manure Total 0-30 min	------- Time intervals (min) ------- 0-5	5-10	10-20	20-30
Non-incorporated	0	1	8920	1190	1220	3040	3470
		2	8810	1220	1480	2650	3460
		3	-	-	-	-	-
		4	17970	1640	2520	6130	7680
	50	1	19040	2120	2590	6540	7790
		2	17840	1200	2320	6550	7770
		3	-	-	-	-	-
		4	23060	1940	3040	8130	9950
	100	1	9590	1140	1280	3210	3960
		2	9000	1150	1360	3100	3390
		3	-	-	-	-	-
		4	-	-	-	-	-
	200	1	-	-	-	-	-
		2	13780	1800	1730	4680	5570
		3	-	-	-	-	-
		4	9290	1060	1130	3290	3810
Incorporated	0	1	19240	1650	2040	6230	9320
		2	12450	1280	1770	4470	4930
		3	-	-	-	-	-
		4	-	-	-	-	-
	50	1	19920	1730	2370	6930	8890
		2	18940	1890	2450	5960	8640
		3	-	-	-	-	-
		4	-	-	-	-	-
	100	1	8490	1150	1120	2840	3380
		2	20870	2290	3000	7150	8430
		3	-	-	-	-	-
		4	14680	1740	1560	5400	5980
	200	1	24060	1870	3060	8800	10330
		2	9470	990	1240	3300	3940
		3	-	-	-	-	-
		4	-	-	-	-	-

[z] Total phosphorus (TP).

Table A4.4. Runoff volumes measured 1 yr after manure application and incorporation at the Beaverlodge site.

Incorporation method	Target TP rate[z] (kg ha^{-1})	Replicate	Volume (mL), residual manure Total 0-30 min	------- Time intervals (min) ------- 0-5	5-10	10-20	20-30
Non-incorporated	0	1	43775	1760	3570	15380	23065
		2	-	-	-	-	-
		3	23370	1180	1270	5700	15220
		4	57415	3195	4340	22560	27320
	25	1	46990	5140	7180	16530	18140
		2	26080	1820	3650	9370	11240
		3	43920	4010	6140	16440	17330
		4	59912	4740	7500	18712	21960
	50	1	42280	3260	4530	16400	18090
		2	52275	3930	7910	19780	20655
		3	20180	1370	1990	5660	11160
		4	23115	1910	2700	7615	10890
	100	1	36430	1850	2960	10160	21460
		2	46770	2780	6030	18930	19030
		3	-	-	-	-	-
		4	49730	4210	7560	18580	19380
Incorporated	0	1	21050	2150	3210	6835	8855
		2	32720	3730	5000	11860	12130
		3	35960	2160	4410	13440	15950
		4	45880	1235	2615	18595	23435
	25	1	53135	3460	6830	19725	23120
		2	25240	1670	2610	8330	12630
		3	28080	1970	2775	8350	14985
		4	24790	1550	2930	9590	10720
	50	1	62070	6020	10090	22220	23740
		2	43020	4490	6190	15280	17060
		3	51340	5165	7575	18725	19875
		4	31690	1510	2520	10420	17240
	100	1	44860	4380	7180	16250	17050
		2	24450	1680	2810	8550	11410
		3	48840	5010	7850	17600	18380
		4	27600	1320	1670	7650	16960

[z] Total phosphorus (TP).

Table A4.5. Runoff volumes measured 1 yr after manure application and incorporation at the Lacombe site.

Incorporation method	Target TP rate[z] (kg ha^{-1})	Replicate	Volume (mL), residual manure Total 0-30 min	Time intervals (min) 0-5	5-10	10-20	20-30
Non-incorporated	0	1	31580	2910	4150	10800	13720
		2	29130	2460	3495	10160	13015
		3	15640	1610	2170	5380	6300
		4	20730	1705	2045	5920	11060
	50	1	18845	1750	2340	6435	8320
		2	41520	5140	6330	14690	15360
		3	16385	1720	2190	5470	7005
		4	6915	1020	1040	2155	2700
	100	1	31365	2650	4310	10930	13475
		2	31960	3360	4560	11430	12610
		3	10010	1100	1310	3370	4230
		4	12205	1410	1760	4090	4945
	200	1	32630	5200	5150	10330	11950
		2	26230	3030	3630	8820	10750
		3	15875	1580	2180	5490	6625
		4	-	-	-	-	-
Incorporated	0	1	33560	3310	5200	11800	13250
		2	23560	2380	3370	8350	9460
		3	14890	1200	1630	4925	7135
		4	16040	1690	2260	5780	6310
	50	1	16030	1630	1910	4760	7730
		2	12430	1210	1650	4410	5160
		3	-	-	-	-	-
		4	11425	1400	1700	3870	4455
	100	1	23845	1485	2350	8710	11300
		2	-	-	-	-	-
		3	-	-	-	-	-
		4	15190	1440	1980	5110	6660
	200	1	15940	1340	1930	5360	7310
		2	12780	1590	1820	4140	5230
		3	7830	1020	1130	2490	3190
		4	12365	1125	1390	3920	5930

[z] Total phosphorus (TP).

