*1174*

# TECHNICAL ARTICLES

# PHOSPHORUS AVAILABILITY TO BARLEY FROM MANURES AND FERTILIZERS ON A CALCAREOUS SOIL

A. B. Leytem and D. T. Westermann

High concentrations of animal production in the United States have increased the concern about the environmental fate of phosphorus (P) in manures. We conducted a growth chamber study to develop phosphorus source coefficients (PSCs) for manures and fertilizers typically land applied and incorporated into calcareous soils of the western United States as well as to determine the potential plant P availability of these sources. Six manure types (swine solids from low phytate and regular barley diets, swine liquid, dairy liquid, beef solid, and dairy compost) and four fertilizer (mono calcium phosphate, mono ammonium phosphate, polymer-coated mono ammonium phosphate, and ammonium polyphosphate) P amendments were applied to two Portneuf soils at a rate of 60 mg P $kg^{-1}$, incubated for 2 weeks, then planted with barley grown for 7 weeks. Soil samples were analyzed before barley planting and then at 4 and 7 weeks after planting, whereas plant samples were analyzed at 4 and 7 weeks. Increases in soil water soluble (WS-P) and bicarbonate P (Olsen P) from P additions generally followed the pattern [fertilizer P] > [liquid manures] > [solid or composted manures]. Plant shoot biomass and plant P accumulation were similar except swine manures were greater than inorganic P sources and beef manure was less than both. Determining relative P solubility of manure and fertilizer sources will be beneficial when estimating P losses from land application of manures and may be used to assign weighting coefficients to manure sources in risk assessments such as a P site index, with limited impact on P availability to crops. (Soil Science 2005;170:401-412)

Key words: Phosphorus, manure, plant availability, C:P ratio, microbial P, calcareous soil.

INCREASINGLY concentrated animal production in the United States has created new regulations and risk assessments to ensure that these production facilities have the least possible impact on the environment. One of the main issues associated with these concentrated animal production operations is the management of manure nutrients to benefit the producer yet not adversely affect water quality. Of particular concern is phosphorus (P) loading both on production sites and at manure field application sites, which tends to be problematic in these production scenarios. Traditionally manure is applied to meet the nitrogen requirement of crops, which overapplies P, due to the low N:P ratio of most manures (Mikkelsen, 2000). This practice builds up soil test P concentrations in regions dominated by concentrated animal production sites (Kellog and Lander, 1999).

In response to the buildup of soil P and the potential impact on water quality, the United States Department of Agriculture Natural

Resource Conservation Service requires manure application to high P soils be based on either crop P requirements, a threshold soil test P value, or the use of a Phosphorus Site Index (NRCS, 2003). In areas with overly high soil test P concentrations, manure applications are either prohibited or limited to a crop P removal rate, which puts pressure on producers having a limited land base yet substantial production of manure at their facilities.

In many P site risk assessments and nutrient management plans, the P in manures is weighted the same as P in fertilizer. There has been a great deal of work examining manure and fertilizer P sources demonstrating differences between manure and fertilizer P as well as differences within various manure types (Kleinman et al., 2002; Leytem et al., 2004; Sharpley and Moyer, 2000). Recently, data have been published exploring the relationships between the surface application of manures to soils and pastures and runoff P (Kleinman et al., 2002; Penn et al., 2004; Smith et al., 2004a; Smith et al., 2004b; Vadas et al., 2004). The general conclusion of much this work demonstrates that when manures are surface applied to soils and pastures the P in runoff can be predicted with the water-soluble P concentration of the applied materials. However, in cases where organic materials are incorporated into soils, the water-soluble P concentration of the manures is not a good predictor of P losses in runoff (Daverede et al., 2004; Kleinman et al., 2002).

The idea of using phosphorus source coefficients (PSCs) to assign relative weightings to organic P sources was first promoted by Leytem et al. (2004). This work determined the relative differences in organic P sources that were typically applied in the North Atlantic region of the United States, where the materials were incorporated into the soils as opposed being surface applied. They suggested using an incubation approach when organic materials are incorporated into soils to develop a comprehensive database of PSCs for use in P site risk assessments. These PSCs rank the impact of organic sources on increasing soil test P, which is a good predictor of soluble P losses (Cox and Hendricks, 2000; Pote et al., 1999) and may be more appropriate for situations where the materials are incorporated into the soils.

Most published data evaluating the differences in manure and fertilizer P were performed on Eastern U.S. soils, where rain-fed agriculture occurs on primarily acidic soils, and the dynamics of P in soil are primarily controlled by Al and Fe. In contrast, agricultural soils of the Western United States are typically irrigated and contain high calcium carbonate concentrations 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 semi-arid Western United States. El-Baruni and Olsen (1979) examined the effects of farmyard manure and fertilizer on the solubility of P in calcareous soils, whereas another study (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 are no reported comprehensive studies on the effects of organic P source materials on increases in soil test P buildup on irrigated calcareous soils. This is unsatisfactory because the recent expansion of the animal industry in the Western United States means that managing manure nutrients is an urgent priority. Although the data generated for eastern acidic soils can be used as a guideline in some cases, experience shows that data from these soils is not easily adaptable to the semi-arid west. Our goals for this study were to develop PSCs for manures and fertilizers typically land applied and incorporated into calcareous soils of the Western United States, as well as identify the potential plant P availability of these sources.

## MATERIALS AND METHODS

### Soil Collection and Characterization

The soils used in this study were Portneuf silt loams from the 0- to 20-cm depth located at the Northwest Irrigation and Soils Research Laboratory near Kimberly, ID (Table 1). After collection, the bulk soil samples were air-dried, sieved through a 7-mm screen, and analyzed before use in the growth chamber studies. Particle size was determined by the hydrometer method (Gee and Bauder 1986); organic carbon

| Soil property | Selecte |
| --- | --- |
| Clay, g kg$^{-1}$ | |
| OC*, g kg$^{-1}$ | |
| CCE$^\dagger$, g kg$^{-1}$ | |
| Water-soluble P, mg kg$^-$ | |
| Olsen P, mg kg$^{-1}$ | |

*Organic carbon; $^\dagger$calciu

(OC) by the meth (1934); calcium carl the titrimetric meth (1965); sodium bic the method of Ols soluble P by extrac water at a dilution c and filtered with a ( concentrations wer phomolybdate blue 1962).

The two soils v ilar physical and cl exception that one tractable P concent allows examination ments on a soil tha mum crop product of those receiving high-P soil is a to| a greater organic c soluble (16.8 g kg$^-$ kg$^{-1}$) extractable P P soil. The low-P face irrigation and l and calcium carbor lower water-soluble ate P (4.0 g kg$^{-1}$).

### Manure Collec

There were 11 ing 6 manure type: a control. Manure solid manures from nure from beef catt manure from dairy sources of each mai cept for the two there was not enou accommodate both ously. The first sv the lagoon of a sv ranging from wean]

controlled by Al and
soils of the Western
rrigated and contain
.centrations and low
ns. Phosphorus re-
aventionally consid-
rily by Ca (Lindsay,
:s found that P sorp-
more closely related
y complexed Fe and
nn, 2003), the iron
Iamad et al., 1992;
Torrent, 1989), and
id Torrent, 1998).
:s, there is little in-
P availability of or-
alcareous soils of the
itates. El-Baruni and
: effects of farmyard
ne solubility of P in
mother study (Goss
gated the efficiency
: manure by alfalfa.
)0) investigated the
l cheese-whey waste
calcareous soils. To
comprehensive stud-
c P source materials
buildup on irrigated
nsatisfactory because
e animal industry in
means that manag-
urgent priority. Al-
or eastern acidic soils
in some cases, expe-
m these soils is not
-arid west. Our goals
op PSCs for manures
l applied and incor-
ils of the Western
dentify the potential
sources.

