Linking Manure Properties to Phosphorus Solubility in Calcareous Soils: Importance of the Manure Carbon to Phosphorus Ratio

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ABSTRACT

Land application of manure can increase P transfer in runoff, although the risk depends in part on the characteristics of the manure. We assessed this for calcareous soils using manures from swine (*Sus domesticus*) fed one of five barley varieties (*Hordeum vulgare* L.), including four low phytate mutants and a normal variety, to produce manures with a range of total P (6.8–4.9 g P kg^{-1}), water-soluble P (4.3–8.0 g P kg^{-1}), total N/P ratios (2.5:1–5.5:1), and total C/P ratios (31:1–67:1). Two experiments were conducted. First, manures were incorporated into three soils on a N (150 mg N kg^{-1} soil) or P (27.5 mg P kg^{-1} soil) basis three times during a 7-wk incubation. Second, 10 additional soils were incubated for 2 wk following a single P-based manure application (82.5 mg P kg^{-1} soil). Water and $NaHCO_3$ (Olsen) extractable P were determined at regular intervals, with microbial P determined by fumigation–extraction after each incubation. For N-based application (i.e., variable P amendment), extractable P increased with total P applied. For P-based applications, the increase in soil P was more closely correlated to microbial P concentration than manure P composition or soil properties. These results suggest that stimulation of the microbial biomass by added organic C is important in determining soil P solubility following manure application.

The number of pork production operations in the USA decreased from approximately 700 000 in 1980 to <100 000 in 2002 (NASS, 2002), yet pork production remained constant at around 9 billion kilograms per year (NASS, 2003). Such consolidation of animal production has serious environmental implications, because nutrient imports in feed and mineral fertilizer generate regional and farm-scale nutrient surpluses that contribute to nonpoint source nutrient pollution of water bodies (Sharpley et al., 1994; Sims et al., 1998). Phosphorus is a particular problem, because it accumulates in soil to concentrations above those needed for optimum crop production. This is due in part to unfavorable N/P ratios in manures relative to the uptake of these nutrients by most crops, which results in overapplication of P when manures are applied to meet the N requirement of the crop (Mikkelsen, 2000). In response to concern over the buildup of soil P and its potential impact on water quality, the USDA's NRCS now requires that manure application to high P soils be regulated on the basis of crop P requirements, a threshold soil test P value, or a P Site Index (Natural Resources Conservation Service, 2003).

Soluble P release to runoff from manure-amended soils varies considerably depending on the type of manure applied. This is primarily due to differences in the concentrations of total and soluble P in the manure (Sharpley and Moyer, 2000; Kleinman et al., 2002a, 2002b; Vadas et al., 2004), but may also be due in part to variability in other manure properties. Identifying such properties may therefore improve our ability to predict the risk of P transfer following manure application to soil.

Variability in soluble P in runoff from manure-amended soils is also linked to differences in soil properties. However, most studies have been performed in the Eastern USA, where rain fed agriculture occurs on acidic soils, and the dynamics of P in soil are primarily controlled by Al and Fe. In contrast, agricultural soils of the Western USA are typically irrigated and contain high $CaCO_3$ and low organic matter concentrations. Phosphorus reactions in such soils are conventionally considered to be controlled primarily by Ca (Lindsay, 1979), although some studies found that P sorption in calcareous soils was more closely related to the amount of organically complexed Fe and Mn (Leytem and Westermann, 2003), the iron oxide and clay content (Hamad et al., 1992; Ryan et al., 1985; Solis and Torrent, 1989), and aluminum oxides (Castro and Torrent, 1998).

Despite these differences, there is little information on the effect of P availability of organic sources on irrigated calcareous soils of the semiarid Western USA. El-Baruni and Olsen (1979) examined the effects of farmyard manure and fertilizer on the solubility of P in calcareous soils, while Goss and Stewart (1979) investigated the efficiency of P utilization of feedlot manure by alfalfa. Robbins et al. (1999, 2000) investigated the effects of dairy manure and cheese-whey waste on soil test P in irrigated calcareous soils. To date there have been no comprehensive studies on the effects of manure applications on soil test P buildup in these soils. This is unsatisfactory, because the recent expansion of the dairy and swine industry in the Western USA means that managing manure nutrients is an urgent priority. While the data generated for eastern acidic soils can be used as a guideline in some cases, experience has shown that data from these soils are not easily adaptable to the arid west.

Recent research demonstrated that varying the concentration of phytic acid in swine diets reduced manure total P but had little effect on the distribution of P fractions in the manures (Leytem et al., 2004). In particular, phytic acid concentrations in manures were small, which was probably due to hydrolysis of phytic acid in

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Abbreviations: WSP, water-soluble P.

the hindgut. Swine manures are therefore dominated (>90%) by inorganic phosphate, irrespective of the composition of the initial diet. Despite the similarity in P composition it is possible that other characteristics of manures from modified diets might influence P solubility following application to soil. The objectives of this study were to identify manure and soil characteristics that regulate increases in water soluble and bicarbonate extractable soil P following incorporation of swine manure in calcareous soils of the Western USA.

