Phosphorus Loading and Environmental Analysis in Manured Saskatchewan Soils

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Phosphorus (P) is a key element in plant nutrition, but excessive amounts can accumulate in the soil if manure P application rates exceed crop uptake over time. Risk of potential P movement and contamination of surface waters is directly related to the soluble P content of the surface soil. Thus it is important to have an accurate and efficient method of analysis that can be utilized for both agronomic and environmental purposes. On four long-term (five to eight years of annual application) manure research sites in Saskatchewan, four assessments of labile P in soils were compared: sodium bicarbonate extractable, water extractable, anion exchange membrane (PRS^{tm}) supply rate, and Modified Kelowna (MK) extractable on soils that received annual manure application rates in excess of recommended levels. All methods were highly correlated with one another, with the exception of MK. The soil P indices increased with manure P application rate and were correlated with plant P concentration and uptake.

Key Words: phosphorus, phosphate, PRS, kelowna, sodium bicarbonate, water soluble, swine manure, cattle manure, effluent

Introduction

The rapid expansion of intensive livestock operations on the Canadian prairies is generating interest in establishing a widely accepted soil test phosphorus (STP) method that will ensure manure land applications are agronomically and environmentally sustainable. The average nitrogen {N}:P ratio of manure is sometimes narrower than the N:P ratio needed by most arable crops, thus under long-term manure management, soil P elevation can occur (Eghball, 2003). Phosphorus testing is currently used to ensure adequate soil P for crop uptake over the growing season, but may not adequately represent P fractions that pose an environmental risk. Further understanding of P fractionation and the appropriate testing method is essential to establishing guidelines for environmentally sustainable use of manure.

Phosphorus soil tests are developed for a specific range of soil properties. Plant availability and potential movement off site are dependent on soil pH, texture, organic matter, slope, and mineralogy. The P fraction found in soil solution, is replenished from easily desorbed P held on the solid phase, or organic matter mineralization. In calcareous soil, labile P can be measured using Modified Kelowna (MK) (Qian et al, 1994), Sodium Bicarbonate Extractable Olsen (Olsen et al, 1954), Water Soluble (Schoenau and Huang, 1991), and Anion Exchange Membrane (AEM) (Qian et al, 1992) methods. Of these extracting solutions, for agronomic purposes, MK has indicated the best correlation with plant uptake over a growing season in a wide range of soils (Ashworth and Mrazek 1989, 1995). The MK extraction is commonly used in commercial labs, however the anion exchange membrane technique has more recently been utilized in routine soil testing for agronomic purposes in the form of the plant root simulator (PRS^{tm}) probe. Further study is needed to determine the most accurate P test for both agronomic and environmental purposes.

The objectives of this study were to 1) determine the relationship between manure application rate and soil test phosphorus on four long-term Saskatchewan sites under manure management, and 2) to determine the correlation between four measures of labile P: Water Soluble, MK, PRS^{tm}, and Olsen.

Materials and Methods

This project encompassed four sites across Saskatchewan at Dixon, Melfort, Plenty and Riverhurst. The Dixon study began in 1997, thus 2004 was its eighth year of operation, and it is located on a loam textured Black Chernozem (Cudworth Association) soil. Experimental design, for both the liquid hog manure (LHM) and solid cattle manure (SCM) studies at this site, is a randomized complete block design (RCBD) replicated four times. The test plots for the LHM and SCM sites are 3m by 30m and 3m by 3m respectively. The Melfort site was developed as a RCBD replicated four times in 1999, thus 2004 was its fifth year of study and it is situated on a loam textured Gray-Black Chernozem (Kamsack Association) soil. Liquid hog manure was applied on 6m by 30m test plots. The final two sites, Plenty and Riverhurst, were initiated in 1998 on a heavy clay Dark Brown Chernozem (Regina Association) and a sandy-loam, Brown Chernozem (Birsay Association) soil respectively. A RCBD experimental design was used, replicated three times in test plots of 6m by 30m strips, and LHM was used. The crop rotations for all four sites are shown in Table 1. There is large variation between these sites due to different soil characteristics (Table 2), climate, land management practices, crop rotations, and variation in manure application. Results will be compared statistically within each site and general comparisons made between sites.

