Phosphorus Accumulation in Cultivated Soils from Long-Term Annual Applications of Cattle Feedlot Manure

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ABSTRACT

Historically, manure has been recognized as an excellent soil amendment that can improve soil quality and provide nutrients for crop production. In areas of high animal density, however, the potential for water pollution resulting from improper storage or disposal of manure may be significant. The objective of this study was to determine the P balance of cultivated soils under barley (*Hordeum vulgare* L.) production that have received long-term annual manure amendments. Nonirrigated soils at the study site in Lethbridge, AB, Canada, have received 0, 30, 60, or 90 Mg manure ha^{-1} (wet wt. basis) while irrigated plots received 0, 60, 120, and 180 Mg ha^{-1} annually for 16 yr. The amount of P removed in barley grain and straw during the 16-yr period was between 5 and 18% of the cumulative manure P applied. There was a balance between P applied in manure and P recovered in crops and soils (to the 150-cm depth) of nonirrigated plots during the 16-yr study. In irrigated plots, as much as 1.4 Mg P ha^{-1} added (180 Mg ha^{-1} yr^{-1} treatment) was not recovered over 16 yr, and was probably lost through leaching. The risk of ground water contamination with P from manure was greater in irrigated than nonirrigated plots that have received long-term annual manure amendments. Manure application rates should be reduced in nonirrigated and irrigated plots to more closely match manure P inputs to crop P requirements.

A MAJOR CONCERN in areas of high animal density is the potential for water pollution resulting from improper storage or disposal of animal manure. In Alberta, intensive confined livestock production has been increasing for 20 yr, and it is estimated that 4800 cattle (*Bos taurus*) feedlots, ranging in size from 1000- to 50 000-head operations, with a capacity of 1.2 million cattle per year are currently operating (Canada–Alberta Environmentally Sustainable Agriculture Agreement, 1998). Manure from commercial feedlots is generally disposed through land application, but most feedlots have a limited land base, and it is often not economical to broaden the land base by hauling manure long distances (Freeze et al., 1999; McKenzie et al., 2000). As a result, the land closest to cattle feedlots may be amended with large quantities of feedlot manure on a continual basis.

Current manure application guidelines in Alberta are based on crop N requirements. Cattle feedlot manure has a lower N to P ratio (4:1 to 5:1) than crops (6:1 to 8:1), and manure applications based on crop N requirements tend to provide P in excess of crop P requirements (Intensive Livestock Operations Committee, 1995). Over time, this can result in P accumulation in soils and increase the risk of P transport to water bodies through leaching, erosion, and runoff processes (Sharpley et al., 1994; Lennox et al., 1997). The transport of soil P to water bodies depends on many factors including climate, soil type and hydrology, soil P content, agronomic practices, and landscape position (Lemunyon and Gilbert, 1993; Heathwaite, 1997). In general, it is expected that the risk to water quality from P pollution will be greater in conventionally cropped than low-intensity grassland soils, and greater in coarser (sandy) than fine-textured (clay) soils (Sonzogoni et al., 1980).

The objective of this study was to determine the system-level P balance in irrigated and nonirrigated soils that have received manure amendments annually for 16 yr.

MATERIALS AND METHODS

The research site is located at the Lethbridge Research Centre in southern Alberta, Canada. In 1973, an experiment was initiated to determine the effects of repeated annual application of cattle feedlot manure on the productivity of nonirrigated and irrigated soils. The soil in the study area is a calcareous Orthic Dark Brown Chernozemic (Typic Haploborolls) clay loam, and from 1974 to 1995 was cropped annually with barley (*Hordeum vulgare* L. cv. Galt). Soil characteristics at the study site prior to initiation of the study are given in Table 1. Further details of the research site and the effect of long-term manure amendments on soil chemistry, fertility, and physical properties have been reported (Sommerfeldt and Chang, 1985; Chang et al., 1990, 1991, 1993; Chang and Janzen, 1996).