MATERIALS AND METHODS

Manure Collection and Analysis

All incubation studies were conducted using five different manure sources. Fresh manure samples (mix of feces and some urine) were collected daily, over 4 d, from swine housed in concrete pens without bedding. The swine had been fed diets prepared using one of five barley lines generating five different manure types. These consisted of the cultivar Harrington, which serves as a control and produces seed with normal levels of phytic acid, and four 'low phytic acid' lines derived from the cultivar Harrington (Dorsch et al., 2003). These low phytate lines are similar to the Harrington in nearly every way except that they are homozygous for a single low phytic acid mutation: M422 (low phytic acid 1-1), M635 (low phytic acid 3-1), M955, and M1070 (low phytic acid 2-1). The grains used in this study contained between 3.2 and 3.7 g P kg^{-1}, while the phytic acid contents ranged between 0.85 and 2.0 g P kg^{-1}.

After collection manures were immediately frozen (−80°C), lyophilized, and ground (2 mm) for analysis and use in the incubation study. Analysis of the manures were as follows: (i) total elements (Al, Ca, Fe, Mn, P) were determined by microwave-assisted digestion of a 0.5-g dried sample with 8 mL of concentrated HNO_3 and 2 mL of 30% (v/v) H_2O_2 with ICP–OES detection; (ii) water soluble phosphate (WSP) was determined in a 1:10 manure to deionized water ratio, shaken for 1 h, filtered through a 0.45-μm membrane, and analyzed by ICP–OES; (iii) phytic acid was determined by HPLC (Dorsch et al., 2003); and (iv) total N and C were determined by combustion of a 50 mg sample in a FlashEA1112 CNH analyzer (CE Elantech, Lakewood, NJ).

Manure characteristics are given in Table 1. For mutant barley diets, total P concentrations in manures ranged between 6.8 and 11.2 g P kg^{-1}, and were therefore between 25 and 54% less than manures from animals fed the Harrington diet (14.9 g P kg^{-1}). Water-soluble phosphate concentrations ranged between 4.3 and 8.0 g P kg^{-1}. There was a positive linear relationship between total P and WSP (WSP = 0.59 total P, r^2 = 0.89***).

The manure from swine fed the Harrington barley diet had the greatest phytic acid concentration (1.2 g kg^{-1}) followed by M422 > M635 > M1070 > M955 (0.1 g P kg^{-1}). Due to the consistency of manure N concentrations, there was a range of total N/P ratios (2.5:1–5.5:1), with the manure from the M955 diet having the most favorable ratio relative to the typical ratio utilized by crops (~5–6) (Mengel and Kirby, 1987). The total C/P ratios also varied (31:1–67:1), with manure from the M422 diet having the highest ratio. Total Ca and Fe in the manures ranged between 8.8 and 16.2 g Ca kg^{-1} and between 0.9 and 1.7 g Fe kg^{-1}, respectively. Total Al (~0.3 g Al kg^{-1}) and Mn (~0.2 g Mn kg^{-1}) concentrations were similar for all the manures.

Table 1. Select properties of the manures used in the incubation studies (all measurements on a dry weight basis).

Manure property	Harrington	M422	M635	M955	M1070
Total Al, g kg^{-1}	0.3	0.2	0.4	0.2	0.3
Total Ca, g kg^{-1}	16.2	11.6	10.5	10.2	8.8
Total Fe, g kg^{-1}	1.7	0.9	3.7	1.7	1.5
Total Mn, g kg^{-1}	0.2	0.1	0.2	0.2	0.2
Total P, g kg^{-1}	14.9	6.8	9.9	7.5	11.2
Water soluble P, g kg^{-1}	8.0	4.3	6.1	4.5	7.2
% Water soluble P of Total P	53.7	63.2	61.6	60.0	64.3
Phytic acid, g kg^{-1}	1.2	0.9	0.8	0.1	0.3
% Phytic acid of Total P	7.7	13.6	8.4	1.3	2.6
Total N, g kg^{-1}	37	33	44	41	43
Total C, g kg^{-1}	460	460	470	470	460
N/P	2.5	4.9	4.4	5.5	3.8
C/P	31	67	47	63	41

Soil Sampling and Analysis

Thirteen soils (0- to 30-cm depth) were selected to represent a range of soil properties commonly associated with irrigated agricultural soils in the semiarid Western USA (Table 2). Details of soil collection and analysis can be found in Leytem and Westermann (2003). The majority of the soils either had calcic horizons or were classified as calcareous or carbonatic and all but two soils had a pH > 7.0. An acidic soil (Palouse, pH 4.9) was included because it is one of the major agricultural soil groups in Northern Idaho and has a higher organic C content (25.7 g kg^{-1}) than the other soils, which ranged between 2.6 and 13.5 g C kg^{-1}. The Roza soil (pH 6.4) was also selected as it is a common desert soil typically converted to irrigated agriculture and has higher clay content (246 g kg^{-1}) than the other soils, which ranged between 25 and 180 g kg^{-1}.

These soils were also selected because they varied in chemical properties commonly associated with P sorption and had a wide range of WSP (0.10–6.18 mg kg^{-1}) and bicarbonate extractable P (Olsen P, 2.8–67.8 mg kg^{-1}). Crop responses to P additions are not expected in soils with Olsen P concentrations >20–25 mg P kg^{-1} (McDole and Westermann, 2005). The soils had a range of calcium carbonate equivalent lime concentrations (CCE, 0–496 g kg^{-1}). Amorphous Al and Fe (oxalate extractable) concentrations were between 0.27 and 1.30 and 0.29 and 2.02 g kg^{-1}, respectively. Organically complexed Fe and Mn (NTA-extractable) concentrations were between 0.14 and 1.35 and 0.07 and 0.32 mg kg^{-1}, respectively.