Table 1. Crop rotations for Dixon, Melfort, Plenty and Riverhurst.

Site	Year							
	1997	1998	1999	2000	2001	2002	2003	2004
Dixon	canola	wheat	barley	canola	wheat	flax	barley	canola
Melfort	----------	----------	----------	wheat	canola	oats	canola	oats
Plenty	----------	----------	wheat	canary seed	wheat	crop failure	wheat	canary seed
Riverhurst	----------	----------	pinto beans	barley	barley	crop failure	wheat	potatoes

Table 2. Soil characteristics for Dixon, Melfort, Plenty and Riverhurst.

Site	Texture	pH†	E.C.† (mS cm^{-1})	Org. Carbon† (%)
		---------------- 0-15 cm	----------------	----------------
Dixon	Loam	7.4	0.23	2.7
Melfort	Loam	6.8	0.17	3.8
Plenty	Heavy Clay	8.2	0.39	1.8
Riverhurst	Sandy Loam	6.9	0.20	1.5

† Averages from spring 2003 soil samples.

The treatment application procedure was slightly different at each site. At Dixon, LHM and SCM were applied every season at low (1X ~ 100 kg N ha^{-1}), medium (2X ~ 200 kg N ha^{-1}), and high rates (4X ~ 400 kg N ha^{-1}) using either injection (LHM) or broadcast and incorporation (B&I) (SCM) techniques. The low rate may be considered an agronomic rate, with the amount of N added in balance with crop requirement for that year. Urea was applied at low (1X = 56 kg N ha^{-1}), medium (2X = 112 kg N ha^{-1}) and high rates (4X = 224 kg N ha^{-1}). On the Dixon hog manure site a sub-treatment of 12-51-0 fertilizer was banded across the end of each block, at a rate of 15 kg P_2O_5 ha^{-1} in 2002 and 2003, to provide P fertilizer sub-plots (PF plots). At Melfort LHM was applied at low rates (1X ~ 100 kg N ha^{-1}) every year, medium rates (2X ~ 200 kg N ha^{-1}) every second year, and high rates (3X ~ 300 kg N ha^{-1}) every third year. Urea was applied every year at an agronomic rate (1X = 80 kg N ha^{-1}). Sub-plots were created using a band of potassium sulfate and a band of elemental sulfur (S) at rates of 40 kg S ha^{-1} in the spring of 2002. Plenty and Riverhurst LHM treatments were applied every year at low (1X ~ 100 kg N ha^{-1}) and high (2X ~ 200 kg N ha^{-1}) rates. Urea treatments were also applied annually at low (1X = 40 kg N ha^{-1}) and high (2X = 80 kg N ha^{-1}) rates.

Analysis was conducted for several phosphorus parameters. In the spring of 2003 soil samples were collected from the 0-15 cm soil depth using PVC cores, and total digestible phosphorus (Thomas et al. 1967) was determined using a Technicon Autoanalyzer. In the fall of 2003 plant samples were collected from $1m^2$ plots to determine grain and straw yield. These were then dried, ground and digested in sulfuric acid-peroxide using a temperature-controlled digestion block (Thomas et al. 1967), and run on a Technicon autoanalyzer to determine plant P concentrations. In spring 2004 soil samples were collected from 0-15 cm depth using a hydraulic punch truck, air dried, passed through a 2 mm sieve, and then extracted using the following methods. The MK extraction (Qian et al. 1994) was run through an autoanalyzer, but the water extractable (Schoenau and Huang, 1991), sodium bicarbonate (Olsen et al. 1954), and PRS (Qian et al, 1992) supernatants were analyzed using molybdenum-blue color development (Murphy and Riley, 1962).