Table A4.6. Runoff volumes measured 1 yr after manure application and incorporation at the Wilson site.

Incorporation method	Target TP rate[z] (kg ha^{-1})	Replicate	Volume (mL), residual manure Total 0-30 min	------- Time intervals (min) ------- 0-5	5-10	10-20	20-30
Non-incorporated	0	1	9720	1230	1440	3480	3570
		2	18730	1400	2530	7300	7500
		3	19995	2330	3050	6770	7845
		4	7850	1050	1100	2600	3100
	50	1	20240	2710	3220	6990	7320
		2	27710	2250	3790	10210	11460
		3	12800	1500	1770	4380	5150
		4	19730	1840	2740	6910	8240
	100	1	23090	2840	3590	8200	8460
		2	-	-	-	-	-
		3	8310	1110	1270	3020	2910
		4	31290	3280	4910	11190	11910
	200	1	6920	1020	1080	2340	2480
		2	19140	2340	2910	6520	7370
		3	7700	1120	1180	2670	2730
		4	10520	1060	1410	3560	4490
Incorporated	0	1	10170	1390	1630	3490	3660
		2	32725	2020	3615	12450	14640
		3	7840	1140	1310	2640	2750
		4	28415	2040	3485	10210	12680
	50	1	19990	2490	3310	6910	7280
		2	16690	1910	2460	5790	6530
		3	9210	1050	1220	3210	3730
		4	19250	1600	2210	6590	8850
	100	1	8315	1035	1160	3005	3115
		2	21820	2130	3280	7940	8470
		3	7040	960	1020	2290	2770
		4	15425	1405	2130	5530	6360
	200	1	10735	1205	1500	3650	4380
		2	10600	1210	2330	2780	4280
		3	11870	1300	1650	4040	4880
		4	14640	1240	1680	4670	7050

[z] Total phosphorus (TP).

Appendix 5. Phosphorus concentrations in runoff.

Table A5.1. Total phosphorus (TP) time interval concentrations and flow-weighted mean concentrations (FWMC) in runoff measured directly after manure application and incorporation at the Beaverlodge site.

Incorporation method	Target TP rate (kg ha^{-1})	Replicate	TP concentration (mg L^{-1}), fresh manure: FWMC 0-30 min	Time intervals (min): 0-5	5-10	10-20	20-30
Non-incorporated	0	1	0.69	1.21	0.76	0.81	0.43
		2	-	-	-	-	-
		3	1.24	1.43	1.30	1.30	1.06
		4	0.75	0.74	0.89	0.84	0.65
	25	1	2.75	3.22	2.62	2.73	2.80
		2	5.16	6.26	5.61	5.24	4.69
		3	-	-	-	-	-
		4	-	-	-	-	-
	50	1	3.72	4.47	3.92	3.35	3.66
		2	-	-	-	-	-
		3	5.49	4.18	7.14	5.67	5.07
		4	4.25	5.26	3.65	3.99	4.34
	100	1	7.62	8.69	8.14	7.95	6.53
		2	13.03	15.89	12.78	11.76	13.46
		3	15.87	16.54	16.42	16.18	15.14
		4	-	-	-	-	-
Incorporated	0	1	0.68	0.77	0.60	0.76	0.63
		2	1.12	0.43	1.26	1.27	1.11
		3	1.24	1.48	1.17	1.34	1.14
		4	1.02	1.16	1.08	0.69	1.24
	25	1	-	-	-	-	-
		2	1.86	2.02	2.11	1.56	1.99
		3	1.15	1.29	1.07	1.12	1.17
		4	0.89	0.94	0.90	0.86	0.90
	50	1	1.74	2.65	1.14	1.84	1.58
		2	-	-	-	-	-
		3	1.39	1.33	1.16	1.55	1.35
		4	1.87	1.66	1.89	1.78	1.97
	100	1	4.68	5.24	4.80	4.94	4.16
		2	3.13	3.70	2.71	2.45	3.64
		3	2.81	2.16	2.68	2.80	2.93
		4	2.19	1.12	2.09	2.37	2.31

Table A5.2. Total phosphorus (TP) time interval concentrations and flow-weighted mean concentrations (FWMC) in runoff measured directly after manure application and incorporation at the Lacombe site.