Experiment 1

An initial experiment was conducted on three soils to determine the time required for P solubility to reach short-term equilibrium following manure addition and to examine the buildup of soil test P due to multiple manure applications over time at both N-based and P-based application rates. Each manure was incorporated individually (in triplicate) into 100-g portions of each of three soils (numbers 1, 2, and 3 in Table 2) at either an N based (120 mg N kg^{-1}) or P based (27.5 mg P kg^{-1}) application rate. An inorganic P source (KH_2PO_4) was applied at the same P rate to represent mineral fertilizer, and a control (unamended soil) was included for each soil.

Application rates were typical of those recommended for potato (*Solanum spp.*) production in Idaho. Recommended N application rates can range from 0 to 75 mg N kg^{-1}, depending on soil test N, while recommended P applications range from 0 to 36 mg P kg^{-1}, depending on Olsen P concentration and soil lime content (McDole and Westermann, 2005). We assumed approximately 50% of manure N and 70% of manure P would be available (Eghball et al., 2002), so our application rates were close to the maximum recommended rates.

For N-based applications, since manures were similar in

Table 2. Selected physical and chemical properties for soils used in incubation studies, samples collected from the 0- to 30-cm depth.

Soil no.	Soil series	Soil classification	Clay†	OC‡	pH§	CCE¶	WSP#	Olsen P††	Al_{ox}‡‡	Fe_{ox}‡‡	Fe_{nta}¶¶	Mn_{nta}¶¶
			— g kg^{-1} —			g kg^{-1}	— mg kg^{-1} —		— g kg^{-1} —			
1	Declo	coarse-loamy, mixed superactive, mesic Xeric Haplocalcids	132	8.2	7.9	114.3	0.40	12.6	0.78	0.59	0.30	0.20
2	Warden	coarse-loamy, mixed superactive, mesic Xeric Haplocambids	62	4.3	7.1	13.7	0.83	9.3	0.62	1.64	0.19	0.06
3	Portneuf	coarse-silty, mixed superactive, mesic Durinodic Xeric Haplocalcids	180	7.5	7.6	170.0	0.03	4.0	0.65	0.45	0.50	0.27
4	Millville	coarse-silty, carbonatic, mesic Typic Haploxeroll	146	13.5	7.9	496.0	2.33	18.8	0.96	0.97	0.46	0.29
5	Greenleaf	fine-silty, mixed, superactive, mesic Xeric Calciargids	162	8.0	7.5	19.7	4.90	28.0	1.02	2.02	0.62	0.25
6	Roza	fine smectic, mesic Xerertic Haplocambid	246	5.3	6.4	40.0	1.36	19.0	0.74	0.56	0.44	0.19
7	Palouse	fine-silty, mixed, superactive, mesic Pachi Ultic Haploxerolls	157	25.7	4.9	0.0	5.37	67.8	1.30	1.98	1.03	0.30
8	Rad	coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocambids	145	13.0	7.6	91.0	6.18	45.7	0.79	0.65	0.14	0.29
9	Wolverine	mixed, rigid, Xeric Torripsamments	110	16.0	7.7	38.0	1.78	25.1	0.77	0.55	0.80	0.32
10	Terreton	fine, smectic, calcareous, frigid Typic Torriorthents	155	2.6	7.8	86.0	0.10	2.8	0.43	0.55	1.35	0.14
11	Portneuf	coarse-silty, mixed superactive, mesic Durinodic Xeric Haplocalcids	125	6.4	7.5	186.0	0.60	51.1	0.65	0.58	0.30	0.21
12	Wodskow	coarse-loamy, mixed superactive mesic Aquic Haplocalcids	115	9.4	7.7	25.0	2.28	41.8	0.92	0.29	0.16	0.23
13	Kecko	coarse-loamy, mixed superactive mesic Xeric Haplocacids	25	5.0	7.3	5.0	1.45	14.5	0.27	0.75	0.15	0.07

† Particle size determined by method of Gee and Bauder (1986).
‡ Organic carbon (Walkley and Black, 1934).
§ pH determined with 1:1 soil/solution ratio.
¶ Calcium carbonate equivalent (Allison and Moodie, 1965).
# Water soluble P.
†† Bicarbonate P.
‡‡ Oxalate-extractable Al and Fe (Jackson et al., 1986).
¶¶ Nitrilotriacetate extractable Fe and Mn (Yuan et al., 1993).

total N, we applied the same total amount of manure to each soil, based on a calculated N rate for the Harrington manure. Application of identical amounts of manure allowed comparison of the buildup of soil test P between manure sources, which would be the common practice in areas not restricted to P-based manure applications. After incorporation, the soils were incubated in 250-mL polyethylene containers in a constant temperature room (22°C) in a completely randomized design. Two holes were made in the tops of the incubation containers to allow gas exchange and prevent anaerobic conditions during the incubation. Soil moisture content (20% by weight) was maintained by adding deionized water at weekly intervals, and varied <1% between adjustments.