Statistical Analyses

Soil and plant phosphorus data was statistically compared using least significant difference (LSD) from a standard analysis of variance technique. All LSD calculations were conducted using the GLM procedure (SAS 1985), and Pearson correlation coefficients were calculated using SPSS 11.5

Results and Discussion

Dixon

The Dixon P balance at the LHM site was estimated for the past eight years (Table 3). The manure source at this site did not have excessive P relative to available N. The addition of the microbial phytase enzyme in the hogs' diet increases P solubility and hog uptake, and reduces P manure concentrations by an estimated 20-30 % (Cromwell et al. 1993, 1995, 2000). This resulted in low amounts of P added relative to N, and no P surplus at the 1X (agronomic N based) or 2X rate (Table 3). To compensate for this deficiency, 30 kg P_2O_5 ha $^{-1}$ was banded to create phosphorus fertilizer (PF) sub-plots, and net calculations indicated extra P in PF sub-plots versus no phosphorus fertilizer (NPF) plots. However, P fertilizer combined with manure nutrients like N and S, increases plant development, grain uptake, and final export of P off site, thus residual P (A-B) on PF sub-plots was negative, except for 2X and 4X rates (Table 3). In all plots, 4X manure treatments had the highest surplus P, and represent conditions where both excess N and P application is occurring. Calculations on the PF sub-plots indicate the control should have higher residual P compared to the 1X manure rate, because N deficiencies in the control limit P uptake and export off site (Table 3). This effect is important for both agronomic and environmental reasons.

Table 3. Dixon LHM Phosphorus Balance from 1997 to 2004.

Treatment	Total P					
	Inputs‡ (A)		Outputs§ (B)		Net (A-B)	
	No P	With P†	No P	With P†	No P	With P†
	------------------------------------ kg ha $^{-1}$ ------------------------------------					
Control	0	13	27	26	-27	-13
1X Injected	35	48	70	70	-35	-22
2X Injected	70	83	84	82	-14	1
4X Injected	139	152	90	88	49	64
1X B&I	0	13	60	61	-60	-48
2X Urea	0	13	64	67	-64	-54

† Refers to an additional 30 kg ha $^{-1}$ P_2O_5 applied in Spring 2002/2003

‡ Calculated from manure P concentration applied each year

§ Calculated from grain yield * %P concentration in grain

Monitoring soil P under annual cattle manure application is very important because the P balance calculations, as shown in Table 4, indicate that the 4X treatment has surplus P (A-B is positive) for 1X, 2X, and 4X treatments, with the greatest excess in the 4X treatment. Cattle manure has higher P concentrations, lower N mineralization rates, and B&I application increases N volatilization loss, which decreases the already low, manure N:P ratio. Overall, the P surplus associated with cattle manure addition is much higher than the swine manure, reflecting the low SCM N:P ratio. Cumulative N use efficiency at the SCM site was reported to be between 7-10% across all treatments (Mooleki et al. 2003), and crop P uptake would be limited even under increasing manure rate. This results in high residual P levels near the soil surface that are more susceptible to runoff and erosion offsite.

Table 4. Dixon cattle manure P balance for crop seasons 1997 to 2004.

Treatment	Total P		
	Inputs† (A)	Outputs‡ (B)	Net (A-B)
	---------------------- kg ha^{-1} ----------------------		
Control	0	32	-32
1X B&I	265	52	213
2X B&I	531	72	459
4X B&I	1062	90	972
2X B&I Urea	0	73	-73

† Calculated from manure P concentration applied each year
‡ Calculated from grain yield * %P concentration in grain

At Dixon, in spring 2003, the total soil P concentrations were not significantly different between treatments (Fig. 1), yet the P balance equations (Tables 3 and 4) suggest that a P surplus occurs under high manure rates over time. The grain and straw P uptake from fall 2003 (Fig. 2) shows increasing uptake on higher manure rates, thus a shift in plant available soil P is occurring. Total soil P assessment is not sensitive enough to reflect small differences that are occurring under the LHM site, however it is important to note that SCM does elevate total soil P, but the increase is not statistically significant. Labile P analysis methods are more useful for agronomic and environmental purposes as they more accurately reflect changes in plant available P on soil under manure application.