## METHODS

### *haracterization*

study were Portneuf
20-cm depth located
l and Soils Research
ID (Table 1). After
nples were air-dried,
creen, and analyzed
h chamber studies.
d by the hydrometer
986); organic carbon

## TABLE 1

Selected soil properties

| Soil property | High P | Low P |
|---|---|---|
| Clay, g kg$^{-1}$ | 180 | 210 |
| OC*, g kg$^{-1}$ | 9.3 | 7.4 |
| CCE[†], g kg$^{-1}$ | 105 | 119 |
| Water-soluble P, mg kg$^{-1}$ | 16.8 | 3.3 |
| Olsen P, mg kg$^{-1}$ | 26.9 | 4.0 |

*Organic carbon; [†]calcium carbonate equivalent.

(OC) by the method of Walkley and Black
(1934); calcium carbonate equivalent (CCE) by
the titrimetric method of Allison and Moodie
(1965); sodium bicarbonate extractable P by
the method of Olsen et al. (1954); and water
soluble P by extraction of soil with deionized
water at a dilution of 1:100 for 1 h, centrifuged,
and filtered with a 0.45-μm filter. Extractable P
concentrations were determined by the phos-
phomolybdate blue method (Murphy and Riley,
1962).

The two soils were chosen because of sim-
ilar physical and chemical properties with the
exception that one soil had a much greater ex-
tractable P concentration than the other. This
allows examination of the effects of P treat-
ments on a soil that is deficient in P (for opti-
mum crop production) as well as a soil typical
of those receiving manure applications. The
high-P soil is a topsoil with little erosion and
a greater organic carbon (9.3 g kg$^{-1}$), water-
soluble (16.8 g kg$^{-1}$), and bicarbonate (26.9 g
kg$^{-1}$) extractable P concentration than the low-
P soil. The low-P soil was eroded due to sur-
face irrigation and had greater clay (210 g kg$^{-1}$)
and calcium carbonate (119 g kg$^{-1}$) as well as
lower water-soluble (3.3 g kg$^{-1}$) and bicarbon-
ate P (4.0 g kg$^{-1}$).

### Manure Collection and Characterization

There were 11 different treatments, includ-
ing 6 manure types, 4 inorganic fertilizers, and
a control. Manure types consisted of liquid and
solid manures from swine operations, solid ma-
nure from beef cattle, and liquid and composted
manure from dairy operations (Table 2). Two
sources of each manure material were used, ex-
cept for the two solid swine manures, since
there was not enough growth chamber space to
accommodate both soil experiments simultane-
ously. The first swine liquid (SL1) was from
the lagoon of a swine operation having stock
ranging from weanlings to finishing hogs, where

the material in the lagoon was fairly fresh
(residence time less than 1 month). A second
swine liquid (SL2) was collected from a swine
operation with finishing hogs, which had a
lagoon residence time of more than 1 month.
The swine solid manures were collected in a
feeding trial using both low-phytate (SS-LP) and
wild-type barley (SS-HP) diets to access the
impacts of feeding low-phytate mutant barley
on manure P composition and reactivity in soil.
The dairy liquid (DL) was collected at two dif-
ferent times in the fall (DL1 and DL2) from the
final pond in a three-pond treatment system
receiving parlor wastewater and runoff from
open lots, which is subsequently land applied
through a center pivot irrigation system. The
beef solid (BS) was collected fresh from beef
cattle fed either silage (BS1) or a corn-based
grain (BS2) diet. The dairy compost (DC) was
from a composting operation that uses manure
and bedding from dairy operations (DC1) or an
individual dairy operation that composts their
own manure and bedding collected from a free
stall barn (DC2). Four pelletized or liquid fer-
tilizer treatments were used: Polyon, a plastic
polymer coated MAP (PCMAP, 10–48–0), am-
monium polyphosphate (POLYP, 10–34–0),
mono ammonium phosphate (MAP, 11–52–0),
and mono calcium phosphate (MCP, 0–45–0).

Manure samples were frozen (−80 °C), ly-
ophilized, and ground for analysis and use in the
growth chamber studies. Analysis of the man-
ures were as follows: (i) total elements (Al, Ca,
Fe, Mn, P) by microwave-assisted digestion of
a 0.5-g dried sample with 8 ml of concentrated
HNO$_3$ and 2 ml of 30% H$_2$O$_2$ and quantified
by inductively coupled plasma optical emission
spectroscopy (ICP-OES) detection; (ii) WSP
(1:10 wt:vol, using deionized water, shaken for
1 h, and filtered with a 0.45 μm Whatman filter)
and elemental analysis by ICP-OES; (iii) total
N and C were determined by combustion of
a 50-mg sample in a FlashEA1112 (C. E.
Elantech, Lakewood, NJ).

The phosphorus composition of select ma-
nures was determined by $^{31}$P-NMR to identify
the potential effects of P composition on P sol-
ubility of manure amended soils. Due to the
expense of $^{31}$P-NMR work, one manure sam-
ple was selected from each manure type. The
P composition of each type of manure was
determined by solution $^{31}$P NMR spectroscopy
as described by Turner (2004). Briefly, P was
extracted in triplicate by shaking 2.00 ± 0.01 g
of dried manure with 40 ml of a solution

| rties | | | |
| --- | --- | --- | --- |
| N:P | C:P | C:N | WSP:TP |
| 3.2 | 21 | 6 | 0.65 |
| 1.3 | 8 | 6 | 0.48 |
| 2.6 | 40 | 16 | 0.68 |
| 6.2 | 77 | 13 | 0.73 |
| 4.8 | 38 | 8 | 0.05 |
| 2.5 | 23 | 9 | 0.05 |
| 4.6 | 112 | 24 | 0.12 |
| 5.7 | 112 | 20 | 0.29 |
| 1.4 | 17 | 12 | 0.15 |
| 4.3 | 55 | 13 | 0.10 |

otal nitrogen and

ent, there were two
g soil + amendment
ks incubation (for soil
of treatments) and 2 kg
plant growth studies.
vas incorporated (four
with each soil at a rate
application rate repre-
are applied to meet
Urea was added to all
) mg N kg$^{-1}$ to satisfy
he plants. After incor-
were brought to 23%
. irrigation water (1:1
l water) and incubated
ed design in either 4 L
250 ml polyethylene
chamber for 2 weeks
58 μmol s$^{-1}$ m$^{-2}$) and
29 °C day and 13 °C
ent was maintained by
at weekly intervals or
ay.
pation, soils were re-
lene containers (100 g)
and barley (*Hordeum*
he 2-kg soil pots. After
hinned to six per pot,
rvested 4 weeks after
three 7 weeks after
mples were cut 1 cm
weighed, and ground
res (1.9-cm diameter)
h pot 4 weeks after
backfilled with washed

sand to avoid adding additional P into the pots;
at 7 weeks after harvesting, the remaining soil
with roots was subsampled by hand for analysis.
All soil samples were analyzed without drying as
follows: (i) WS-P (1:100, soil:deionized water,
shaken for 1 h, filtered with a 0.45-μm What-
man filter); and (ii) bicarbonate extractable
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). All
P analysis was performed with the phosphomo-
lybdate blue method (Murphy and Riley, 1962).
Dried plant samples were digested by micro-
wave assisted digestion with 2 ml concentrated
HNO$_3$ and 2 ml 30% H$_2$O$_2$, and analyzed for
P, Al, Ca, Fe, K, Mg, Mn, Na, S, Si, and Zn by
ICP-OES. Total tissue N and C content was
determined by combustion of a 25 mg sample in
a FlashEA1112 (C. E. Elantech, Lakewood, NJ).