Soils were incubated for 20 d with subsamples (~3 g) taken after 0, 1, 3, 5, 10, and 20 d. It was determined that a short-term equilibrium was reached after approximately 10 d on the three soils (Fig. 1, Warden soil shown), therefore incubation following additional manure applications was set at 14 d. A second manure or inorganic P application was made at the same initial rate (manure additions were adjusted for reduced soil weights) and incubated for 14 d (subsampled at Day 35), followed by a third treatment application which was again incubated for an additional 14 d (subsampled at Day 49). Control soils were sampled on the same days as the treated soils.

Moist subsamples of the incubation soil mixtures were analyzed as follows: (i) WSP in a 1:100, soil/deionized water ratio, shaken for 1 h and filtered through a 0.45-μm membrane; (ii) Olsen P using the method of Olsen et al. (1954); and (iii) microbial P by $CHCl_3$ fumigation and $NaHCO_3$ extraction (Brookes et al., 1982). Olsen P and WSP were determined by the colorimetric method of Murphy and Riley (1962).

Experiment 2

To determine if trends in manure P reactivity found on the initial three soils would apply to a wider range of soils with varying chemical properties, incubations were performed on 10 additional soils (Numbers 3–13 in Table 2). To compare P solubility in manure-amended soils a single manure application was made at the start of the experiment equivalent to that in the initial experiment after three additions (i.e., 82.5 mg P kg^{-1}), with a control included for each soil. To be consistent soils were incubated for 14 d before analysis and soil moisture content (20% by weight) was maintained by adding deionized water at weekly intervals, and varied <1% between adjustments. Soils were sampled at 14 d and analyzed as described previously.

Calculation of Increase in Water-Soluble and Olsen P

The increase in WSP and Olsen P was calculated for the five manures and inorganic P treatment evaluated in the incubation study. This calculation allows comparison of the increase in soil-test P due to treatment application, thereby normalizing for initial soil test P. After addition of 82.5 mg P kg^{-1} and incubation, we calculated the increase in WSP and Olsen P in soils amended with manure (P_M) or inorganic P (P_I) by as follows:

$$\text{Increase in WSP/OlsenP (mg kg}^{-1}) = \text{Soil } P_M/P_I - \text{Soil } P_{Control}$$

Statistics

All statistical analysis was performed using the Statistical Analysis System (SAS Institute, 1999). We used linear regression analysis (GLM), Pearson correlation, and analysis of variance using Duncan's multiple range test ($P < 0.05$) for mean separation. Slope comparisons made in Exp. 1 were done using the Mixed procedure and were determined to be different as

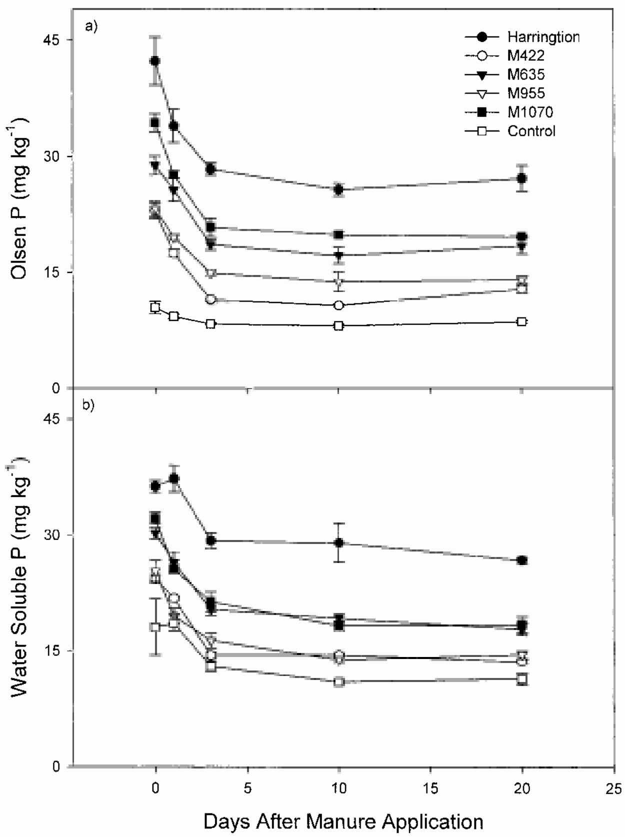

Fig. 1. Change in (a) Olsen P and (b) water-soluble P over 20 d following incorporation of five manures applied at an N-based application rate (120 mg N kg^{-1}) on the Warden soil. Error bars represent the standard deviation of the means.

evidenced by nonoverlap of the associated 95% confidence intervals.

