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Phosphorus Mobility in Calcareous Soils under Heavy Manuring

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ABSTRACT

Confined animal production systems produce large amounts of manure that are usually disposed on limited land areas in proximity to the source. There is concern that continuous heavy manuring may saturate the soil's capacity to retain manure-P and result in groundwater contamination with excessive P. The objectives of this research were to determine the fate of waste-P in heavily manured soils and assess the risk of soil and water quality degradation in turkey (*Meleagris gallopavo*) and beef (*Bos taurus*) feed lot production areas. All soils were calcareous throughout the profile. Samples were collected by 30-cm depth increments to a depth of 210 cm or a limiting layer and were analyzed for $NaHCO_3$-extractable P (including inorganic and organic), and total soil P. Large amounts of extractable organic P in the surface soil layers decreased to background levels within 2 to 3 yr after manuring ceased. In heavily manured fields extractable inorganic P was well above background concentrations to as deep as 210 cm, apparently because of movement and subsequent mineralization of organic P. Organic matter in these soils was about twofold higher than background levels. There appeared to be no practical limit to the P-retention ability of these calcareous soils. Under these conditions the risk of groundwater contamination by organic or inorganic P from waste P disposal to land is negligible.

AMENDING SOIL with animal manures to increase soil fertility has been a common practice throughout recorded history. The fertility values of manures have not diminished but they have been supplanted in importance by the modern chemical fertilizer industry. Currently, field manuring is more an issue of waste disposal than of soil fertility improvement. Modern confinement livestock management systems generate large amounts of manure that accumulate in place, or are applied in large amounts to limited land areas in proximity to the manure source.

Nitrate (NO_3)–N is highly mobile in soil and may move downward to groundwater if rain and/or irrigation regularly exceeds crop water requirements. Consequently, considerable attention has been given to NO_3 contamination of groundwaters in the vicinity of animal enterprises. Phosphorus, on the other hand, is considered to be immobile and its transport in soil has received less attention.

When applied to the soil, inorganic P (e.g., mono- and dicalcium phosphate [MCP and DCP]) and ammoniated phosphate remain localized around the point of application unless cultivation or other mixing processes occur (Lewis and Raca, 1969; Malhi et al., 1992).

Kissel et al. (1985) described the chemisty of P in calcareous soils as a continuum of adsorption, formation of amorphous calcium phosphate compounds, and gradual formation of crystalline phosphate compounds. Sample et al. (1980) indicated that both adsorbed and precipitated P slowly become more stable, less soluble, and less available for plant uptake.

Exposing $CaCO_3$ to concentrated solutions of MCP, simulating band-applied P or surface broadcast P without soil incorporation, resulted in the formation initially of DCP-dihydrate and DCP (Lindsay et al., 1962). At low solution concentrations P was adsorbed by calcite as an incomplete monolayer, and as the solution P concentration increased a nucleation of calcium phosphate crystals occurred at localized sites (Griffin and Jurinak, 1973). These Ca-phosphate precipitates had solubilities analogous to octacalcium phosphate (OCP) and hydroxyapatite (HAP). Soluble organic acids (e.g., humic acid) inhibited OCP crystal growth by adsorption of organic acids on

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Abbreviations: MCP, monocalcium phosphate; DCP, dicalcium phosphate; OCP, octacalcium phosphate; HAP, hydroxyapatite; STP, soil test P–$NaHCO_3$-extractable; STPt, total $NaHCO_3$-extractable P, including organic and inorganic P; TP, total soil P, nitric-perchloric acid extractable P.

OCP surfaces blocking crystal growth sites (Grossl and Inskeep, 1992).

Pierzynski et al. (1990a,b) showed that in excessively fertilized soils, P exists in discrete P-rich particles and that the abundance of P-rich particles was positively correlated with total P concentration. They could not distinguish between P-rich particles formed quickly under concentrated conditions and those formed slowly under dilute conditions.

Despite the fact that inorganic P is practically immobile in soil there is evidence that some P movement may occur when organic materials are applied. Hannapel et al. (1964a,b) showed that P movement occurred when bean (*Phaseolus vulgaris* L.) and barley (*Hordeum vulgare* L.) residues and other organic materials were applied to soil columns, and correlated this movement with the increase of organic P in the soil solution. The formation of soluble organic P was attributed to soil microorganisms since treatment with formaldehyde reduced P movement.