Incorporation method	Target TP rate (kg ha^{-1})	Replicate	TP concentration (mg L^{-1}), fresh manure FWMC 0-30 min	Time intervals (min) 0-5	5-10	10-20	20-30
Non-incorporated	0	1	2.31	2.07	2.16	2.26	2.47
		2	1.93	1.78	1.68	1.88	2.03
		3	1.92	2.16	2.17	1.90	1.79
		4	2.46	2.39	2.59	2.41	2.48
	50	1	4.76	3.89	3.90	4.91	5.13
		2	3.22	3.08	3.72	3.13	3.16
		3	-	-	-	-	-
		4	4.98	5.36	4.42	5.07	4.98
	100	1	9.88	10.86	9.85	10.17	9.45
		2	-	-	-	-	-
		3	8.32	9.57	8.97	8.10	8.01
		4	11.40	11.47	12.37	12.25	10.30
	200	1	11.57	11.11	11.30	11.00	12.29
		2	14.67	17.79	17.36	13.93	13.90
		3	8.93	8.56	9.23	9.23	8.68
		4	11.45	9.59	12.25	12.32	11.26
Incorporated	0	1	1.75	1.99	1.83	1.73	1.67
		2	2.20	2.01	2.40	2.37	2.05
		3	2.65	2.51	2.85	2.59	2.66
		4	2.09	2.36	3.05	2.69	1.19
	50	1	-	-	-	-	-
		2	6.38	6.48	6.17	6.08	6.74
		3	4.78	5.43	5.13	5.07	4.28
		4	5.46	4.65	5.70	4.37	6.53
	100	1	6.22	6.10	7.24	5.92	6.08
		2	6.29	6.55	6.66	6.05	6.28
		3	5.42	5.20	5.81	6.09	4.74
		4	8.27	8.26	7.82	8.27	8.44
	200	1	11.13	10.46	11.73	11.31	10.95
		2	15.58	19.59	18.37	14.93	12.65
		3	9.54	10.75	9.30	9.81	9.18
		4	-	-	-	-	-

Table A5.3. Total phosphorus (TP) time interval concentrations and flow-weighted mean concentrations (FWMC) in runoff measured directly after manure application and incorporation at the Wilson site.

Incorporation method	Target TP rate (kg ha^{-1})	Replicate	TP concentration (mg L^{-1}), fresh manure: FWMC 0-30 min	Time intervals (min): 0-5	5-10	10-20	20-30
Non-incorporated	0	1	0.65	0.58	0.63	0.67	0.67
		2	0.32	0.28	0.34	0.34	0.30
		3	-	-	-	-	-
		4	0.86	0.83	0.95	0.82	0.86
	50	1	5.86	6.31	6.20	5.59	5.85
		2	5.56	3.91	4.63	5.92	5.79
		3	-	-	-	-	-
		4	6.26	5.74	6.34	6.59	6.07
	100	1	19.50	22.15	21.01	19.86	17.95
		2	13.65	16.01	14.30	13.50	12.72
		3	-	-	-	-	-
		4	-	-	-	-	-
	200	1	-	-	-	-	-
		2	23.72	22.60	24.51	24.32	23.33
		3	-	-	-	-	-
		4	23.99	26.83	24.68	24.54	22.53
Incorporated	0	1	1.60	1.68	1.55	1.60	1.60
		2	1.28	1.51	1.36	1.26	1.22
		3	-	-	-	-	-
		4	-	-	-	-	-
	50	1	7.81	9.12	9.04	8.33	6.83
		2	5.33	5.95	5.90	5.55	4.87
		3	-	-	-	-	-
		4	-	-	-	-	-
	100	1	14.79	15.88	13.68	15.80	13.94
		2	7.64	7.20	7.34	7.47	8.01
		3	-	-	-	-	-
		4	4.84	3.81	4.23	5.15	5.01
	200	1	20.14	21.62	20.48	20.10	19.81
		2	21.40	21.86	20.88	21.66	21.22
		3	-	-	-	-	-
		4	-	-	-	-	-

Table A5.4. Total phosphorus (TP) time interval concentrations and flow-weighted mean concentrations (FWMC) in runoff measured 1 yr after manure application and incorporation at the Beaverlodge site.

Incorporation method	Target TP rate (kg ha^{-1})	Replicate	TP concentration (mg L^{-1}), residual manure FWMC 0-30 min	------- Time intervals (min) ------- 0-5	5-10	10-20	20-30
Non-incorporated	0	1	0.61	0.69	0.73	0.60	0.59
		2	-	-	-	-	-
		3	0.80	0.89	0.73	0.70	0.85
		4	0.90	1.06	0.95	0.90	0.87
	25	1	0.57	0.70	0.71	0.56	0.49
		2	1.12	1.43	1.20	1.14	1.02
		3	0.75	1.19	0.91	0.76	0.58
		4	1.10	1.94	2.02	1.21	0.86
	50	1	0.87	0.97	0.99	0.89	0.80
		2	1.32	1.68	1.56	1.34	1.15
		3	1.15	1.19	0.91	0.76	0.58
		4	1.05	1.23	1.13	1.07	0.98
	100	1	1.14	1.22	1.29	1.09	1.14
		2	1.36	1.46	1.48	1.40	1.26
		3	-	-	-	-	-
		4	1.34	1.41	1.43	1.41	1.23
Incorporated	0	1	0.65	1.04	0.84	0.55	0.55
		2	1.00	1.38	1.26	1.00	0.77
		3	0.79	1.27	1.13	0.75	0.67
		4	0.98	1.10	1.26	1.06	0.87
	25	1	0.65	0.87	0.80	0.63	0.58
		2	1.32	1.68	1.60	1.35	1.20
		3	1.22	1.63	1.55	1.35	1.03
		4	1.15	2.07	1.37	1.18	0.93
	50	1	0.90	1.43	0.99	0.79	0.83
		2	1.49	2.08	1.83	1.52	1.18
		3	1.15	1.30	1.10	1.23	1.06
		4	1.28	1.58	1.33	1.44	1.15
	100	1	0.78	0.91	0.86	0.78	0.70
		2	1.41	1.95	1.52	1.41	1.30
		3	2.00	2.50	2.33	2.00	1.73
		4	1.29	1.30	1.08	1.20	1.35