RESULTS

Experiment 1

In all three soils there was an initial increase in both WSP and Olsen P following treatment application at both the N-based and P-based application rates. This was followed by a decline during the first 5 to 10 d, after which extractable P concentrations stabilized (Fig. 1; for N-based application rate on Warden soil only). The treatments, soils, and the interaction treatment by soil were significant ($P < 0.05$) for both the N-based and P-based application rates. After three successive manure applications at an N-based application rate, soils that received the most total P (Harrington diet) had significantly greater increases in WSP and Olsen P concentrations than the other manure treatments (Fig. 2). The rate of WSP increase, as determined by the slope of P applied vs. WSP increase, was greatest for the Harrington treatment followed by M1070, with the M955 and M422 showing the least accumulation of P over time. The rate of Olsen P increase was similar to that of WSP increase. These followed the trend Harrington > M1070 > M635 > M955 > M422 on the Warden soil, while on the Portneuf and Declo soils there were no significant differences between the M955 and M422 treatments. Comparisons of treatment means following three N-based applications of manure are shown in Table 3. The greatest increases in WSP following three manure applications were from the Harrington and M1070 treatments, while the M422 and M955 treatments had the least impact on WSP. The trends in increases of Olsen P following manure addition were the same on all three soils (Harrington > M1070 > M635 > M955 > M422).

The response in WSP and Olsen P in soils receiving a P-based manure application was similar to that seen in the N-based application, although the increase WSP and Olsen P from the KH_2PO_4 treatment was greater than from the manure treatments (Fig. 3). The rate of WSP increase over three applications was greatest for the KH_2PO_4 treatment on the Warden and Portneuf soils, while on the Declo soil, the KH_2PO_4 treatment was not significantly different from Harrington. There were few differences between the remaining treatments. Comparisons of treatment means following three P-based applications of manure are shown in Table 3. The increase in WSP was greatest from the KH_2PO_4 treatment on the Warden and Portneuf soils, while in the Declo soil both the KH_2PO_4 and Harrington treatment were not significantly different from each other (although both were significantly greater than the other manure treatments).

The rate of Olsen P increase was similar to that of WSP increase with KH_2PO_4 showing the greatest P accumulation while M422 and M955 had the least accumulation. The increase in Olsen P, following three manure applications, has the same trend on the Warden and Portneuf soils with KH_2PO_4 > Harrington > M1070 > M635 > M422 = M955, while on the Declo soil the trend was KH_2PO_4 = Harrington > M1070 > M635 > M422 = M955.

To determine which manure characteristics had the greatest impact on increases in WSP and Olsen P, Pearson correlation coefficients ($P > 0.05$) were calculated for the increase in extractable WSP and Olsen P vs. measured manure properties. The two manure properties most closely associated with increases in WSP and Olsen P were the C/P ($r = -0.56$ and -0.87, respectively) and N/P ($r = -0.61$ and -0.88, respectively) ratios of the manures (Fig. 4, C/P vs. Olsen P data). This inverse relationship between soluble P and the C/P ratio appeared to be due to microbial P uptake following stimulation of the microbial biomass by decomposable C addition, because there was a linear relationship between microbial P and both WSP and Olsen P (Fig. 5).

Experiment 2

In Exp. 2, the treatments, soils, and the interaction treatment by soil were significant ($P < 0.05$). To further explore the relationship between manure properties and increases in WSP and Olsen P, Pearson correlations coefficients for the 10 soils in Exp. 2 were calculated (Table 4). The manure characteristics having the greatest effect on increases in WSP and Olsen P were the C/P and N/P ratio of the manures. For all soils tested, there was a negative relationship between the amount

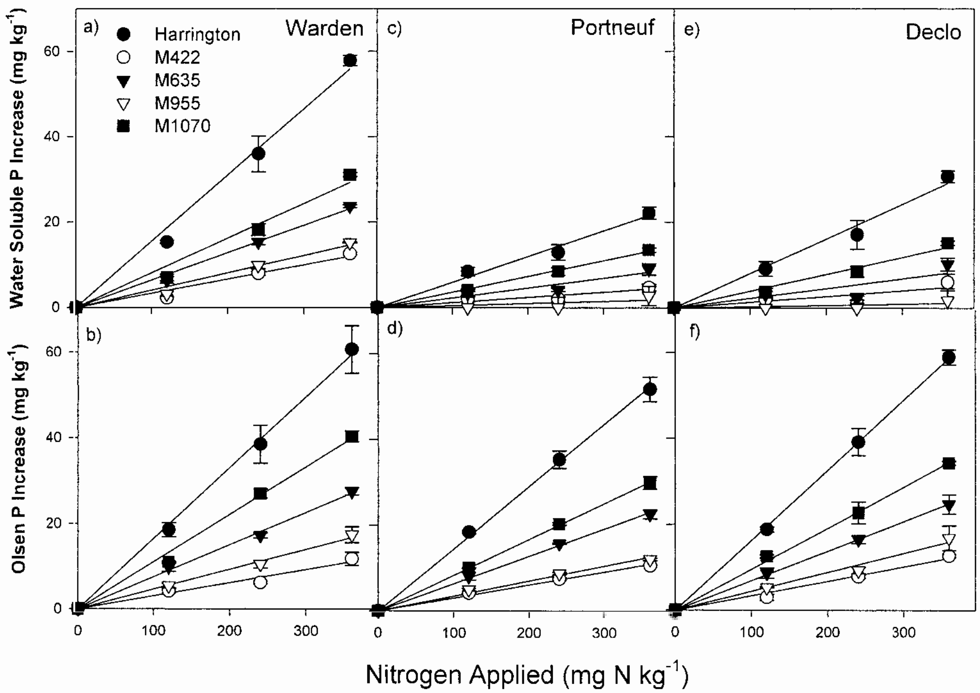

Fig. 2. Increase in (a, c, e) water-soluble P and (b, d, f) Olsen P following application of five manures at 120, 240, and 360 mg N kg^{-1} on the (a, b) Warden, (c, d) Portneuf, and (e, f) Declo soils. Error bars represent the standard deviation of the means.