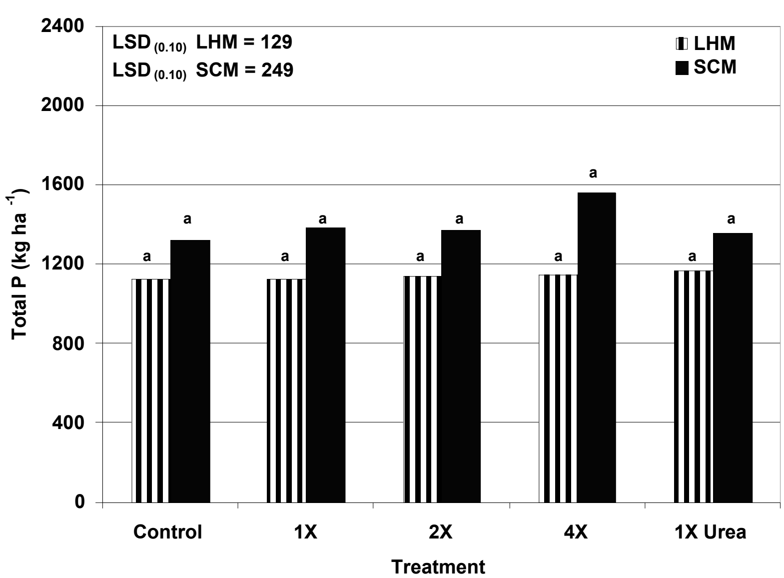

Fig. 1. Total soil P at Dixon site (0-15cm) measured in spring 2003, for LHM and SCM sites.

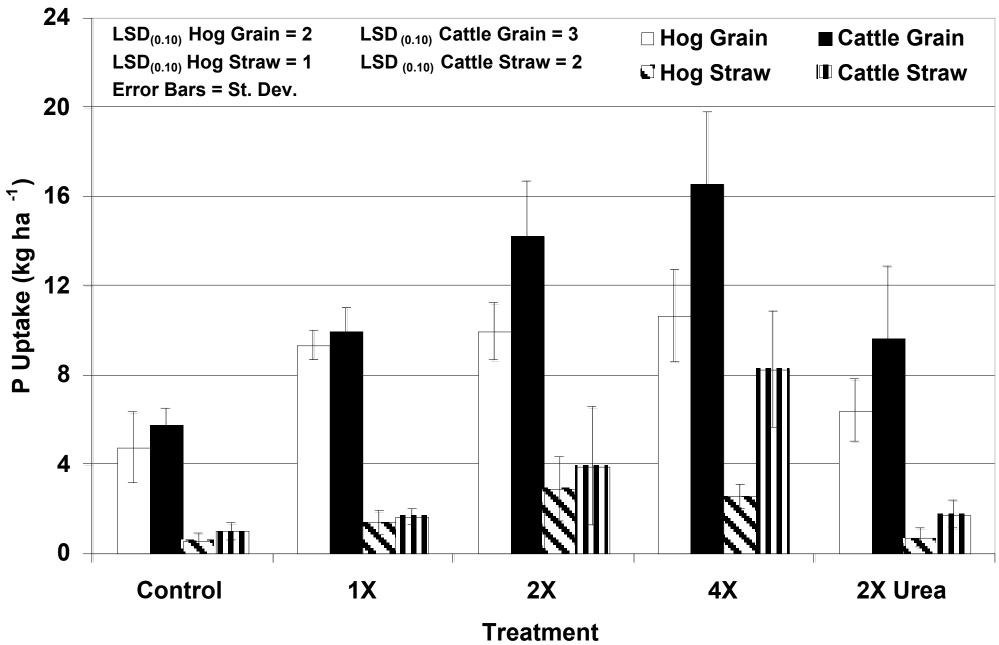

Fig. 2. Grain and straw P uptake as influenced by hog or cattle manure addition at the Dixon site, fall 2003.