Table A5.5. Total phosphorus (TP) time interval concentrations and flow-weighted mean concentrations (FWMC) in runoff measured 1 yr after manure application and incorporation at the Lacombe site.

Incorporation method	Target TP rate (kg ha^{-1})	Replicate	TP concentration (mg L^{-1}), residual manure: FWMC 0-30 min	Time intervals (min): 0-5	5-10	10-20	20-30
Non-incorporated	0	1	1.20	1.23	1.45	1.17	1.15
		2	1.43	1.17	1.62	1.46	1.40
		3	2.14	3.22	2.47	2.10	1.86
		4	1.58	1.72	1.40	1.63	1.56
	50	1	2.35	2.28	2.25	2.05	2.62
		2	4.67	4.27	5.13	4.88	4.41
		3	2.10	2.02	2.10	2.12	2.10
		4	2.07	2.36	2.20	2.14	1.85
	100	1	3.33	4.41	3.44	3.22	3.17
		2	2.90	3.54	3.29	2.81	2.67
		3	3.42	3.73	3.45	3.56	3.22
		4	2.49	2.23	2.42	2.63	2.48
	200	1	5.00	6.08	5.37	4.94	4.42
		2	5.64	11.49	9.91	8.75	n/s
		3	4.07	4.17	4.65	3.95	3.96
		4	-	-	-	-	-
Incorporated	0	1	1.12	1.37	1.22	0.93	1.18
		2	1.12	1.44	1.38	1.04	1.01
		3	1.89	2.30	2.08	1.96	1.72
		4	1.13	2.30	2.08	1.96	1.72
	50	1	1.37	1.59	1.14	1.46	1.33
		2	1.38	0.94	1.40	1.59	1.30
		3	-	-	-	-	-
		4	1.86	2.40	2.12	1.75	1.69
	100	1	1.82	1.65	1.79	1.97	1.73
		2	-	-	-	-	-
		3	-	-	-	-	-
		4	2.06	2.33	2.27	2.28	1.76
	200	1	3.97	4.95	4.32	4.36	3.41
		2	6.20	7.92	6.82	6.21	5.46
		3	2.99	3.63	3.07	2.89	2.83
		4	4.05	2.36	2.84	3.49	5.02

Table A5.6. Total phosphorus (TP) time interval concentrations and flow-weighted mean concentrations (FWMC) in runoff measured 1 yr after manure application and incorporation at the Wilson site.

	Target		TP concentration (mg L^{-1}), residual manure				
Incorporation	TP rate		FWMC	------- Time intervals (min) -------			
method	(kg ha^{-1})	Replicate	0-30 min	0-5	5-10	10-20	20-30
Non-incorporated	0		0.33	0.42	0.36	0.30	0.32
		2	1.45	0.41	0.68	1.65	1.72
		3	0.48	0.59	0.51	0.45	0.46
		4	0.42	0.50	0.44	0.42	0.38
	50	1	1.78	1.38	1.68	1.83	1.92
		2	3.02	2.62	3.20	3.07	3.00
		3	1.67	1.72	1.91	1.71	1.54
		4	3.24	3.78	3.34	3.06	3.24
	100	1	4.52	4.49	4.70	4.64	4.34
		2	-	-	-	-	-
		3	2.34	1.55	1.65	2.42	2.87
		4	6.70	6.24	6.87	6.84	6.63
	200	1	6.86	6.80	6.83	6.92	6.85
		2	3.53	4.26	3.73	3.55	3.20
		3	2.38	2.37	2.38	2.31	2.44
		4	5.70	5.36	5.46	5.64	5.90
Incorporated	0	1	1.47	1.68	1.65	1.47	1.29
		2	0.99	1.27	1.08	0.97	0.94
		3	0.37	0.38	0.40	0.39	0.34
		4	0.35	0.35	0.32	0.34	0.37
	50	1	2.10	2.39	2.09	2.05	2.07
		2	1.72	1.95	1.66	1.58	1.79
		3	1.87	1.69	1.80	1.84	1.97
		4	0.88	0.50	0.77	0.95	0.93
	100	1	0.89	0.79	0.82	0.92	0.92
		2	4.18	3.98	4.40	4.17	4.16
		3	0.95	0.83	0.75	0.93	1.08
		4	1.71	1.11	1.13	1.77	1.99
	200	1	9.51	11.73	10.42	9.25	8.81
		2	5.00	5.36	5.18	4.94	4.85
		3	3.88	3.74	3.83	4.00	3.84
		4	10.94	9.88	10.62	11.19	11.04

Table A5.7. Dissolved reactive phosphorus (DRP) time interval concentrations and flow-weighted mean concentrations (FWMC) in runoff measured directly after manure application and incorporation at the Beaverlodge site.