of C added with the manure treatment and the increase in Olsen P. There is some variability in the data due to the differences among soils, but when linear regressions were calculated for all treatments on individual soils, the regression fits (r^2) ranged between 0.82 and 0.99 with slopes between −0.26 and −0.46 (Table 5). Relationships between increases in WSP and the manure C/P ratio were not as strong as with Olsen P. Linear regression of the increase in WSP and the manure C/P ratio by soil gave slopes ranging between −0.06 and 0.43 with r^2 values between 0.38 and 0.93 (data not shown).

Forward stepwise regressions were performed for the increase in WSP and Olsen P with all manure properties measured ($P > 0.01$). Stepwise regression selected the equations: increase in WSP = 31.6 − 0.25 manure C/P ratio ($R^2 = 0.21$); and increase in Olsen P = 43.0 − 0.41 manure C/P ratio ($R^2 = 0.49$). The relationship between microbial P and both WSP and Olsen P was not as strong in the 10 soils as it was on the three original soils; regression coefficients (r^2) were 0.07 and 0.17, respectively.

Since there was a wide range in chemical properties that influence P sorption in these soils, Pearson correlations coefficients for the 10 soils in Exp. 2 were calculated for the increase in extractable WSP and Olsen P vs. measured soil properties (Table 4). The soil characteristic most closely associated with changes in both WSP and Olsen P was the organically complexed Mn concentration. Additional soil properties that were significantly related to increases in both WSP and Olsen P were the P sorption capacity, amorphous Al, and the total Ca and Al. Forward stepwise regressions were performed for the increase in WSP and Olsen P with all soil properties measured ($P > 0.01$). The stepwise

Table 3. The increase in water soluble P (WSP) and Olsen P from three applications of manure (360 mg N kg^{-1} for N-based applications or 82.5 mg P kg^{-1} for P-based applications) on soils from Exp. 1.

	Increase in Water Soluble P			Increase in Olsen P		
	Declo	Warden	Portneuf	Declo	Warden	Portneuf
	mg kg^{-1}					
			N-based application			
Harrington	30.7a†	57.8a	22.2a	59.2a	61.5a	51.6a
M422	6.1c	12.6e	4.8c	12.9e	12.6e	10.5e
M635	10.2bc	23.7c	9.1bc	25.0c	28.4c	22.5c
M955	2.0d	15.2d	2.8d	17.1d	18.3d	12.0d
M1070	15.2ab	31.0b	13.6ab	34.5b	41.2b	29.7b
			P-based application			
Harrington	22.5a	29.2b	9.7b	37.7a	26.4b	25.0b
M422	5.5c	13.5e	5.0c	15.1d	15.4e	10.6e
M635	4.2c	18.7d	4.1c	19.3c	20.5d	15.8d
M955	4.3c	14.2e	4.4c	14.6d	16.4e	11.4e
M1070	12.1b	21.2c	8.0b	23.7b	23.8c	20.6c
KH_2PO_4	34.3a	46.1a	28.1a	40.8a	50.2a	48.9a

† Within column means (for each application rate) followed by the same letters are not significantly different at $P < 0.05$.

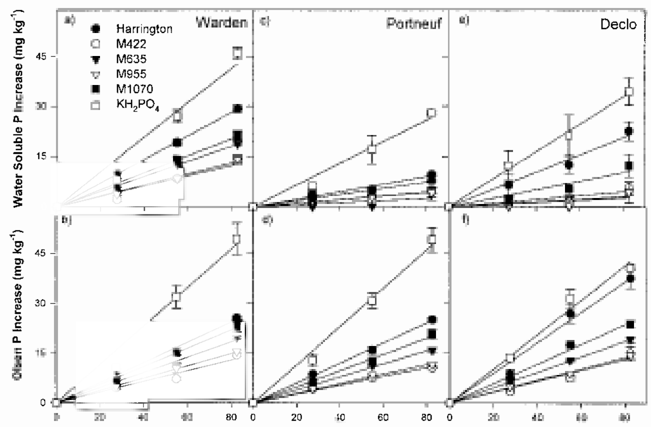

Fig. 3. Increase in (a, c, e) water-soluble P and (b, d, f) Olsen P following application of five manures at 27.5, 55, and 82.5 mg P kg^{-1} on the (a, b) Warden, (c, d) Portneuf, and (e, f) Declo soils. Error bars represent the standard deviation of the means.

regression selected the equations: increase in WSP = 31.7 − 0.06 Mn_{NTA} (R^2 = 0.33), and increase in Olsen = 34.3 − 0.05 Mn_{NTA} (R^2 = 0.24).

DISCUSSION

The manures used in this study were unique in that they were produced from a group of similar age swine with essentially identical diets except for the substitution of one of five barley varieties as the main ingredient. This allowed examination of the impact of varying manure chemical characteristics without changing production or handling, thereby minimizing changes in manure physical properties.