### Estimation of RPE

We used the approach of Leytem and Sims
(2004) to determine the relative percent ex-
tractable P (RPE) for each of the treatments
evaluated. The P extractability in the soil
amendment with manure (MPS) or fertilizer
P sources (FPS) after 2 weeks' incubation was
calculated as follows:

$$\text{Extractability of P(\%)} \qquad (1)$$

$$= \frac{[\text{Soil P}_{\text{MPS/FPS}} - \text{Soil P}_{\text{Control}}, \text{mg P kg}^{-1}] \times 100}{[\text{Total P added} = 60 \text{ mg P kg}^{-1}]}$$

We then calculated, for each soil P extrac-
tant, a RPE by normalizing P extractability for
each MPS and FPS relative to mono calcium
phosphate (MCP). By definition, this assigns a
relative P extractability value of 100% to the
MCP treatment:

$$\text{RPE} = [\text{P extractability}_{\text{MPS/FPS}} \div \qquad (2)$$

$$[\text{P extractability}_{\text{MCP}}] \times 100$$

### Statistics

All statistical analyses of the data were per-
formed by using the PROC GLM (general
linear models) and PROC ANOVA procedures
of the Statistical Analysis System (SAS). The
least significant difference (LSD) method, with
a probability value of 0.05, was used to deter-
mine significant differences between treatment
means. Relationships significant at the 0.05,
0.01, and 0.001 probability levels are marked as
*, **, ***, respectively.

## RESULTS

### Manure Properties

Total P concentrations in the ten manure
sources ranged from a low of 2,550 mg P kg$^{-1}$
for a dairy compost (DC2), to a high of 30,210
mg P kg$^{-1}$ for a swine liquid (SL2, Table 2) and
were reasonably consistent with concentrations
reported for these manure types (Leytem and
Sims, 2004; Sharpley et al., 1998). The total
P concentration in the liquid swine manure
(SL) was greater than that in the solid swine
manure (SS). There was a large difference be-
tween the two dairy compost (DC) samples,
with one having a total P greater than the BS
and DL manures (10,830 mg P kg$^{-1}$), whereas
the other had less (2,550 mg P kg$^{-1}$). Water-
soluble P concentrations in the manures ranged
from 261 to 14,447 mg P kg$^{-1}$ and were highest
in the swine liquids. The ratios of water-soluble
P to total P (WSP:TP) were close to 50% or
greater for the swine manures, whereas the
other manures had much lower WSP:TP ratios
(Table 2).

Total Ca (Table 2) had a wide range and
was highest in the dairy liquid (DL2) and beef
solid (BS2, ~ 34 000 mg kg$^{-1}$). There was a
range in total carbon (C) within the manures
with the greatest C concentrations in the swine
and beef solids, whereas the dairy composts had
the least. Total N was greatest in the swine
liquids, whereas the dairy composts had the
least. The C:P ratios varied from >100 in the
beef solids to only 8 in swine liquid (SL2),
whereas C:N ratios ranged from 6 to 24.

The $^{31}$P-NMR data describing manure P
fractions is presented in Table 3. In general,
results were consistent with available literature
data (Turner, 2004). Recovery rates for total P
from the manure extracts was between 93 and
99%. Orthophosphate comprised the greatest
fraction of P in the manures and ranged from a
low of 60% in the beef solid to 97% in the swine
liquid. There was <10% of the total manure P
present as phytic acid, whereas orthophosphate
monoesters comprised between 3 and 38% of
the total manure P.

### Effect of Treatments on Extractable Soil Phosphorus and RPE

The water soluble and bicarbonate extract-
able soil P at all sampling dates was highly corre-
lated, with bicarbonate P being approximately
1.6 times greater than water-soluble P ($r^2$ =
0.85***, Fig. 1). Turner et al. (2004) conducted

TABLE 2

Selected manure properties

| Manure type | Study | | Manure Properties | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | High P | Low P | TP* | WSP† | Ca* | C‡ | N‡ | N:P | C:P | C:N | WSP:TP |
| | | | --------mg kg$^{-1}$-------- | | | -g kg$^{-1}$- | | | | | | |
| Swine liquid 1 (SL1) | X | | 17,270 | 11,150 | 31,010 | 360 | 56 | 3.2 | 21 | 6 | 0.65 |
| Swine liquid 2 (SL2) | | X | 30,210 | 14,447 | 18,105 | 233 | 39 | 1.3 | 8 | 6 | 0.48 |
| High phytate swine (SS-HP) | X | X | 11,260 | 7,042 | 12,450 | 455 | 29 | 2.6 | 40 | 16 | 0.68 |
| Low phytate swine (SS-LP) | X | X | 6,160 | 4,468 | 7,920 | 474 | 38 | 6.2 | 77 | 13 | 0.73 |
| Dairy liquid 1 (DL1) | X | | 7,615 | 345 | 11,647 | 289 | 37 | 4.8 | 38 | 8 | 0.05 |
| Dairy liquid 2 (DL2) | | X | 9,460 | 426 | 33,960 | 217 | 24 | 2.5 | 23 | 9 | 0.05 |
| Beef solid 1 (BS1) | X | | 3,870 | 450 | 26,523 | 435 | 18 | 4.6 | 112 | 24 | 0.12 |
| Beef solid 2 (BS2) | | X | 4,210 | 1,236 | 33,600 | 472 | 24 | 5.7 | 112 | 20 | 0.29 |
| Dairy compost 1 (DC1) | X | | 10,830 | 1,600 | 31,946 | 180 | 15 | 1.4 | 17 | 12 | 0.15 |
| Dairy compost 2 (DC2) | | X | 2,550 | 261 | 19,160 | 141 | 11 | 4.3 | 55 | 13 | 0.10 |

*Total P, Al, Ca, Fe, and Mn determined by microwave-assisted digestion; †water-soluble P; ‡total nitrogen and C determined by combustion.

containing 0.5 $M$ NaOH and 0.05 $M$ EDTA for 4 h at 20 °C. Extracts were centrifuged at 10,000$g$ for 30 min and aliquots analyzed for total P by ICP–OES. The remaining solutions from the triplicate extracts were combined, frozen rapidly at −80 °C, lyophilized, and ground to a fine powder. Freeze-dried extracts were redissolved in 0.1 ml of $D_2O$ (for signal lock) and 0.9 ml of a solution containing 1 $M$ NaOH and 0.1 $M$ EDTA and then transferred to a 5-mm NMR tube. Solution $^{31}$P NMR spectra were obtained by using a Bruker Avance DRX 500 MHz spectrometer operating at 202.456 MHz for $^{31}$P. We used a 5-μs pulse (45°), a delay time of 5.0 s, an acquisition time of 0.8 s, and broadband proton decoupling for all samples. The number of scans varied between 9,000 and 14,000, and spectra were plotted with a line broadening of 1 Hz. Chemical shifts of signals were determined in parts per million (ppm) relative to 85% $H_3PO_4$ and assigned to individual P compounds or functional groups, based on literature reports (Turner et al., 2004). Signal areas were calculated by integration and P concentrations calculated by multiplying the proportion of the total spectral area assigned to a specific signal by the total P concentration (g P kg$^{-1}$ dry manure) in the original extract. This NMR procedure detects concentrations of P compounds of approximately 0.1 mg P kg$^{-1}$ of dry manure (Turner, 2004).