Incorporation method	Target TP rate[z] (kg ha^{-1})	Replicate	DRP concentration (mg L^{-1}), fresh manure: FWMC 0-30 min	Time intervals (min): 0-5	5-10	10-20	20-30
Non-incorporated	0	1	0.04	0.05	0.03	0.04	0.03
		2	-	-	-	-	-
		3	0.08	0.08	0.07	0.08	0.07
		4	0.15	0.66	0.43	0.06	0.05
	25	1	1.15	0.98	1.16	1.19	1.11
		2	2.01	1.47	1.94	2.17	2.03
		3	-	-	-	-	-
		4	-	-	-	-	-
	50	1	1.67	1.57	1.91	1.69	1.61
		2	-	-	-	-	-
		3	2.51	2.58	2.72	2.59	2.33
		4	1.45	1.20	1.51	1.51	1.47
	100	1	3.24	3.82	3.39	3.20	2.94
		2	2.96	3.10	3.58	2.10	3.43
		3	4.33	4.02	4.24	4.38	4.42
		4	-	-	-	-	-
Incorporated	0	1	0.01	0.01	0.01	0.01	0.01
		2	0.06	0.07	0.07	0.05	0.05
		3	0.26	0.26	0.26	0.26	0.27
		4	0.14	0.20	0.17	0.14	0.12
	25	1	-	-	-	-	-
		2	0.23	0.19	0.18	0.23	0.25
		3	0.09	0.08	0.09	0.09	0.09
		4	0.20	0.22	0.21	0.20	0.19
	50	1	0.71	0.96	0.87	0.67	0.61
		2	-	-	-	-	-
		3	0.40	0.32	0.35	0.40	0.42
		4	0.56	0.32	0.31	0.63	0.62
	100	1	2.07	2.08	2.11	2.08	2.03
		2	0.16	0.09	0.10	0.12	0.24
		3	0.96	0.92	0.97	0.97	0.96
		4	0.70	0.69	0.73	0.73	0.68

[z] Total phosphorus (TP).

Table A5.8. Dissolved reactive phosphorus (DRP) time interval concentrations and flow-weighted mean concentrations (FWMC) in runoff measured directly after manure application and incorporation at the Lacombe site.

Incorporation method	Target TP rate[z] (kg ha^{-1})	Replicate	DRP concentration (mg L^{-1}), fresh manure FWMC 0-30 min	------- Time intervals (min) ------- 0-5	5-10	10-20	20-30
Non-incorporated	0	1	1.90	1.51	1.69	1.93	2.07
		2	1.54	1.20	1.27	1.55	1.66
		3	1.33	1.35	1.40	1.35	1.28
		4	1.29	1.15	1.34	1.33	1.28
	50	1	4.31	3.47	3.55	4.25	4.81
		2	2.47	2.33	2.71	2.46	2.43
		3	-	-	-	-	-
		4	3.69	3.93	3.64	3.58	3.75
	100	1	8.71	9.24	9.03	8.91	8.35
		2	-	-	-	-	-
		3	7.81	7.75	7.85	7.83	7.80
		4	9.86	10.64	10.76	10.01	9.17
	200	1	9.19	8.97	9.37	9.32	9.08
		2	10.78	11.07	11.44	10.87	10.47
		3	7.29	6.23	7.35	7.43	7.39
		4	8.57	8.81	8.89	8.64	8.21
Incorporated	0	1	1.69	1.65	1.71	1.73	1.67
		2	1.79	1.70	1.82	1.83	1.78
		3	2.20	1.87	2.26	2.22	2.23
		4	1.12	0.73	0.90	1.20	1.19
	50	1	-	-	-	-	-
		2	4.09	4.32	3.94	4.05	4.11
		3	2.89	2.41	2.61	2.87	3.11
		4	4.33	4.06	3.99	4.37	4.50
	100	1	5.42	5.12	5.15	5.35	5.68
		2	4.66	4.10	4.53	4.77	4.79
		3	4.22	3.45	3.87	4.24	4.54
		4	6.45	6.44	6.37	6.48	6.46
	200	1	9.56	7.42	8.95	9.63	10.33
		2	15.56	14.60	15.13	15.94	15.82
		3	7.58	7.68	7.44	7.60	7.60
		4	-	-	-	-	-

[z] Total phosphorus (TP).