In calcareous soils used for disposal of industrial food processing waste waters, organic plus hydrolyzable P fractions comprised 30 to 50% of the P in soil water extracts and more than 2 mg P/L was found 150 cm deep in soils with low clay content (Robbins and Smith, 1977).

In soils exposed to manure over extended periods, P enrichment occurs below the surface 20-cm layer (Gilliam et al., 1985; Kuo and Baker, 1982; Mozaffari and Sims, 1994; Sharpley et al., 1984). Campbell and Racz (1975) showed elevated levels of P at 120 to 150 cm in a calcareous soil below a beef cattle feed lot.

In nonsterile soil, the concentration of organic P in soil solution was higher than the concentration of inorganic P and microbial activity was more important than P fertilizer in maintaining organic P in solution (Seeling and Zanoski, 1993). Dalal (1977) concluded that the accumulation of organic P in soils was primarily a result of microbial activity and that organic P may become available to plants by mineralization. Dalal categorized soil organic P in three forms: Inositol-phosphate, the most abundant form comprising up to 50% of total soil P; phospholipids that comprise up to 7% of total P; and nucleic acids that comprise <3% of total P. In temperate regions, inorganic P was the main form of P influencing crop nutrition while the contribution of organic P to crop nutrition was much more important in tropical regions (Anderson, 1980).

The objectives of this research were to: (i) determine the fate of manure P in soils that have received varying amounts of waste-P for up to four decades; (ii) determine whether, or to what extent, subsoil P enrichment occurs in heavily manured calcareous soils; and (iii) assess the risk of P contamination of groundwater in excessively manured soils.

MATERIALS AND METHODS

Farm fields were selected that had a broad range of manuring history, ranging from none to annual or more frequent applications over the past two to four decades. Fields with a history of little or no manuring were included to establish background levels of soil P and organic matter. Farmers were interviewed to obtain the manuring history of each field sampled.

The sample represented eight soil series and two geographic areas of Utah. Table 1 includes soil physical and chemical properties and the USDA-NRCS soil classification of fields in the sample. The manure sources were turkeys (Sanpete County) and beef feed lots (Cache County). All of the soils in the study are calcareous throughout the profile and generally productive under irrigation. There was a hint of salinity and sodicity in some subsoils.

Soil cores were taken by 30-cm increments to 210 cm or a water table (Table 1). Soil cores were 5.1 cm in diameter; nine cores were taken to represent 2- to 4-ha field areas. Cores were composited within fields to provide one sample for each depth. Soil samples were air-dried and ground to pass a 2-mm screen.

Three types of soil P extractions were made (Olsen and Sommers, 1982): (1) bicarbonate-extractable inorganic P, the routine Olsen test for available P (P measured by the ascorbic acid colorometric method); (2) digestion of the bicarbonate extract in hot HNO_3–$HClO_4$ and total P measurement by ICP (The difference between procedure (1) and (2) is extractable

Table 1. Some physical and chemical properties and NRCS soil descriptions in fields sampled for surface and subsoil P.

Site†	pH ECe	Depth 0–30	 30–60	 60–90	 90–120	 120–150	 150–180	 180–210	Limiting layer‡
		cm							
WoA§	pH	7.9	7.9	7.9	8.0	8.1	8.1	8.1	C
(1)	ECe	0.6	0.6	0.8	0.8	0.8	0.5	0.6	
GeB§	pH	8.0	8.0	8.1	8.1	–	–	–	WT
(1)	ECe	0.9	0.9	1.0	1.0	–	–	–	
Mfc	pH	8.0	8.1	8.2	8.2	8.1	8.2	8.1	C
(1)	ECe	1.3	1.1	1.1	1.0	1.0	0.9	0.8	
GeB	pH	7.7	7.9	8.1	8.0	8.2	8.1	7.8	
(2)	ECe	1.0	0.7	0.8	0.7	0.8	1.0	3.1	
Md	pH	8.1	8.8	8.9	9.1	8.6	8.5	–	WT
(1)	ECe	0.9	1.2	2.0	2.1	5.1	6.2	–	
MfC	pH	7.7	7.8	7.9	7.8	7.8	7.8	–	WT
(2)	ECe	0.6	0.6	0.6	0.7	0.7	0.7	–	C
WoA	pH	7.6	7.9	7.9	8.1	8.1	8.1	8.1	C
(2)	ECe	0.8	0.8	0.7	0.7	0.6	0.6	0.8	
WoA	pH	7.8	8.2	8.5	8.6	8.0	8.5	–	WT
(3)	ECe	0.8	0.6	1.0	1.2	4.1	1.1	–	C
NcA§	pH	7.7	7.8	7.9	7.9	8.0	8.0	8.0	
(1)	ECe	0.5	0.5	0.4	0.4	0.5	0.4	0.4	
NcA	pH	7.8	7.8	7.9	8.0	8.0	8.0	8.1	C
(2)	ECe	1.3	1.0	1.1	1.1	1.2	1.0	1.0	
GsA§	pH	7.7	8.0	8.0	–	–	–	–	WT
(1)	ECe	1.1	0.5	0.5	–	–	–	–	
GsA	pH	7.9	8.1	8.2	8.2	8.1	–	–	WT
(2)	ECe	1.2	2.4	1.5	0.9	0.9	–	–	