### Growth Chamber Study

Growth chamber studies with the individual soils were conducted in two sequential experi-

ments. For each treatment, there were two mixtures prepared: 100 g soil + amendment for sampling after 2 weeks incubation (for soil analysis after application of treatments) and 2 kg soil + amendment for plant growth studies. Each of the P sources was incorporated (four replicates of each source) with each soil at a rate of 60 mg P kg$^{-1}$, a P application rate representative when manures are applied to meet crop N requirements. Urea was added to all treatments at a rate of 150 mg N kg$^{-1}$ to satisfy the N requirements of the plants. After incorporation, amended soils were brought to 23% moisture using simulated irrigation water (1:1 vol/vol tap and deionized water) and incubated in a completely randomized design in either 4 L closed bottomed pots or 250 ml polyethylene containers in the growth chamber for 2 weeks with 14-h light day$^{-1}$ (368 μmol s$^{-1}$ m$^{-2}$) and a temperature regime of 29 °C day and 13 °C night. Soil moisture content was maintained by adding water to the cups at weekly intervals or to the pots every other day.

After 2 weeks incubation, soils were removed from the polyethylene containers (100 g) for subsequent analysis, and barley (*Hordeum vulgare*) was planted into the 2-kg soil pots. After emergence, plants were thinned to six per pot, three of which were harvested 4 weeks after planting and the other three 7 weeks after planting. Whole plant samples were cut 1 cm above soil surface, dried, weighed, and ground for analysis. Two soil cores (1.9-cm diameter) were collected from each pot 4 weeks after planting, with the holes backfilled with washed

sand to avoid addi[n]
at 7 weeks after h
with roots was sub:
All soil samples we:
follows: (i) WS-P
shaken for 1 h, filt
man filter); and
P using the metho[
(iii) microbial P
NaHCO$_3$ extractio
P analysis was perf[
lybdate blue metho
Dried plant sample
wave assisted diges[
HNO$_3$ and 2 ml 3
P, Al, Ca, Fe, K, N
ICP-OES. Total ti
determined by com
a FlashEA1112 (C.

*Estir*

We used the a[
(2004) to determir
tractable P (RPE)
evaluated. The P
amendment with [
P sources (FPS) aft
calculated as follow:

Extractability of P(%

$$= \frac{[\text{Soil } P_{\text{MPS/FPS}} - \text{S}}{[\text{Total P }}$$

We then calcul
tant, a RPE by nor
each MPS and FP:
phosphate (MCP).
relative P extractab
MCP treatment:

RPE = [P e

[P e

All statistical an[
formed by using t
linear models) and F
of the Statistical A
least significant diff[
a probability value
mine significant dif
means. Relationshi[
0.01, and 0.001 pro
*, **, ***, respecti[

TABLE 3

Phosphorus composition of manure extracts from ^{31}P NMR spectra

| | Total Manure P | NaOH-EDTA Extractable P | | | | |
|---|---|---|---|---|---|---|
| | | Total P* | Orthophosphate[†] | Orthophosphate Monoesters[†] | Pyrophosphate[†] | Phytic Acid[†] |
| | | | | g P kg^{-1} | | |
| SS-HP | 14.89 | 14.32 ± 0.21 (96) | 11.66 (81) | 2.46 (17) | 0.20 (1.4) | 1.04 (7.3) |
| SS-LP | 7.47 | 6.91 ± 0.12 (93) | 4.82 (70) | 1.92 (28) | 0.17 (2.4) | 0.16 (2.4) |
| SL2 | 30.70 | 30.00 ± 0.30 (99) | 29.15 (97) | 0.75 (3) | 0.09 (0.3) | nd |
| DL2 | 9.43 | 8.80 ± 0.10 (93) | 7.93 (90) | 0.82 (9) | 0.06 (0.6) | 0.37 (4.2) |
| BS2 | 4.21 | 4.20 ± 0.10 (99) | 2.51 (60) | 1.60 (38) | 0.09 (2.1) | 0.34 (8.0) |
| DC2 | 2.55 | 2.50 ± 0.01 (98) | 2.28 (91) | 0.22 (9) | 0.004 (0.2) | 0.03 (1.3) |

*Values are mean ± standard deviation of triplicate extracts; values in parentheses are the proportion (%) of the total manure P determined by microwave digestion.
[†]Values in parentheses are the proportion (%) of the NaOH-EDTA extracted P.

experiments on irrigated calcareous soils relating soluble P in runoff to a variety of soil P measurements and found that bicarbonate P was the best predictor of runoff P for these soils. Since the bicarbonate P (Olsen P) test is commonly utilized in soil testing labs in the Western United States as an indicator of plant available P, they concluded that the bicarbonate P soil test could also be used to predict soluble P losses in runoff. Therefore, the soil water-soluble P data are not shown to simplify the results and discussion. Amending the soils with equal amounts of P (60 mg P kg^{-1}) from either manure or fertilizer increased bicarbonate extractable soil P at all sample dates, but the increase varied with P source and soil (Tables 4 and 5). Bicarbonate soil P before planting in the high-P soil (Table 4) was highest in the

fertilizer treatments (MAP, MCP, and POLYP), whereas the manures and the controlled release fertilizer (PCMAP) had less effect. Bicarbonate soil P before planting on the low-P soil was highest with MCP, whereas MAP, DL, and SL were the second highest group. Bicarbonate P on both soils decreased after plant growth in all but the PCMAP treatment (Table 4 and 5). At week 7, the DL and POLYP treatments had the highest bicarbonate P on the low-P soil, whereas the higher bicarbonate P concentrations on the high-P soil were for the four fertilizer treatments.

RPEs were generally lower on the low-P soil than on the high-P soil (Table 6). The swine and dairy liquid materials were exceptions to this trend. The RPEs for PCMAP were much less than those for the other materials, especially
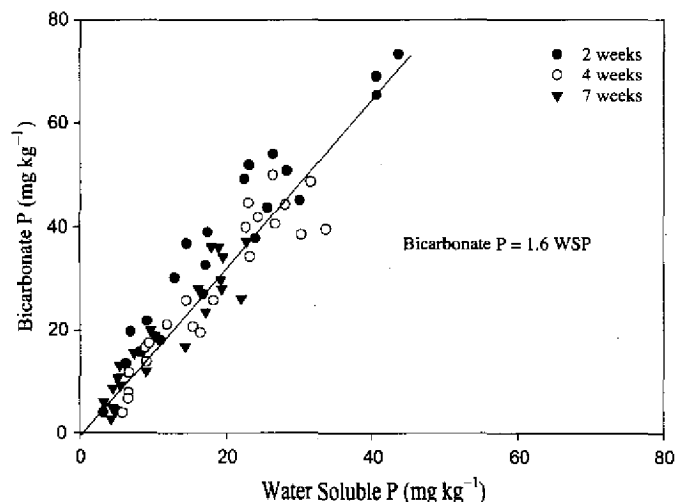


Fig. 1. Relationship between water-soluble and bicarbonate P at all sampling dates on both soils.

(plot) Bicarbonate P = 1.6 WSP

• 2 weeks
○ 4 weeks
▼ 7 weeks

| hosphate[†] | Phytic Acid[†] |
|---|---|
| 20 (1.4) | 1.04 (7.3) |
| 17 (2.4) | 0.16 (2.4) |
| 09 (0.3) | nd |
| 06 (0.6) | 0.37 (4.2) |
| 09 (2.1) | 0.34 (8.0) |
| 04 (0.2) | 0.03 (1.3) |

ion (%) of the total manure

, MCP, and POLYP),
the controlled release
ss effect. Bicarbonate
i the low-P soil was
as MAP, DL, and SL
t group. Bicarbonate
after plant growth in
nent (Table 4 and 5).
d POLYP treatments
e P on the low-P soil,
onate P concentrations
for the four fertilizer

lower on the low-P
l (Table 6). The swine
s were exceptions to
PCMAP were much
er materials, especially

    cs
    cs
    cs

80

ates on both soils.