Table A5.9. Dissolved reactive phosphorus (DRP) time interval concentrations and flow-weighted mean concentrations (FWMC) in runoff measured directly after manure application and incorporation at the Wilson site.

Incorporation method	Target TP rate[z] (kg ha^{-1})	Replicate	DRP concentration (mg L^{-1}), fresh manure: FWMC 0-30 min	------- Time intervals (min) ------- 0-5	5-10	10-20	20-30
Non-incorporated	0	1	0.43	0.33	0.38	0.45	0.46
		2	0.10	0.11	0.10	0.11	0.09
		3	-	-	-	-	-
		4	0.42	0.37	0.41	0.43	0.43
	50	1	4.61	4.48	4.53	4.62	4.66
		2	4.23	3.16	3.17	4.49	4.49
		3	-	-	-	-	-
		4	5.32	5.16	5.27	5.60	5.14
	100	1	14.25	15.61	15.23	14.56	13.29
		2	11.25	12.94	12.02	11.06	10.55
		3	-	-	-	-	-
		4	-	-	-	-	-
	200	1	-	-	-	-	-
		2	19.04	17.54	18.96	19.59	19.08
		3	-	-	-	-	-
		4	19.00	19.23	20.12	19.90	17.84
Incorporated	0	1	0.26	0.00	0.30	0.28	0.29
		2	0.72	0.74	0.74	0.76	0.68
		3	-	-	-	-	-
		4	-	-	-	-	-
	50	1	5.98	6.48	6.31	6.07	5.73
		2	3.90	3.78	3.97	3.92	3.88
		3	-	-	-	-	-
		4	-	-	-	-	-
	100	1	11.48	12.07	12.19	11.98	10.62
		2	6.30	5.78	6.08	6.42	6.43
		3	-	-	-	-	-
		4	3.73	3.13	3.34	3.86	3.89
	200	1	13.28	12.67	12.63	13.23	13.62
		2	16.68	16.26	16.06	17.20	16.56
		3	-	-	-	-	-
		4	-	-	-	-	-

[z] Total phosphorus (TP).

Table A5.10. Dissolved reactive phosphorus (DRP) time interval concentrations and flow-weighted mean concentrations (FWMC) in runoff measured 1 yr after manure application and incorporation at the Beaverlodge site.

Incorporation method	Target TP rate[z] ($kg\ ha^{-1}$)	Replicate	DRP concentration ($mg\ L^{-1}$), residual manure				
			FWMC	------- Time intervals (min) -------			
			0-30 min	0-5	5-10	10-20	20-30
Non-incorporated	0	1	0.25	0.22	0.21	0.25	0.26
		2	-	-	-	-	-
		3	0.45	0.46	0.38	0.37	0.49
		4	0.54	0.55	0.41	0.56	0.55
	25	1	0.46	0.52	0.52	0.47	0.42
		2	0.87	1.02	1.01	0.93	0.76
		3	0.35	0.48	0.42	0.35	0.30
		4	0.58	1.06	0.90	0.66	0.48
	50	1	0.64	0.75	0.72	0.66	0.58
		2	1.06	1.32	1.31	1.09	0.89
		3	0.86	0.48	0.42	0.35	0.30
		4	0.70	0.80	0.70	0.70	0.69
	100	1	0.58	0.69	0.63	0.53	0.59
		2	1.19	1.30	1.32	1.23	1.10
		3	-	-	-	-	-
		4	1.06	1.03	1.13	1.12	0.99
Incorporated	0	1	0.44	0.85	0.53	0.41	0.33
		2	0.81	1.20	0.98	0.80	0.64
		3	0.49	0.81	0.63	0.49	0.41
		4	0.58	0.31	0.36	0.69	0.54
	25	1	0.35	0.46	0.43	0.36	0.30
		2	1.09	1.41	1.28	1.16	0.96
		3	0.93	1.29	1.18	1.02	0.79
		4	0.35	0.18	0.32	0.39	0.36
	50	1	0.64	0.91	0.78	0.62	0.53
		2	1.05	1.44	1.30	1.06	0.84
		3	0.80	0.80	0.87	0.82	0.76
		4	1.04	1.15	1.06	1.17	0.96
	100	1	0.55	0.64	0.59	0.56	0.50
		2	1.24	1.60	1.34	1.23	1.16
		3	1.27	1.51	1.45	1.30	1.09
		4	0.96	0.97	0.77	0.83	1.03

[z] Total phosphorus (TP).

Table A5.11. Dissolved reactive phosphorus (DRP) time interval concentrations and flow-weighted mean concentrations (FWMC) in runoff measured 1 yr after manure application and incorporation at the Lacombe site.