Labile soil P was measured using four separate methods of analysis: MK, Olsen, water extractable, and PRS^{tm}. The MK technique is commonly used in commercial labs as a measure of crop available P, but was poorly correlated with the other three methods at both the LHM and SCM sites (Tables 5 and 6). Phosphorus testing on soils amended with inorganic P fertilization has indicated strong correlations between PRS^{tm}, MK, and Olsen methods (McKenzie and Bremer, 2003), however manure P reacts differently in the soil, and in this experiment the Olsen, water extractable, and PRS^{tm} were strongly correlated and most accurately predicted soil elevations in labile P. Under long-term manure management MK may not be the most sensitive method for identifying increasing labile P levels. It is important to note that MK was measured using the Technicon Autoanalyzer and the other measures of labile P were measured manually. Also this experiment was limited in sample size, thus further investigation should be conducted to either prove or disprove the suitability of the MK method on manured soils.

Table 5. Pearson correlation (N=20) coefficients for labile soil P (0-15cm) assessment at the Dixon SCM site.

	PRS^{tm}	Modified Kelowna	Total Olsen	Inorganic Olsen	Organic Olsen	Water Extractable
PRS^{tm}	1					
Modified Kelowna	0.170	1				
Total Olsen	0.929**	-0.078	1			
Inorganic Olsen	0.904**	-0.133	0.993**	1		
Organic Olsen	0.940**	-0.034	0.996**	0.977**	1	
Water Extractable	0.962**	0.303	0.854**	0.824**	0.870**	1

** Correlation is significant at the 0.01 level (2-tailed).

Table 6. Pearson correlation (N=24) coefficients for labile soil P (0-15cm) assessments at the Dixon LHM site.

	PRS^{tm}	Modified Kelowna	Total Olsen	Inorganic Olsen	Organic Olsen	Water Extractable
PRS^{tm}	1					
Modified Kelowna	0.009	1				
Total Olsen	.884**	-0.028	1			
Inorganic Olsen	.844**	-0.108	.965**	1		
Organic Olsen	.871**	0.038	.977**	.888**	1	
Water Extractable	.876**	0.197	.889**	.876**	.854**	1

** Correlation is significant at the 0.01 level (2-tailed).

Labile soil test P, as assessed by Olsen, water extractable, and PRS^{tm} methods, increased with increasing manure rate applied over time (Figs. 3 and 4). The assessments of labile P are more sensitive and effective than the total soil P measure, in revealing the extent of soil P loading and surplus. The agronomic (1X) rate of LHM did not significantly elevate labile P over the control, and the 4X SCM treatment had the highest labile P concentrations, consistent with P balance calculations indicating SCM had the highest P surplus.

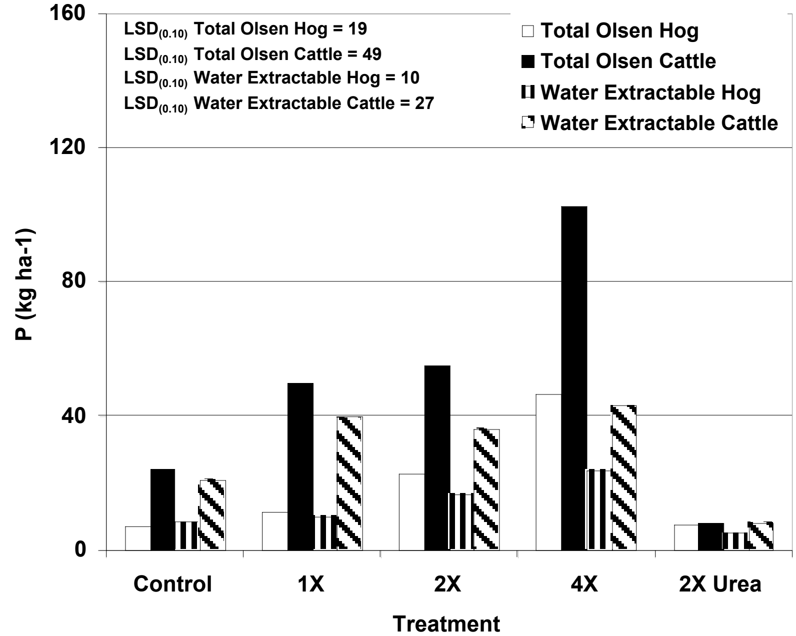

Fig. 3 Total Olsen and water extractable soil test P (kg P ha^{-1}) at Dixon site, spring 2004