When the manures were applied based on N content (i.e., a similar amount of each manure applied), differences in P solubility were dominated by the total P concentration of the manures. As expected, the solubility of P in the amended soils was greater for treatments in which greater amounts of total P were added. Many studies reported a positive relationship between the amount of total P applied (manure, compost, and fertilizer treatments) and extractable P in soil (e.g., Eghball and Power, 1999; Gale et al., 2000; Novak et al., 2000; Whalen and Chang, 2001). Reddy et al. (1980) found a positive relationship between total P added as swine lagoon effluent and the amount of P desorbed after four extractions with 0.01 *M* $CaCl_2$. Ebeling et al. (2002)

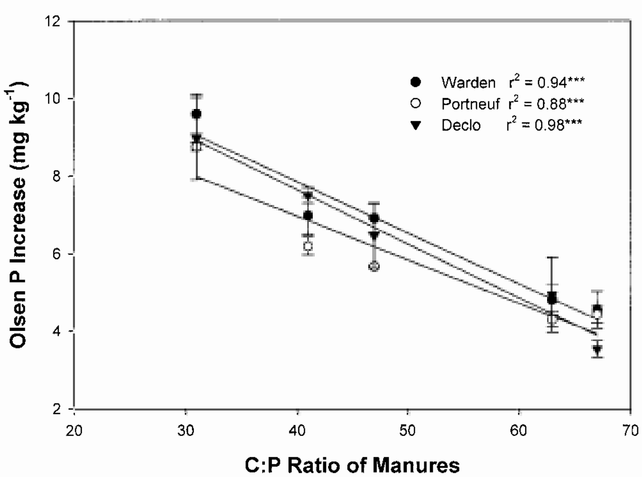

Fig. 4. Relationship between the C/P ratios of manure treatments and Olsen P increase on the Warden, Portneuf, and Declo soils after addition of 82.5 mg P kg^{-1}. Error bars represent the standard deviation of the means.

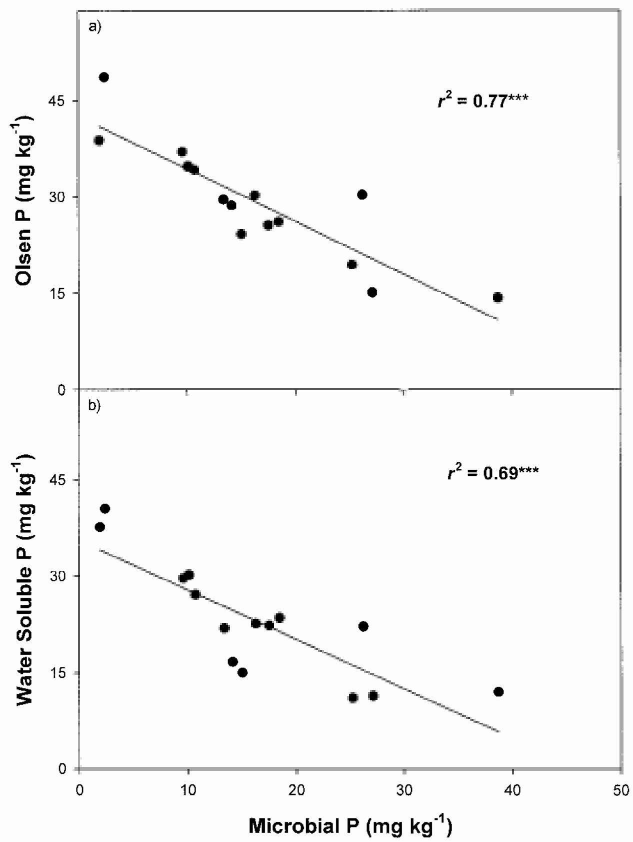

Fig. 5. Relationship between (a) Olsen P and (b) water-soluble P and microbial P following addition of 82.5 mg P kg^{-1} (as manure) on the Warden, Portneuf, and Declo soils.

Table 4. Pearson correlation coefficients for the increase in water soluble P (WSP) and Olsen P and manure and soil properties after addition of 82.5 mg kg^{-1} manure total P on the 10 soils in Exp. 2.

	Soil P	
	WSP increase	Olsen P increase
Manure property		
C/P	−0.47**	−0.71***
N/P	−0.41**	−0.63***
WSP/TP	−0.19	−0.32*
WSOP/TP	0.27*	0.31
Soil property		
NTA_{Mn}	−0.58***	−0.49**
P sorption capacity	−0.51**	−0.34*
Al_{ox}	−0.45**	−0.29*
Total Ca	−0.40**	−0.33**
Total Al	−0.37**	−0.38**
OC	−0.36**	−0.25
CCE	−0.31*	−0.29*
Total Fe	−0.26	−0.29*

* Significant at the 0.05 probablility level.
** Significant at the 0.01 probablility level.
*** Significant at the 0.001 probablility level.

Table 5. Regression parameters for the relationship between increase in Olsen P (y, mg kg^{-1}) and the manure C/P ratio (x, g g^{-1}) for the soils in Exp. 2.