Experimental Design

Beginning in 1973, solid cattle feedlot manure was applied annually each fall after barley harvest and incorporated immediately after application by one of three methods: plow, rototiller, and cultivator plus disk. Within each tillage treatment (7.5- by 64-m main plot), manure was applied to subplots (7.5 by 15 m) at the following rates: 0, 30, 60, and 90 Mg ha^{-1} (wet wt.) in nonirrigated soils and 0, 60, 120, and 180 Mg ha^{-1} (wet wt.) in irrigated soils. The annual P application rate between 1973 and 1989 was approximately 0, 134, 268, and 402 kg P ha^{-1} (dry wt.) in nonirrigated soils, and 0, 268, 536, and 804 kg P ha^{-1} (dry wt.) in irrigated soils. Main and subplot treatments were assigned randomly and replicated three times. Recommended annual manure applications in Lethbridge, AB, Canada were 30 Mg manure (wet wt.) ha^{-1} for nonirrigated soils and 60 Mg ha^{-1} (wet wt.) for irrigated soils at the initiation of the experiment (Alberta Agriculture, 1980). Soil properties and crop production were not affected significantly by tillage (Sommerfeldt et al., 1988; Chang et al., 1990) and from 1986 to present, manure has been incorporated in all subplots with a cultivator, which increased the number of replicate manure treatments thereafter to nine. In 1986, manure applications to three subplots of each manure treatment were stopped to evaluate the residual effects of manure on

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Table 1. Soil physico-chemical properties in soil layers to the 150-cm depth in 1973 prior to manure applications. Values are the mean of 72 replicate determinations.

Soil depth	Sand	Silt	Clay	pH	Organic matter
cm		$g\ kg^{-1}$			$g\ kg^{-1}$
0 to 15	386	220	394	7.75	21.3
15 to 30	387	213	400	7.78	16.6
30 to 60	478	225	297	7.90	9.5
60 to 90	399	257	343	7.89	6.3
90 to 120	458	247	293	7.86	5.0
120 to 150	473	227	300	7.82	4.4

Table 2. Influence of manure treatments on mean aboveground yield (grain plus straw), biomass N, biomass P, and N to P ratio of barley. Data are means (±standard errors) for crops harvested between 1991 and 1995 in nonirrigated and irrigated plots.

Manure rate	Yield (grain+straw)	Biomass N	Biomass P	N to P ratio
$Mg\ ha^{-1}$ (wet wt.)	$Mg\ ha^{-1}$	$kg\ ha^{-1}$		
		Nonirrigated		
0	10.1 ± 0.8	160 ± 13	26 ± 2	6.2 ± 0.3
30	11.4 ± 1.1	230 ± 23	35 ± 3	6.6 ± 0.3
60	12.6 ± 1.3	264 ± 27	41 ± 3	6.4 ± 0.4
90	11.8 ± 1.3	252 ± 26	41 ± 3	6.1 ± 0.4
		Irrigated		
0	10.6 ± 0.3	168 ± 9	29 ± 1	5.8 ± 0.2
60	12.8 ± 0.9	218 ± 14	41 ± 2	5.3 ± 0.3
120	12.6 ± 0.9	225 ± 15	44 ± 2	5.1 ± 0.3
180	14.2 ± 1.3	258 ± 22	52 ± 3	5.0 ± 0.3

soil properties and crop production. Water table levels were monitored periodically each year of the study with 21 wells installed in the study area.

Manure applied in this study from an open, unpaved commercial cattle feedlot contained no bedding, and was stored 1 to 2 yr before application. The quantity and quality of manure applied varied from year to year, although the manure applied in a given year was from the same source (Chang et al., 1991). Manure applied between 1973 and 1989 contained, on a dry weight basis, an average (±standard error) of 16 ± 1 g N kg^{-1} (Kjeldahl N; Bremner, 1965), 6.2 ± 0.3 g P kg^{-1} (Na_2CO_3–fusion; Jackson, 1958), and 0.72 ± 0.06 kg H_2O kg^{-1} manure (oven dried at 105°C for 48 h). The manure also contained, on a dry weight basis, an average of 1.3 ± 0.2 g NH_4–N kg^{-1}, 0.2 ± 0.05 g NO_3–N kg^{-1} (2 *M* KCl; Bremner, 1965), and 2.6 ± 0.2 g P kg^{-1} ($NaHCO_3$–soluble P, Olsen et al., 1954).