Incorporation method	Target TP rate[z] (kg ha^{-1})	Replicate	DRP concentration (mg L^{-1}), residual manure FWMC 0-30 min	------- Time intervals (min) ------- 0-5	5-10	10-20	20-30
Non-incorporated	0	1	0.66	0.76	0.71	0.65	0.63
		2	0.80	0.79	0.81	0.84	0.76
		3	1.48	1.98	1.38	1.50	1.41
		4	1.11	1.10	1.28	1.15	1.05
	50	1	1.94	1.89	1.55	1.89	2.10
		2	1.82	1.83	1.86	1.90	1.72
		3	1.25	0.93	1.05	1.46	1.22
		4	1.75	1.93	1.63	1.83	1.66
	100	1	2.52	3.25	3.32	1.64	2.83
		2	2.46	2.90	2.72	2.39	2.30
		3	2.63	2.90	3.01	2.71	2.37
		4	2.13	2.00	1.87	2.12	2.27
	200	1	3.33	3.55	3.43	4.17	2.48
		2	5.03	10.47	9.26	7.56	n/s
		3	2.84	3.61	3.65	2.58	2.60
		4	-	-	-	-	-
Incorporated	0	1	0.77	0.68	0.76	0.80	0.76
		2	0.80	1.13	0.91	0.78	0.70
		3	1.00	1.10	1.20	1.06	0.90
		4	0.66	0.78	0.71	0.63	0.62
	50	1	0.58	0.82	0.80	0.49	0.54
		2	1.07	0.79	0.81	1.12	1.19
		3	-	-	-	-	-
		4	1.14	1.33	1.42	1.09	1.02
	100	1	1.06	0.95	1.10	1.24	0.94
		2	-	-	-	-	-
		3	-	-	-	-	-
		4	1.67	2.33	2.27	2.28	1.76
	200	1	3.24	1.92	3.68	3.62	3.10
		2	4.99	7.15	5.75	4.43	4.51
		3	1.81	2.13	1.86	1.59	1.87
		4	2.73	1.92	2.41	2.70	2.98

[z] Total phosphorus (TP).

Table A5.12. Dissolved reactive phosphorus (DRP) time interval concentrations and flow-weighted mean concentrations (FWMC) in runoff measured 1 yr after manure application and incorporation at the Wilson site.

Incorporation method	Target TP rate[z] (kg ha^{-1})	Replicate	DRP concentration (mg L^{-1}), residual manure FWMC 0-30 min	Time intervals (min) 0-5	5-10	10-20	20-30
Non-incorporated	0	1	0.18	0.19	0.19	0.19	0.16
		2	1.02	0.13	0.31	1.10	1.35
		3	0.20	0.18	0.21	0.21	0.19
		4	0.34	0.38	0.36	0.33	0.32
	50	1	1.40	1.21	1.32	1.43	1.48
		2	2.54	2.06	2.69	2.65	2.50
		3	1.37	1.42	1.38	1.35	1.38
		4	2.79	3.47	2.94	2.73	2.65
	100	1	4.06	4.03	4.11	4.11	4.01
		2	-	-	-	-	-
		3	1.72	1.18	1.29	1.62	2.21
		4	6.02	5.88	6.58	6.43	5.43
	200	1	6.14	6.00	6.02	6.18	6.22
		2	3.04	3.64	3.24	2.98	2.82
		3	2.16	2.19	2.19	2.14	2.15
		4	4.36	4.23	3.95	4.12	4.71
Incorporated	0	1	0.75	0.77	0.73	0.77	0.74
		2	0.22	0.22	0.21	0.23	0.22
		3	0.17	0.16	0.17	0.17	0.17
		4	0.15	0.16	0.18	0.15	0.15
	50	1	1.56	1.68	1.51	1.55	1.54
		2	1.45	1.53	1.44	1.42	1.45
		3	1.31	1.18	1.24	1.32	1.37
		4	0.61	0.32	0.57	0.68	0.63
	100	1	0.68	0.70	0.65	0.68	0.70
		2	3.55	3.51	3.66	3.51	3.57
		3	0.76	0.59	0.64	0.74	0.87
		4	1.22	0.86	0.91	1.22	1.40
	200	1	8.92	11.38	9.57	8.80	8.14
		2	4.43	4.80	4.49	4.40	4.32
		3	3.16	3.13	3.15	3.18	3.15
		4	10.41	9.49	10.04	10.78	10.41

[z] Total phosphorus (TP).

Appendix 6. Soil phosphorus from screened and unscreened soil samples.

Table A6.1. Soil-test phosphorus (STP) values from unscreened soil samples collected 1 yr after manure application from the three study sites.