Soil no.	Intercept	Slope	r^2
4	29.0	−0.29	0.99***
5	31.0	−0.30	0.90**
6	41.5	−0.40	0.91**
7	30.2	−0.26	0.86*
8	37.6	−0.46	0.94**
9	29.8	−0.30	0.90**
10	32.8	−0.32	0.99***
11	36.4	−0.40	0.99***
12	44.4	−0.40	0.88**
13	41.9	−0.28	0.82*
Combined soils	43.0	−0.41	0.49***

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.

reported that soils amended with manure from dairy cows (*Bos taurus*) fed a high P diet released 10 times the amount of dissolved P to runoff compared to soils amended with manure from a low P diet (the manure was applied at the same rate).

In this case, the use of the low phytic acid barley varieties as a feed would have an environmental benefit. If manures are applied to meet crop N needs, then the application of P is reduced for manures from the low phytic acid barley diets. Crops typically grown in the Western USA (barley, corn [*Zea mays*], potatoes) have an N/P uptake ratio of approximately 5.5 (Mengel and Kirby, 1987), the same as the manure generated from the M955 diet. If the normal barley diet were used (N/P ratio of 2.5) there would be more than twice the amount of P needed by the crop applied with the manure, and therefore P would accumulate at a greater rate.

To compare the relative P solubility of the manures, we used P-based application treatments (different amounts of manure added to soils). As the proportion of WSP to total P was similar in all manures, this allowed us to examine the influence of other manure characteristics on P solubility in amended soils. The most striking finding was that the amount of C added with the manure had the greatest influence on changes in extractable P. The soil test P most closely correlated to the manure C/P ratio was Olsen P, a soil test used to predict plant available P and more recently shown to be the best soil test for predicting P losses in runoff from calcareous Western USA soils (Turner et al., 2004).

A negative trend existed between C added (C/P ratio) and changes in Olsen P on all soils, with some variability in slope and intercept. The majority of slopes were between −0.3 and −0.4 (increase in Olsen P in mg P kg^{-1} vs. C/P ratio in g g^{-1}, Table 5). Slopes that varied greatly from this range were for soils with poor linear fits, which may be better described with polynomial models. The differences in the intercepts are most likely due to differences in soil P sorption capacity and the extent to which the soils are already saturated with P. Attempts to further normalize the data by accounting for soil properties such as P sorption capacity, percentage of P saturation, and other factors regulating P sorption, were unsuccessful.

The inverse relationship between the increase in extractable soil P and the addition of C in manure strongly suggests the importance of microbial processes in regulating P solubility following manure application to calcareous soils. This is potentially important, because few models or indexes account for microbial immobilization. Heterotrophic soil microbes are commonly limited by the availability of organic substrate, and can respond rapidly when this becomes available (De Nobili et al., 1996). Microbial processes also exert a marked influence on P concentrations in solution (Seeling and Zasocki, 1993; Turner and Haygarth, 2001). In the current study, application of manures with wide C/P ratios resulted in greater microbial biomass P concentrations. The importance of this was demonstrated by the strong negative correlation between added C (and the C/P ratio) and the increase in extractable P for all soils, irrespective of the soil chemical or physical properties considered likely to regulate P solubility. This phenomenon is rarely, if ever, considered in studies of manure P dynamics following land application. However, given that microbes in almost all soils are strongly limited by the availability of labile C, it is likely to be highly important wherever manure is applied to soil.

The soil characteristic most commonly associated with P sorption in calcareous soils is the $CaCO_3$ content (Lindsay, 1979). Sharpley et al. (1984) found that extractable P was negatively correlated to $CaCO_3$ concentrations following addition of fertilizer to 20 calcareous soils. In other studies, P sorption in calcareous soils has been linked to the Fe oxide and clay content (Hamad et al., 1992; Ryan et al., 1985; Solis and Torrent, 1989), as well as to Al oxides (Castro and Torrent, 1998). In contrast, the increases in soil test P from manure additions on our soils were most closely related to the amount of organically complexed Mn, while $CaCO_3$, clay, and metal oxide concentrations were only weakly correlated to soil test P increases following manure addition. These results are consistent with the findings of Leytem and Westermann (2003), who reported that the P sorption maxima on these soils were related to the amount of organically complexed Fe and Mn. Although regression does not elucidate actual interactions of soil properties, the continual selection of organically complexed metals does suggest that these metals are an important component of P sorption. This may be due to P complexation with organic matter through metal bridges, or possibly organic C interferes with Ca-P and metal oxide precipitation by coating the surfaces of carbonates and retaining P in these surface complexes through metal interactions.

CONCLUSIONS

Manipulation of swine diets alter the chemical composition of the resulting manure, which influences P solubility following manure application to soil. The use of low phytate barley varieties reduces total P in manures and subsequently reduces soluble soil P when manures are applied on an equivalent weight. When these manures are applied on a P-based application rate, other manure characteristics influence soil P solubility. For semiarid calcareous soils, which tend to have low organic C concentrations, the C/P ratio of added manure is a key regulator of subsequent soil P solubility. This effect overrides the influence of soil chemical properties such as $CaCO_3$ concentration, clay content, pH, or amorphous metal concentrations on soil P sorption, at least in the short term. It is likely that manure additions stimulate microbial P uptake, so we suggest that microbial processes should be considered carefully in future studies of manure P amendment. In addition, it is possible that organic C in manure amendments forms stable complexes with P and enhances P retention in manure amended calcareous soils. These relationships should be further explored.

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