TABLE 4

Bicarbonate extractable P before planting (after 2-wk incubation) after P application $(60 \text{ mg P kg}^{-1})$ on the low- and high P soils

| P Source | High P Soil | Low P Soil |
|---|---|---|
|  | ----------$\text{mg kg}^{-1}$--------- | |
| SL | 53.9 | 30.1 |
| SS-HP | 50.7 | 21.7 |
| SS-LP | 43.6 | 15.7 |
| DL | 45.0 | 32.6 |
| BS | 37.8 | 13.4 |
| DC | 49.1 | 19.7 |
| PCMAP | 36.0 | 4.5 |
| MAP | 65.4 | 31.6 |
| MCP | 69.0 | 39.0 |
| POLYP | 73.3 | 18.1 |
| Control | 26.9 | 4.0 |
| $\text{LSD}_{0.05}$ | 8.0 | 5.7 |

among the fertilizer materials. PCMAP is coated with a plastic polymer to protect the fertilizer granule from dissolution and subsequent chemical reaction with the soil and soil solution. It also significantly reduced P extractability on the low-P soil. The fertilizer treatments (MAP and POLYP) had the larger RPEs on the high-P soil. The RPE for POLYP (10–34–0) was substantially lower on the low-P soil compared with the high-P soil. It was also much lower than MAP on the low-P soil, whereas it had a slightly higher RPE on the high-P soil. MAP had the highest RPE on the low-P soil, similar to the two liquid manures. The RPE for BS on both soils was the lowest of all the manures. Smaller differences occurred between the remaining manure treatments (SS-HP, SS-LP, and DC) on both soils.

Although different manure samples (SL, DL, BS, DC) with varying chemical characteristics (Table 2) were used for each soil, the DL was the only manure source that had significantly different RPE values between the two soils (Table 6). The relationship between the manure RPEs between soils is almost 1:1 if the DL point is removed ($r^2 = 0.84^{***}$, slope = 1.1). The RPE values for the fertilizer sources on the two soils had a poor linear relationship, even though the same materials were used on both soils ($r^2 = 0.54^{*}$, slope = 0.8). We averaged the RPE for each treatment across soils to obtain a general overall RPE for the treatment (Table 6). The overall trend in P extractability for the treatments is uncoated fertilizer P and liquid manures being somewhat similar, followed by solid and composted manures being progres-

sively less soluble, with the controlled release fertilizer being the least soluble.

We attempted to determine if any manure characteristics could be used to predict the relative extractable P concentrations of manure treated soils. The RPE for bicarbonate soil P was highly correlated to the carbon:total phosphorus ratio (C:P) of the manures on both soils (high-P soil, $r = -0.89^{***}$; low-P soil, $r = -0.92^{***}$). Forward stepwise regression also selected the manure C:P ratio to describe the RPE for bicarbonate soil P. As the C:P of the manures increased, the RPE of the bicarbonate P decreased in a nonlinear fashion (Fig. 2).

### Shoot Biomass Production and Plant P Accumulation

To determine if there was an impact on shoot biomass production due to different nitrogen (N), additions between treatments (150 to 520 mg kg$^{-1}$), total plant tissue N was determined at both harvest dates. The tissue N concentrations at four weeks on both soils were between 4.2 and 4.8%, whereas at 7 weeks it ranged from 2.0 to 4.1%. The dairy lagoon treatment at 7 weeks had the lowest tissue N (2.0%), whereas the rest of the treatments were all above 3.2%. Because all of our tissue samples were in the adequate N tissue concentration range (Reuter and Robinson, 1997) and there was no relationship between percent tissue N (with or without P variables) and dry matter production (Data not shown), we believe that N did not appreciably influence plant growth differences in this study.

TABLE 5

Bicarbonate extractable soil P at first (4 weeks) and second (7 weeks) plant harvests on the two soils

| P Source | High P Soil | | Low P soil | |
|---|---|---|---|---|
|  | 4 wk | 7 wk | 4 wk | 7 wk |
|  | --------------$\text{mg kg}^{-1}$-------------- | | | |
| SL | 44.1 | 29.6 | 25.7 | 15.5 |
| SS-HP | 40.5 | 27.9 | 16.5 | 13.2 |
| SS-LP | 34.1 | 23.6 | 11.7 | 8.7 |
| DL | 38.5 | 26.1 | 19.5 | 19.0 |
| BS | 25.7 | 16.9 | 8.0 | 5.0 |
| DC | 44.5 | 28.1 | 13.9 | 10.9 |
| PCMAP | 26.9 | 36.0 | 4.1 | 6.2 |
| MAP | 38.9 | 36.2 | 17.4 | 10.7 |
| MCP | 38.3 | 34.2 | 12.3 | 9.3 |
| POLYP | 48.5 | 37.2 | 49.8 | 19.9 |
| Control | 20.7 | 12.1 | 3.9 | 2.8 |
| $\text{LSD}_{0.05}$ | 5.5 | 3.7 | 6.6 | 3.9 |

TABLE 6

Relative percent extractable (RPE) phosphorus (bicarbonate) calculated on the high and low P soils before planting

| | RPE % | | |
|---|---|---|---|
| | High P | Low P | Average |
| SL | 64.3 | 74.9 | 69.6 |
| SS-HP | 56.8 | 50.9 | 53.9 |
| SS-LP | 39.9 | 33.7 | 36.8 |
| DL | 43.1 | 82.0 | 62.6 |
| BS | 26.1 | 27.0 | 26.5 |
| DC | 53.0 | 45.0 | 49.0 |
| PCMAP | 21.8 | 1.3 | 11.6 |
| MAP | 91.1 | 79.5 | 85.3 |
| MCP | 100.0 | 100.0 | 100.0 |
| POLYP | 110.5 | 40.6 | 75.6 |
| LSD$_{0.05}$ | 16.2 | 13.9 | 16.2 |

Barley stand establishment was satisfactory in all pots on both the high- and low-P soils. There was no visual evidence of P deficiency on the high-P soil, whereas the control treatment was visibly P deficient on the low-P soil. We combined the shoot biomass produced at 4 and 7 weeks to determine the total amount of biomass produced per treatment for comparisons (Table 7). The increase in shoot biomass production over the control on the high-P soil ranged from 0 to 57%, with the dairy liquid, beef solid, and swine liquid being equivalent to the control. The largest increases were for the swine solids, dairy compost, PolyP, and PCMAP. The increase in shoot biomass pro-

duction on the low-P soil varied from 210 to 400%, with fewer differences between treatments (Table 7). On the low-P soil, all treatments were significantly greater than the control, whereas the beef solid, dairy compost, and MCP had significantly less biomass than the rest of the treatments.