Site	Incorporation method	Target TP rate[z] (kg ha^{-1})	n	Mean	SE	1	2	3	4[x]
				Unscreened STP[y] (mg kg^{-1})					
						Replicates			
Beaverlodge	Non-incorporated	0	4	43	2	38	44	46	42
		25	4	51	4	47	64	47	47
		50	4	73	10	68	61	102	60
		100	4	92	6	106	98	81	81
	Incorporated	0	4	45	5	35	59	42	45
		25	4	57	6	49	72	48	60
		50	4	71	1	72	69	72	69
		100	4	93	9	111	105	75	81
		Site mean	*32*	*66*	*4*				
Lacombe	Non-incorporated	0	4	134	10	117	143	116	159
		50	4	165	23	121	135	180	225
		100	4	219	25	162	282	224	208
		200	4	332	62	308	242	267	513
	Incorporated	0	4	109	11	105	80	131	121
		50	4	155	33	114	112	251	145
		100	3	149	11	137	138	171	na
		200	4	243	51	156	390	217	207
		Site mean	*31*	*190*	*17*				
Wilson	Non-incorporated	0	4	45	3	39	44	50	48
		50	4	194	24	201	134	194	249
		100	4	439	108	210	710	339	494
		200	4	779	175	598	436	839	1242
	Incorporated	0	4	54	5	62	49	42	62
		50	4	151	27	194	175	74	163
		100	4	279	27	271	207	300	337
		200	4	564	75	526	397	573	759
		Site mean	*32*	*313*	*50*				
		All sites mean	*95*	*189*	*21*				

[z] Total phosphorus (TP).

[y] Shaded values were included in comparisons between unscreened and screened samples but were excluded from all other analysis.

[x] Not analyzed, sample destroyed (na).

Table A6.2. Soil-test phosphorus (STP) values from screened soil samples collected 1 yr after manure application from the three study sites.

Site	Incorporation method	Target TP rate[z] (kg ha^{-1})	n	------ Screened STP (mg kg^{-1}) ------ Mean	SE	---- Replicates ---- 1	2	3	4[y]	Mean Difference[x] (mg kg^{-1})	t-test[w] (P-value)
Beaverlodge	Non-incorporated	0	4	41	2	36	47	39	43	2	0.50
		25	4	54	5	49	68	47	52	-2	0.14
		50	4	78	11	69	66	112	64	-5	0.06*
		100	4	96	7	101	114	86	83	-4	0.41
	Incorporated	0	4	48	6	42	65	40	43	-2	0.40
		25	4	56	6	50	73	48	53	1	0.54
		50	4	68	1	66	67	66	71	3	0.17
		100	4	94	9	101	114	74	89	-1	0.78
		Site mean	*32*	*67*	*4*					*-1*	*0.24*
Lacombe	Non-incorporated	0	4	113	5	102	107	116	127	20	0.09*
		50	4	156	23	124	119	165	218	9	0.15
		100	4	212	18	172	250	231	196	7	0.52
		200	4	342	42	277	449	273	371	-10	0.90
	Incorporated	0	4	101	11	104	76	128	97	8	0.24
		50	4	144	28	120	107	227	121	12	0.21
		100	3	134	11	134	115	154	na	14	0.15
		200	4	210	18	168	257	209	207	33	0.41
		Site mean	*31*	*178*	*15*					*12*	*0.24*
Wilson	Non-incorporated	0	4	46	3	37	47	48	53	-1	0.51
		50	4	246	82	167	93	253	471	-52	0.46
		100	4	401	95	217	666	342	379	37	0.28
		200	4	688	114	569	469	719	993	91	0.23
	Incorporated	0	4	53	6	64	49	38	61	1	0.48
		50	4	196	28	261	195	123	206	-45	0.02**
		100	4	338	45	291	235	412	412	-59	0.07*
		200	4	562	97	308	519	689	733	2	0.98
		Site mean	*32*	*316*	*45*					*-3*	*0.84*
		All sites mean	*95*	*187*	*19*					*2*	*0.71*

[z] Total phosphorus (TP).
[y] Not analyzed, sample destroyed (na).
[x] Mean difference = unscreened STP (Table A6.1) – screened STP.
[w] t-test was used to identify significant differences between the unscreened and screened STP values for each treatment.
* *P*<0.05, ** *P*<0.01.

Appendix 7. Soil phosphorus at various depths.

Soil-test phosphorus (STP) of various depths from selected target manure total phosphorus (TP) application rates of the incorporated treatments collected 1 yr after manure application and incorporation at all three sites.

	Target	STP (mg kg^{-1})											
	TP rate	-------- 0 to 2.5 cm --------				-------- 2.5 to 5 cm --------				-------- 5 to 15 cm --------			
Site	(kg ha^{-1})	Rep 1	Rep 2	Rep 3	Rep 4	Rep 1	Rep 2	Rep 3	Rep 4	Rep 1	Rep 2	Rep 3	Rep 4
Beaverlodge	0	35	42	42	39	19	39	41	36	20	39	34	52
	50	36	59	58	65	33	44	47	35	42	37	48	26
	100	39	72	87	96	39	39	55	27	36	35	38	39
Lacombe	0	109	124	97	66	91	83	90	61	79	43	61	43
	100	194	206	96	110	91	83	90	61	79	43	61	43
	200	188	184	332	227	178	118	220	249	93	67	83	105
Wilson	0	55	43	37	52	49	34	28	50	27	11	14	51
	100	337	294	163	133	188	175	192	101	57	46	56	59
	200	240	502	221	1250	150	338	97	594	58	75	37	113