† NRCS soil mapping symbol, soil type and classification (numbers in parenthesis indicate multiple sites of the same soil series. ECe is in dS/m).

‡ Limiting layer above 210 cm depth: WT = water table (no cores taken); C = very slowly permeable clay layer about 30 cm thick beginning at 60 to 80 cm.

§ Fields selected to show background environmental levels of soil P and organic matter where little if any manure was applied over the years.

WoA = Woodrow silty clay loam (fine-silty, mixed (Calcareous), mesic xeric torrifluvents).
MfC = Moroni silty clay (fine, montmorillonitic, mesic entic Chromoxererts).
GeB = Genola loam (fine-silty, mixed (calcareous), mesic xeric Torrifluvents).
KcB = Keigley silty clay loam (fine-silty, mixed, mesic cumulic Haploxerolls).
Md = Mellor silt loam (fine-silty, mixed, mesic xerollic Natrargids).
NcA = Nibley silty clay loam (fine, mixed, mesic aquic Argiustolls).
GsA = Greenson loam (fine-silty, mixed, mesic aquic Calciustolls).

infrequent moderate rates to yearly or more frequent large rates. The STP concentrations were very high in the surface layer of all these fields. The STP concentrations below 90 cm, to as low as 210 cm depending on site, were higher than in the "control" fields (Table 3A). The STPt was essentially equal to STP in all the subsoils of the manured fields and in the surface soil at the Mfc (1) site. In the surface 30-cm layer of the other soils the concentration of STPt was 18 to 78% higher than the concentrations of STP. These results reflect the frequency and currency of manuring. High STPt concentrations occurred only when large amounts of manure had been applied within the last 2 yr (compare MfC(1) and GeB(2) soils with all others in Table 3B).

The TP concentrations in the manure-affected Sanpete soils were above background in the surface soil layer but generally not distinguised from TP in the subsurface layers (Fig. 1).

Cache Soils

Background STP concentrations were moderate to low and decreased with depth in the Cache County soils (Table 4A). The surface STP was somewhat higher than the same layers in the Sanpete soils, probably because these reference nonmanured fields were more intensively fertilized and managed for alfalfa (*Medicago sativa* L.) and silage corn (*Zea mays* L.) production.

Concentrations of P in alfalfa and corn fields that have received large amounts of feedlot manure annually or semi-annually since the 1940s are shown in Table 4B. In these soils concentrations of STPt were similar to concentrations of STP except for the surface layers where STPt averaged 84% higher than STP. Also, subsoil STP concentrations were considerably higher than background to the depths sampled at these two sites.

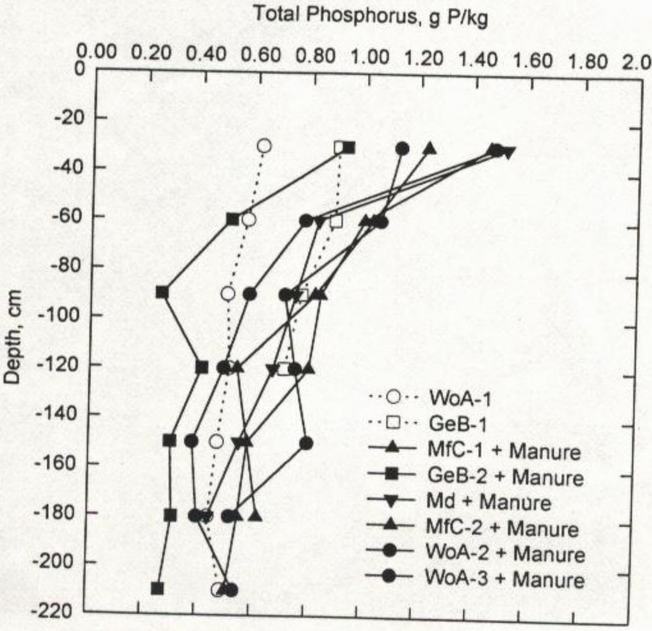

Fig. 1. Distribution of total soil P in Sanpete soils. Open circles are reference soils with little or no manuring. See Table 1 for soil descriptions.