The shoot P accumulations for the 4- and 7-week samples were also summed to calculate a total P removal over the growth period (Table 7). Total shoot P accumulation increased from 12 to 103% above the control on the high-P soil and 277 to 631% on the low-P soil. The swine manures (SS-HP, SS-LP, and SL) and DC had greater total shoot P accumulation on the high-P soil than the DL and BS treatments, which were not different than the control. The P accumulations for the fertilizer treatments were significantly different and followed the trend POLYP > PCMAP > MAP > MCP on the high-P soil. The total shoot P accumulation on the low-P soil was different among some of the manure treatments with the liquid manures and the SS-HP treatment having the greatest P accumulation, followed by the SS-LP, which was greater than the DC and BS treatments (Table 7). The POLYP treatment had a greater P accumulation than MCP and PCMAP but was similar to SS-HP and the liquid manures on the low-P soil. The BS and DC treatments were both lower than the other treatments on this soil. All manure and fertilizer treatments on the low-P soil had greater P accumulation than the control.
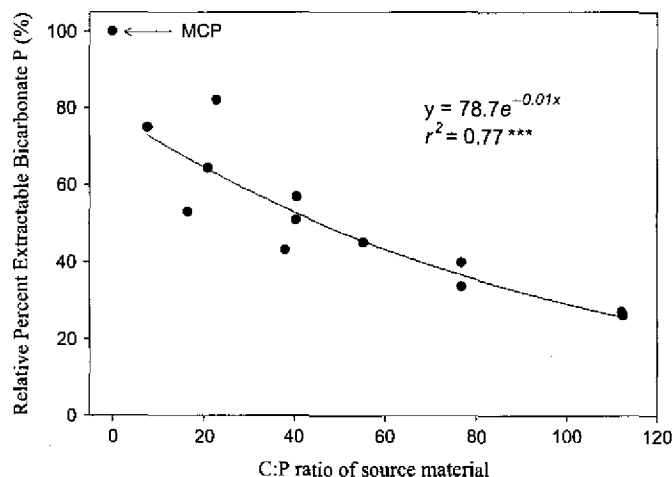


Fig. 2. Relationship between the carbon to phosphorus ratio of the manures and the relative percent extractable bicarbonate P on the two soils before planting (MCP point is not included in the regression).

il varied from 210 to
ences between treat-
: low-P soil, all treat-
ly greater than the
f solid, dairy compost,
y less biomass than the

lations for the 4- and
so summed to calcu-
ver the growth period
accumulation increased
le control on the high-
on the low-P soil. The
S-LP, and SL) and DC
accumulation on the
L and BS treatments,
than the control. The
e fertilizer treatments
ent and followed the
P > MAP > MCP on
shoot P accumulation
fferent among some of
ith the liquid manures
t having the greatest P
by the SS-LP, which
C and BS treatments
reatment had a greater
CP and PCMAP but
the liquid manures on
ld DC treatments were
ler treatments on this
lizer treatments on the
accumulation than the

Forward stepwise regression was used to determine which manure properties had the greatest influence on total shoot P accumulation. There were no variables selected for the high-P soil, but for the low-P soil the C:P and WSP:TP ratios of the manures were selected ($R^2 = 0.91$**). The C:P ratio of the manure also influenced the RPE bicarbonate soil P (Fig. 2). A lack of a relationship in the high-P soil would be expected since a P-yield response was not expected. Shoot biomass and P accumulation was linearly related across both soils ($r^2 = 0.84$***).

The soil property most closely related to shoot P accumulation was the 2-week bicarbonate extractable P for both soils (Fig. 3). The percent tissue P was also related to bicarbonate extractable P at 2 weeks ($r^2 = 0.78$**, data not shown) for all treatments, as well as for only the manure treatments ($r^2 = 0.84$***, data not shown). There should be a relationship between soil test P concentration and plant P uptake or concentration if the soil test procedure estimates plant nutrient availability. In this study, these relationships help confirm the effects of the applied materials on soil test P changes, since shoot P accumulation was similarly affected.

An attempt was made to assess the relative effect of the different treatments on plant shoot biomass production and shoot P accumulation similar to the RPE evaluation in Table 6. The data given in Table 7 were first averaged across soils. The control average was then subtracted, and the resultant number divided by MCP and

multiplied by 100 to obtain a relative value for treatment comparison. In all cases, the relative indexes were >100%, except for the BS treatments, which were 60% for dry-matter production and 63.2% for P uptake (data not shown). Relative effects of SL, SS-HP, and SS-LP (140 to 180%) on dry matter and P uptake were generally greater than those for MAP and PCMAP (123 to 153%), whereas DC and DL (113 to 129%) were similar to the fertilizer materials. POLYP was similar to the swine manures.

## DISCUSSION

The addition of identical amounts of P from fertilizers or manures to soils did not uniformly increase extractable P concentrations (Tables 4 and 5). The greatest initial increases in extractable P were from fertilizer treatments not coated for controlled release (MAP, MCP, POLYP), and in some cases the liquid manure treatments were equally as effective as these fertilizers. When manure treatments were either a solid or composted material, the increase in extractable soil P tended to be smaller, the exception to this was the compost used on the high-P soil. This particular compost (DC1) had higher concentrations of total and soluble P compared with DC2 as well as high concentrations of Fe and Al (data not shown). This suggests that DC1 was probably immature and had a significant amount of soil contamination, which may have caused it to behave similarly to the other manure treatments. The controlled release fertilizer (PCMAP) behaved as expected and released small amounts of P over the duration of the experiment due to the protective coating on the fertilizer particles. As a result of this controlled release, the bicarbonate soil P increased between the 4- and 7-week sampling dates.

In general, extractable P in most treatments decreased over the course of the experiment from the combination of continued soil P reaction and plant uptake. One notable exception was the extractability of P from the POLYP treatment on the low-P soil, which increased between planting and the 4-week sampling date (Tables 4 vs 5). The RPE values for the treatments were similar on both soils, with the exception of PCMAP and POLYP treatments, which decreased from the high- to low-P soils and the DL treatment, which increased from the high- to low-P soils (Table 6). Since the PCMAP is a controlled release fertilizer, there may be little P released during the 2-week

---

120

lative percent extractable
ssion).

TABLE 7

Average total shoot biomass production and total shoot P accumulation from the eleven treatments on high P and low P soils

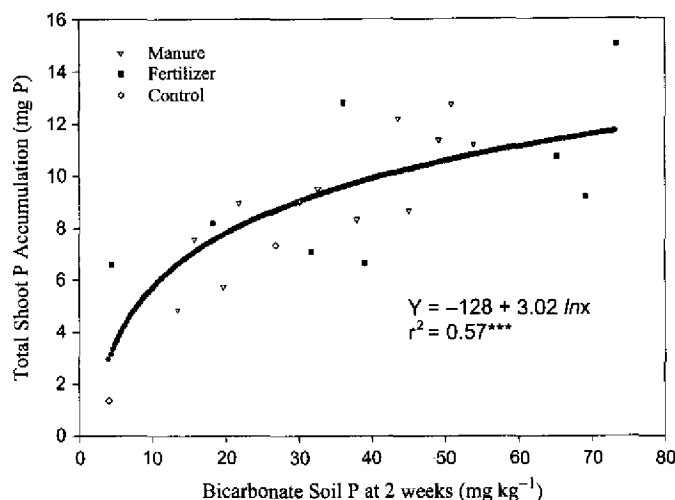|  | Shoot Biomass (g/pot) | | Shoot P Accumulation (mg/pot) | |
|---|---|---|---|---|
|  | High P | Low P | High P | Low P |
| SL | 4.4 | 4.4 | 11.2 | 9.0 |
| SS-HP | 5.5 | 4.5 | 12.7 | 9.0 |
| SS-LP | 5.8 | 4.2 | 12.2 | 7.6 |
| DL | 3.7 | 4.3 | 8.7 | 9.5 |
| BS | 3.7 | 2.8 | 8.3 | 4.9 |
| DC | 5.2 | 3.3 | 11.4 | 5.7 |
| PCMAP | 5.3 | 3.8 | 12.8 | 6.6 |
| MAP | 4.8 | 3.8 | 10.7 | 7.1 |
| MCP | 4.3 | 3.4 | 9.2 | 6.7 |
| POLYP | 5.2 | 3.9 | 15.0 | 8.2 |
| Control | 3.7 | 0.9 | 7.4 | 1.3 |
| $LSD_{0.05}$ | 0.6 | 0.6 | 1.3 | 1.1 |

Fig. 3. Relationship between bicarbonate P extracted before planting and the total plant P uptake from the 11 treatments on the two soils.

incubation. Also, the P that was released may be strongly sorbed in the low P soil due to the lower P saturation of the low-P soil (higher clay and CCE content with lower extractable P, Table 1). The decrease in RPE of the POLYP treatment on the low-P soil is probably due to the rate of hydrolysis of this form of P. It is unclear why hydrolysis was apparently delayed in this soil, since soil pH and temperature should be similar to the high-P soil. It is also possible that the polyphosphate was sorbed or precipitated and therefore protected from hydrolysis.