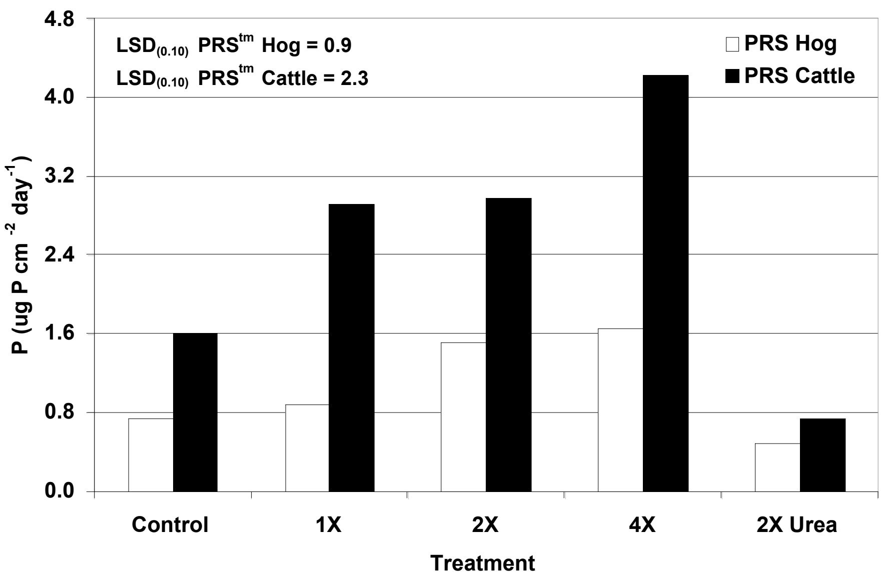

Fig. 4 Phosphorus supply rates (ug P cm^{-2} day^{-1}) at Dixon site, spring 2004.

Melfort

The P balance for Melfort (Table 7) for LHM treatments that received no additional S fertilizer indicated all of the P was being utilized by the crop each year, and P outputs exceeded inputs on all treatments. Additional S fertilizer increases crop growth and P uptake, resulting in even higher P outputs that could potentially cause deficiency concerns on S sub-plots at this site.

Table 7. Melfort LHM Phosphorus Balance from 2000 to 2004.

Treatment	Total P		
	Inputs† (A)	Outputs‡ (B)	Net (A-B)
	-----------------------	kg ha^{-1}	-----------------------
Control	0	28	-28
1X	12	65	-52
2X	18	52	-34
4X	8	56	-47
Urea	0	44	-44

† Calculated from manure P concentration applied each year
‡ Calculated from grain yield * %P concentration in grain

Labile soil P analysis indicated the PRS^{tm} and Olsen methods had the highest correlations at Melfort, and the water extractable and MK methods had the lowest. Melfort has higher soil organic matter that may be responsible for P sorption and formation of organophosphate complexes with inorganic manure P (Havlin et al, 1999). This reduces the proportion of available inorganic P that can be extracted from the soil using weaker mediums like water extraction and MK. The labile P content was relatively constant because of less frequent hog manure applications, which supports the balance calculations that indicate more P was actually being removed by the crop than added as manure. The control and urea treatments had the highest surplus P because other nutrient deficiencies limited crop uptake and export offsite (Fig. 5).