Table 4. Bicarbonate-extractable P; Cache County soils.

Site†	Depth	Inorganic STP	Total STPt
	cm	mg P kg^{-1}	
A. Fields that have a history of little or no manure application.			
NcA (1)	0–30	17	36
	30–60	6	13
	60–90	3	7
	90–120	2	6
	120–150	2	4
	150–180	3	5
	180–210	8	18
GsA (1)	0–30	8	10
	30–60	4	3
	60–90	4	6
B. Fields that have a history of beef feed lot manure application.			
NcA (2)	0–30	134	251
	30–60	60	80
	60–90	15	21
	90–120	7	12
	120–150	5	9
	150–180	9	17
	180–210	10	14
GsA (2)	0–30	136	247
	30–60	92	87
	60–90	31	29
	90–120	13	8
	120–150	18	41

† See Table 1 for soil descriptions.

The TP concentrations in the Cache County soils were very high in the surface layer of the manured soils (Fig. 2).

Soil Organic Matter

As already shown, there was considerable variation in the STP, STPt, and TP concentrations in the fields sampled showing that long-term manure loading rates ranged widely among sites. In contrast, the organic matter percent in manured soils did not differ from that in

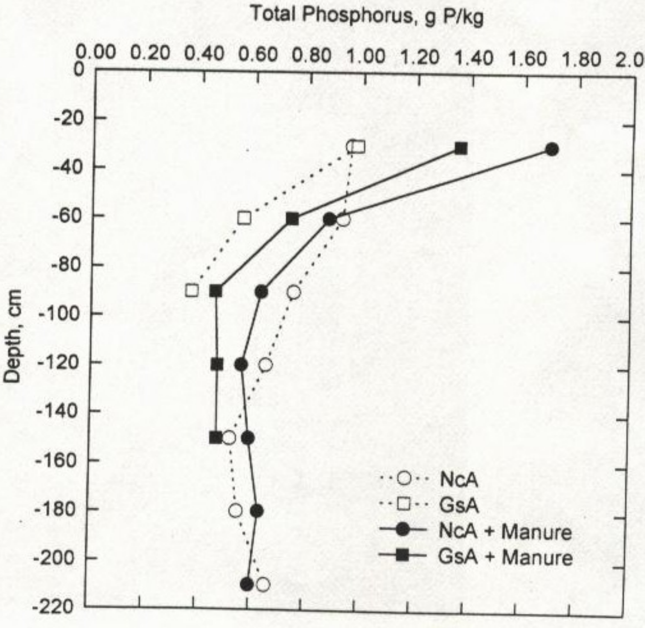

Fig. 2. Distribution of total soil P in Cache soils. Open circles are reference soils with little or no manuring. See Table 1 for soil descriptions.

nonmanured soils (Table 5). This may partially reflect the fact that the "control fields" (irrigated pasture and hay fields not associated directly with animal enterprises) received little or no tillage. The manured fields were plowed and tilled routinely in connection with production of corn, small grains, and alfalfa in rotation.

The organic matter content of the surface layer of nonmanured but tilled irrigated fields in Utah ranges from 1.5 to 2.5% (unpublished data, USU Analytical Lab., Utah State University). Soils receiving a plentiful supply of nutrients and organic residues accumulate organic matter up to an equilibrium level where input and decomposition balance (Anderson, 1980). This equilibrium level seems to have been 3.5% organic matter in the soils of this study.

GENERAL DISCUSSION

Manure Disposal Rates from Farmer Survey

Farmer's recollections of manure application amounts did not correlate well with the amount of soil P detected. A good record of field applications would require regular sampling and analysis for manure solids, water content and total P, which producers would perceive as impractical. It is believed, however, that STP, STPt, and TP collectively provide a good summary of manuring history. High concentrations of extractable organic P (i.e., STPt minus STP) correlated well with manure applied within the most recent 2 or 3 yr.