The increase in RPE of the DL treatment from the high- to low-P soil (Table 6) may be due to the lower C:P ratio of the material used on the low-P soil (Table 2). There was no difference in the amount of WSP added since the same amount of TP was added with the DL treatment and the WSP:TP ratio of the materials was the same (0.05). Therefore, other manure properties must have controlled P solubility in these two treatments. The general RPE trends in the treatments averaged over the two soils were very similar to the findings of Leytem and Sims (2004), with the exception of the DC. In this previous work, the trend in RPE was inorganic P > liquid manures > solid manures > composted manures. In contrast, in the present study, the composted manures in both the high- and low-P soil had a greater RPE than the beef solid manures. In these carbon limited soils, the amount of C added with the manure seems

to influence P solubility and the C:P ratio of the solid manures were almost twice that of the composted manures which may explain these differences.

Changes in extractable P on the soils in the present study were closely associated with the C:P ratio of the materials; as C:P increased, RPE decreased. The decrease in extractable P may be due to microbial uptake of P in these amended soils, stimulated by carbon additions. However, the C:P ratio of the manure and the soil microbial P measured after incubation were not significantly related (data not shown). It is also possible that there was a chemical interaction between carbon added in the manures and P retention in the soils. The greater the carbon concentration, the more P that might be retained by the soils, since Leytem and Westermann (2003) found that the P sorption maxima was related to the amount of organically complexed Fe and Mn in soils from this region. This strong relationship between increases in soil test P and the C:P ratio of applied manures was also documented on thirteen additional soils collected from the Pacific Northwest region (Leytem et al., 2005) as well as in field studies using dairy compost and manures (Leytem, unpublished data).

Increases in shoot biomass production ranged from a maximum of 57% on the high-P soil to 400% on the low-P soil. Since there was already sufficient P for crop production on the high-P soil, the response to P additions was not

as great as on the lc
on the low-P soil r
additions with the 1
a significantly great
than the control.

Relative shoot
greater than shoot
ing from a high c
to 631% on the lo
plant P uptakes wer
swine solids and li
compared with the
(Table 2). The be
treatments had the
on the low-P soil
different from each
(1987) found simil
grass yield in pots
slurry or MCP. In
soil treated with sw
or more grass than
that cumulative P a
the two treatments
Eghball and Powei
nificant differences
accumulation by co
or composted manu
the same P applicat

Calculated RPI
production and shc
that all manures an
were generally more
growth and P uptak
P as MCP. This r
some N (as $NH_4$-N
plant P uptake (Soc
was a very poor lin
bicarbonate RPE
shoot-biomass proc
mulation ($r^2 = 0.1$
erally, manures inc
of that from inorgar
but had a 50% great
(Table 7), especiall
dairy liquid. This s
may be more effecti
traditional fertilizers
rates.

In summary, sol
varies with the typ
differences affect p
potential for off-sit
losses are linked to
tions (Turner et al.,
coefficients for man

and the C:P ratio of
lmost twice that of the
ich may explain these

le P on the soils in the
:ly associated with the
ials; as C:P increased,
crease in extractable P
l uptake of P in these
d by carbon additions.
of the manure and the
ared after incubation
lated (data not shown).
ere was a chemical in-
ı added in the manures
soils. The greater the
e more P that might be
ice Leytem and West-
that the P sorption
e amount of organically
ı soils from this region.

between increases in
atio of applied manures
thirteen additional soils
ific Northwest region
well as in field studies
nd manures (Leytem,

biomass production
ı of 57% on the high-P
-P soil. Since there was
:rop production on the
: to P additions was not

as great as on the low-P soil. The shoot biomass on the low-P soil responded more to treatment additions with the majority of treatments having a significantly greater shoot biomass production than the control.

Relative shoot P accumulations were much greater than shoot biomass with increases ranging from a high of 103% on the high-P soil to 631% on the low-P soil. Across both soils, plant P uptakes were similar or greater when the swine solids and liquid manures were applied compared with the inorganic fertilizer materials (Table 2). The beef solid and dairy compost treatments had the lowest shoot P accumulation on the low-P soil and were not significantly different from each other. Tunney and Pommel (1987) found similar results when comparing grass yield in pots treated with either swine slurry or MCP. In their study, they found that soil treated with swine slurry produced as much or more grass than P fertilizer treatments, and that cumulative P accumulation was similar for the two treatments at a 50 mg P $pot^{-1}$ rate. Eghball and Power (1999) also found no significant differences in grain production or P accumulation by corn when beef feedlot manure or composted manure was applied for 4 years at the same P application rate.

Calculated RPE values for shoot-biomass production and shoot P accumulation suggests that all manures and fertilizers, except for BS, were generally more effective at increasing plant growth and P uptake than an equivalent rate of P as MCP. This may have occurred because some N (as $NH_4$-N) with fertilizer P enhances plant P uptake (Soon and Miller, 1977). There was a very poor linear relationship between the bicarbonate RPE values and the RPEs for shoot-biomass production and shoot P accumulation ($r^2 = 0.1$ and 0.2, respectively). Generally, manures increased soil test P only 50% of that from inorganic MCP fertilizer (Table 6) but had a 50% greater impact on plant P uptake (Table 7), especially the swine manures and dairy liquid. This suggests that some manures may be more effective at supplying plant P than traditional fertilizers at equivalent P application rates.

In summary, solubility of P in manured soils varies with the type of manure applied. These differences affect plant growth as well as the potential for off-site losses of P, as soluble P losses are linked to extractable soil P concentrations (Turner et al., 2004). Different P weighing coefficients for manure effects on crop growth

or water quality should be used to better predict their potential impact. In cases in which manures are incorporated on calcareous soils, it appears possible to determine an appropriate weighting coefficient based on an easily measured manure property, such as the C:P ratio. The relationship between C:P ratios in manures and relative soil P extractability may also help better predict allowable P loadings when combined with manure application rates and appropriate soil properties. However, additional field studies are needed to further develop it for this use.

## REFERENCES

Allison, L. E., and C. D. Moodie. 1965. Carbonate. p. 1379–1396. *In:* C. A. Black et al. (ed.). Methods of soil analysis, part 1, 1st ed. ASA. Madison, WI.

Brookes, P. C., D. S. Powlson, and D. S. Jenkinson. 1982. Measurement of microbial biomass phosphorus in soil. Soil Biol. Biochem. 14:319–329.

Castro, B., and J. Torrent. 1998. Phosphate sorption by calcareous Vertisols and Inceptisols as evaluated from extended P-sorption curves. Eur. J. Soil Sci. 49:661–667.

Cox, F. R., and S. E. Hendricks. 2000. Soil test phosphorus and clay content effects on runoff water quality. J. Environ. Qual. 29:1582–1586.

Daverede, I. C., A. N. Kravchenko, R. G. Hoeft, E. D. Nafziger, D. G. Bullock, J. J. Warren, and L. C. Gonzini. 2004. Phosphorus runoff from incorporated and surface-applied liquid swine manures and phosphorus fertilizer. J. Environ. Qual. 33:1535–1544.