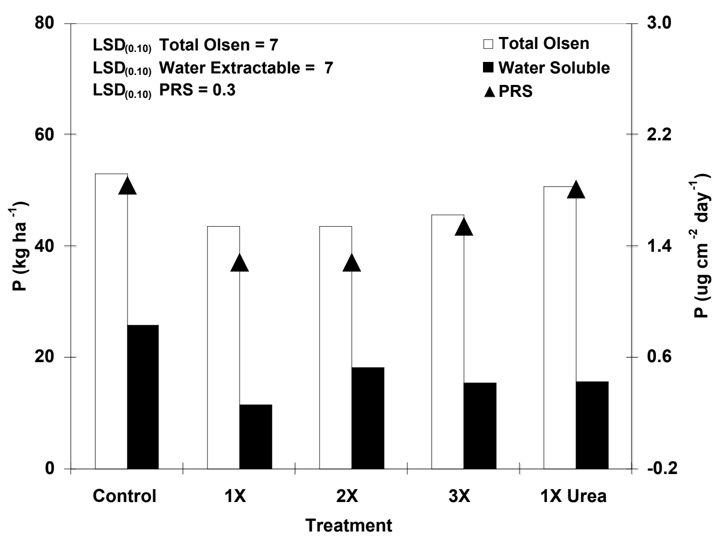

Fig. 5 Total Olsen, PRS^{tm}, and water extractable soil test P at Melfort site, spring 2004,

Plenty and Riverhurst

The results at both Plenty and Riverhurst sites were similar to Dixon. There was a strong correlation between the PRS^{tm}, water extractable, and Olsen methods of P analysis, but not the MK (Tables 7 and 8). There was also a strong positive relationship between manure rate and the water extractable, Olsen, and PRS^{tm} labile P fractions (data not shown).

Table 7. Pearson correlation (N=30) coefficients for labile soil P (0-15cm) assessment at the Plenty LHM site.

	PRS^{tm}	Modified Kelowna	Total Olsen	Inorganic Olsen	Organic Olsen	Water Extractable
PRS^{tm}	1					
Modified Kelowna	-0.231	1				
Total Olsen	.895**	-0.277	1			
Inorganic Olsen	.865**	-0.307	.971**	1		
Organic Olsen	.875**	-0.271	.988**	.927**	1	
Water Extractable	.876**	-0.261	.923**	.896**	.909**	1

** Correlation is significant at the 0.01 level (2-tailed).

Table 8. Pearson correlation (N=30) coefficients for labile soil P (0-15cm) assessment at the Riverhurst LHM site.

	PRS^{tm}	Modified Kelowna	Total Olsen	Inorganic Olsen	Organic Olsen	Water Extractable
PRS^{tm}	1					
Modified Kelowna	.770**	1				
Total Olsen	.898**	.675**	1			
Inorganic Olsen	.858**	.634**	.909**	1		
Organic Olsen	.829**	.622**	.958**	.760**	1	
Water Extractable	.979**	.762**	.944**	.892**		1

** Correlation is significant at the 0.01 level (2-tailed).

Conclusions

The results from labile soil P analysis indicated that soil texture, organic matter content, land management, manure source, rate and application frequency all have a significant impact on the level of soil P accumulation over time. Higher soil clay content increased the buffering capacity of soil, and resisted P loss mechanisms by binding it within the soil matrix. Excess manure application increased surplus P over time when crop uptake and export off site was less than what was applied in manure. Irrigation increased crop P uptake, but also increased potential leaching losses, especially in sandy soils that had a limited capacity to bind P at the soil surface. Hog manure sourced from intensive livestock operations utilizing the phytase enzyme reduced P concentrations in the manure and resulted in lower levels of soil P even on high rates of manure applied over several years. However, cattle manure elevated P levels when it was applied at excess rates over time. Through manure application rates that meet crop P requirements, and supplementation of inorganic N fertilizer to meet crop needs, potential environmental problems from P translocation off site can be avoided.

It is important to choose the proper soil test method to monitor levels when applying manure P in excess of crop needs, and results indicated that the MK test did not accurately reflect increasing P levels on soils under manure management. The PRS[tm], water extractable, and Olsen tests were strongly correlated with one another, and showed increasing labile P levels on high manure rates. This trend was also shown in the grain and straw P uptake. Although MK is often used in commercial testing labs to monitor soil P, the use of PRS[tm], Olsen, or water extractable methods were more accurate at indicating elevated soil P levels over time on manured soils.

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