Soil Phosphorus Mobility Under Heavy Manuring

Our method for extractable organic P was not intended as an exhaustive measure of total soil organic P. A more definitive procedure is described by Nelson and Sommers (1982). However, considerable amounts of organic P were extracted in the routine bicarbonate test for available P, and these amounts depended on waste disposal practices.

The changes in STP with depth indicate that manuring affected subsoil layers as deep as 210 cm, evidently reflecting the mobility of organic P. Subsoil P enrichment under heavy manuring may also be related to the inhibition of inorganic P precipitation that is associated with large amounts of soluble organic material (Grossl and Inskeep, 1992).

TP As a Waste-P Sink

Manuring increased TP in the surface 30 cm by a factor of 1.5 to 2.5 (Fig. 1 and 2) that is equivalent to 6750 to 11 250 kg P ha-30 cm^{-1} above background. Subsoil TP was generally indistinguishable between manured and nonmanured soils. The contrast between manuring effects on subsoil TP and STP is explained by the methods of analysis and the total concentrations of the two forms of soil P; STP measurement is much more sensitive than for TP. The abundance of soluble and exchangeable Ca^{2+} and $CaCO_3$ in these soils indicate that there is no practical limit to the ability of these soils to immobilize waste P.

The complex P forms (OCP, HAP) are biologically inert and therefore environmentally innocuous. In other words, continuous surface and subsoil P enrichment from heavy manuring was neither beneficial or detrimental. This differs from the problem of erosion of P-rich soil into waterways. When manure disposal ceased, the extractable organic P decreased to background levels within 2 or 3 yr. Discontinuing manure disposal will result eventually in decreased STP, but this decrease is probably buffered by the TP pool.

Table 5. Soil organic matter content in fields with manure disposal rates ranging from none to large annual or more frequent applications over the past 20 to 40 yr.

Soil depth	Location							
	WoA† (1)	GeB† (1)	MfC (1)	GeB (2)	Md (1)	MfC (2)	WoA (2)	WoA (3)
cm	%							
(a) Sanpete County.								
0–30	3.15	2.93	3.36	3.00	2.84	3.97	2.86	3.24
30–60	2.07	1.90	2.03	1.66	1.43	3.07	1.59	1.78
60–90	1.52	1.31	1.74	1.02	1.21	1.95	1.07	1.03
90–120	1.40	1.21	1.55	1.00	1.00	1.62	0.97	0.97
120–150	1.33	–	1.29	0.86	0.98	1.41	0.67	0.88
150–180	0.76	–	0.88	0.74	0.81	1.45	0.74	–
180–210	0.88	–	0.62	0.57	–	–	0.86	–

(b) Cache County.

	Location		
	NcA† (1)	NcA (2)	GsA (2)
0–30	3.28	3.06	3.29
30–60	2.03	1.31	1.76
60–90	1.43	0.75	0.74
90–120	1.22	0.58	0.71
120–150	0.55	0.62	0.59
150–180	0.64	0.64	–
180–210	1.09	0.59	–

† Regional reference soils with little or no history of manure disposal. All others have received appreciable amounts of manure during the last two decades. See Table 1 for soil descriptions.

Evidently the calcareous soils in our sample have an exceedingly large capacity to retain waste P in biologically inert forms. Contamination of the groundwater by P does not appear to be likely, especially if manure application rates are limited by acceptable NO_3–N concentrations.

CONCLUSIONS

Long-time manure disposal on land increased the concentration of extractable inorganic P in subsoil layers as deep as 210 cm. Manuring increased extractable organic P concentrations markedly in the 0 to 30 cm layer but this organic P dissipated to background levels within 2 to 3 yr after manuring ceased. Subsoil STP enrichment was attributed to transport and subsequent mineralization of soluble organic P.

Manuring increased TP concentrations of the 0 to 30 cm layer by 1.5 to 2.5 times above background; there was little apparent effect on subsoil TP. Accordingly, most of the manure P is immobilized in the surface layer.

Continuous manuring increased soil organic matter to about 3.5% in these irrigated calcareous soils, at which point decomposition and accumulation appear to be in equilibrium.

Organic P and inorganic P from heavy manuring do not threaten soil or groundwater quality under deep calcareous soils if manure application is limited by acceptable N-loading rates.

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