Eghball, B., and J. F. Power. 1999. Phosphorus and nitrogen-based manure and compost applications: Corn production and soil phosphorus. Soil Sci. Soc. Am. J. 63:895–901.

El-Baruni, B., and S. R. Olsen. 1979. Effect of manure on solubility of phosphorus in calcareous soils. Soil Sci. 128:219–225.

Gee, G. W., and J. W. Bauder. 1986. Particle size analysis, p. 383–411. *In:* Methods of soil analysis, part 1. Physical and mineralogical methods. Am. Soc. Agron. Madison. WI.

Goss, D. W., and B. A. Stewart. 1979. Efficiency of phosphorus utilization by alfalfa from manure and superphosphate. Soil Sci. Soc. Am. J. 43: 523–528.

Hamad, M. E., D. L. Rimmer, and J. K. Syers. 1992. Effect of iron oxide on phosphorus sorption by calcite and calcareous soils. J. Soil Sci. 43:273:281.

Kellog, R. L. and C. H. Lander. 1999. Trends in the potential of nutrient loading from confined livestock operations. *In:* The state of North America's private land. USDA-NRCS, U.S. Government Printing Office, Washington, DC.

Kleinman, P. J. A., A. N. Sharpley, B. G. Moyer,

and G. F. Elwinger. 2002. Effect of mineral and manure phosphorus sources on runoff phosphorus. J. Environ. Qual. 31:2026–2033.

Leytem, A. B., and J. T. Sims. 2004. Determination of phosphorus availability coefficients for organic phosphorus sources: Laboratory studies. J. Environ. Qual. 33:389–393.

Leytem, A. B., B. L. Turner, V. Raboy, and K. Peterson. 2005. Linking manure properties to soil phosphorus solubility: Importance of the carbon to phosphorus ratio. Soil Sci. Soc. Am. J. In press.

Leytem, A. B., B. L. Turner, and P. A. Thacker. 2004. Phosphorus composition of manure from swine fed low-phytate grains: Evidence for hydrolysis in the animal. J. Environ. Qual. 33:2380–2383.

Leytem, A. B., and D. T. Westermann. 2003. Phosphorus sorption by Pacific Northwest calcareous soils. Soil Sci. 168:368–375.

Lindsay, W. L. 1979. Chemical Equilibria in Soils. John Wiley & Sons, New York.

Mikkelsen, R. L. 2000. Beneficial Use of Swine By-products: Opportunities for the Future. In: Land Application of Agricultural, Industrial, and Municipal By-products. Powers, J. F., Dick, W. A. (eds.). Soil Sci. Soc. Am, Madison, WI. Book Series No. 6., 451–480.

Murphy, J., and J. R. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chem. 27: 31–36.

National Resource Conservation Service. 2003. Conservation Practice Standard Nutrient Management Code 590 [Online]. Available at ftp://ftp-fc.sc.egov.usda.gov/NHQ/practice-standards/standards/590.pdf (verified 31 Jan. 2005).

Olsen, S. R., C. V. Cole, F. S. Watatanabe, and L. A. Dean. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circ 939. U.S. Government Printing Office, Washington, DC.

Penn, C. J., G. L. Mullins, L. W. Zelazny, J. G. Warren, and J. M. McGrath. 2004. Surface runoff losses of phosphorus from Virginia soils amended with turkey manure using phytase and high available phosphorus corn diets. J. Environ. Qual. 33: 1431–1439.

Pote, D. H., T. C. Daniel, D. J. Nichols, A. N. Sharpley, P. A. Moore, Jr., D. M. Miller, and D. R. Edwards. 1999. Relationship between phosphorus levels in three Ultisols and phosphorus concentrations in runoff. J. Environ. Qual. 28: 170–175.

Reuter, D. J., and J. B. Robinson. 1997. Plant analysis an interpretation manual. CSIRO Publishing, Collingwood, Australia.

Robbins, C. W., L. L. Freeborn, and D. T. Westermann. 2000. Organic phosphorus source effects on calcareous soil phosphorus and organic carbon. J. Environ. Qual. 29:973–978.

Robbins, C. W., D. T. Westermann, and L. L. Freeborn. 1999. Phosphorus forms and extractability from three sources in a recently exposed calcareous subsoil. Soil Sci. Soc. Am. J. 63: 1717–1724.

Ryan, J., D. Curtin, and M. A. Chema. 1985. Significance of iron oxides and calcium carbonate particle size ion phosphate sorption by calcareous soils. Soil Sci. Soc. Am. J. 49:74–76.

Sharpley, A., W. Gburek, and L. Heathwaite. 1998. Agricultural phosphorus and water quality: sources, transport and management Agric. Food Sci. Finland. 7:297–314.

Sharpley, A. N., and B. Moyer. 2000. Phosphorus forms in manure and compost and their release during simulated rainfall. J. Environ. Qual. 19:1462–1469.

Smith, D. R., P. A. Moore, Jr., C. V. Maxwell, B. E. Haggard, and T. C. Daniel. 2004a. Reducing phosphorus runoff from swine manure with dietary phytase and aluminum chloride. J. Environ. Qual. 33:1048–1054.

Smith, D. R., P. A. Moore, Jr., D. M. Miles, B. E. Haggard, and T. C. Daniel. 2004b. Decreasing phosphorus runoff losses from land-applied poultry litter with dietary modifications and alum addition. J. Environ. Qual. 33: 2210–2216.

Solis, P., and J. Torrent. 1989. Phosphate sorption by calcareous Vertisols and Inceptisols of Spain. Soil Sci. Soc. Am. J. 53:456–459.

Soon, Y. K., and M. H. Miller. 1977. Changes in the rhizosphere due to $NH_4^+$ and $NO_3^-$ fertilization and phosphorus uptake by corn seedlings. Soil Sci. Soc. Am. J. 41:77–80.

Tunney, H., and B. Pommel. 1987. Phosphorus uptake by ryegrass from monocalcium phosphate and pig manure on two soils in pots. Ir. J. Agric. Res. 26:189–198.

Turner, B. L. 2004. Optimizing phosphorus characterization in animal manures by phosphorus-31 nuclear magnetic resonance spectroscopy. J. Environ. Qual. 33:757–766.

Turner, B. L., M. A. Kay, and D. T. Westermann. 2004. Phosphorus in surface runoff from calcareous arable soils of the semi-arid western US. J. Environ. Qual. 33:1814–1824.

Vadas, P. A., J. J. Meisinger, L. J. Sikora, J. P. McMurtry, and A. E. Sefton. 2004. Effect of poultry diet on phosphorus in runoff from soils amended with poultry manure and compost. J. Environ. Qual. 33:1845–1854.

Walkley, A., and I. A. Black. 1934. An examination of the Degtjareff method for proposed modification of the chromic acid titration method. Soil Sci. 37:29–38.

## EASTERN
## FROM LE

Lead a
causing o
may beco
other pur
use plants
tion). Eas
root syste:
study was
from lead
from Mai
(Oxyaquii
(Aqua Re;
As levels c
soils were
incubatior
into the ai
dry matte
treatment:
orchard s(
levels of P
arsenic co
and P-mei
Shoot As
nificant di
gamagrass
soils, maki
arsenate–c

Key wo
soils phyto

LEAD arsenate v
to control the a
pomonella) in orchar
(Merwin et al., 1994
sult, many orchard s
lead and arsenic (P
There are concerns
become an environn
soils are used for oth

¹USDA-ARS, BARC-West, Beltsvill
author. E-mail: codlinge@ba.ars.usd

²USDA-ARS, Beltsville, MD 2070