Soil Analysis

Soil samples were collected annually beginning in 1973 (except 1989) after harvest prior to manure application by extracting two cores from each plot. Soil cores were subdivided by depth into six segments (0 to 15, 15 to 30, 30 to 60, 60 to 90, 90 to 120, and 120 to 150 cm), composited, air-dried, and ground (<2-mm mesh). Sodium bicarbonate–soluble P (*plant-available* P) was determined according to Olsen et al. (1954) and total soil P was measured by Na_2CO_3–fusion (Jackson, 1958). We did not include soil analysis from 1991 to 1995 in this manuscript because methodologies for available and total P analysis of soils changed in 1991.

Plant Analysis

Each year, barley was seeded between 15 and 31 May, and was harvested in late August or early September. Grain and straw yields were determined in barley harvested from a 4-m^2 area of each plot with a small combine. From 1974 to 1990, the protein content of grain was determined by the semimicro-Kjeldahl method (Technicon Industrial Systems, 1978). From 1991 to 1995, total C and N in grain and straw samples were determined by combustion with a Carlo Erba (Milan, Italy) CN analyzer, and total P was determined by wet combustion with concentrated H_2SO_4 and 30% H_2O_2 followed by analysis on a Technicon IV Autoanalyzer (Technicon Industrial Systems, Tarrytown, NY). Since barley straw was not analyzed for total N from 1974 to 1990, data from 1991 to 1995 were used to estimate the N content of straw (straw % N, g N g^{-1}) based on the N content of grain (grain % N, g N g^{-1}):

$$\text{straw \% N} = (0.9314 \times \text{grain \% N}) - 0.9861; \quad (R^2 = 0.6026,\ n = 215) \qquad [1]$$

Neither grain nor straw was analyzed for total P from 1974 to 1990. The P content (g P m^{-2}) of aboveground biomass (grain plus straw) for crops harvested between 1974 and 1990 was calculated as:

$$\text{biomass P} = (\text{biomass N}) \div (\text{N to P ratio}) \qquad [2]$$

where biomass P is the P content (g P m^{-2}) of aboveground biomass, biomass N is the N content (g N m^{-2}) of aboveground biomass, and N to P ratio is the ratio of biomass N and biomass P in barley samples from 1991 to 1995. The N to P ratio of aboveground biomass was calculated for each manure treatment in irrigated or nonirrigated plots, and N to P ratios used in Eq. [2] are reported in Table 2.

Calculations for Phosphorus Budget

The following calculations were used to determine P fluxes and pool sizes. For annual P input:

$$P_{\text{manure}}\ (\text{kg P ha}^{-1}) = \text{manure applied (kg ha}^{-1}\text{, dry wt.)} \times \text{manure P (kg P kg}^{-1}) \qquad [3]$$

For annual P output:

$$P_{\text{crop}}\ (\text{kg P ha}^{-1}) = \text{grain yield (kg ha}^{-1}) \times \text{grain P (kg P kg}^{-1}) + \text{straw yield (kg ha}^{-1}) \times \text{straw P (kg P kg}^{-1}) \qquad [4]$$

Cumulative P fluxes were the sums of annual P inputs and outputs during the 16-yr study. For total soil P pool (to 150 cm, $i = 1$ to 6 for depths separated in each soil core):

$$P_{\text{soil}}\ (\text{kg P ha}^{-1}) = \Sigma\ \text{soil mass (kg ha}^{-1}, \text{depth}_i) \times \text{total P (kg P kg}^{-1}, \text{depth}_i) \qquad [5]$$

For available soil P pool (to 150 cm, $i = 1$ to 6 for depths separated in each soil core):

$$P_{\text{avail}}\ (\text{kg P ha}^{-1}) = \Sigma\ \text{soil mass (kg ha}^{-1}, \text{depth}_i) \times \text{Olsen P (kg P kg}^{-1}, \text{depth}_i) \qquad [6]$$

The predicted increase in P content of manure-amended soils ($P_{\text{soil,pred}}$) to a depth of 150 cm in 1974 was calculated by adding the P_{soil} measured in unamended soils to the P_{manure} input from 1973, and subtracting the difference of P_{crop} removed from manure-amended and unamended soils. In subsequent years, $P_{\text{soil,pred}}$ was the P_{soil} in unamended soils that year plus cumulative P_{manure} input minus the difference of cumulative P_{crop} removed from manure-amended and unamended soils. The percentage recovery of manure P added to soils was calculated by dividing P_{soil} from Eq. [5] by $P_{\text{soil,pred}}$ and multiplying by 100%.

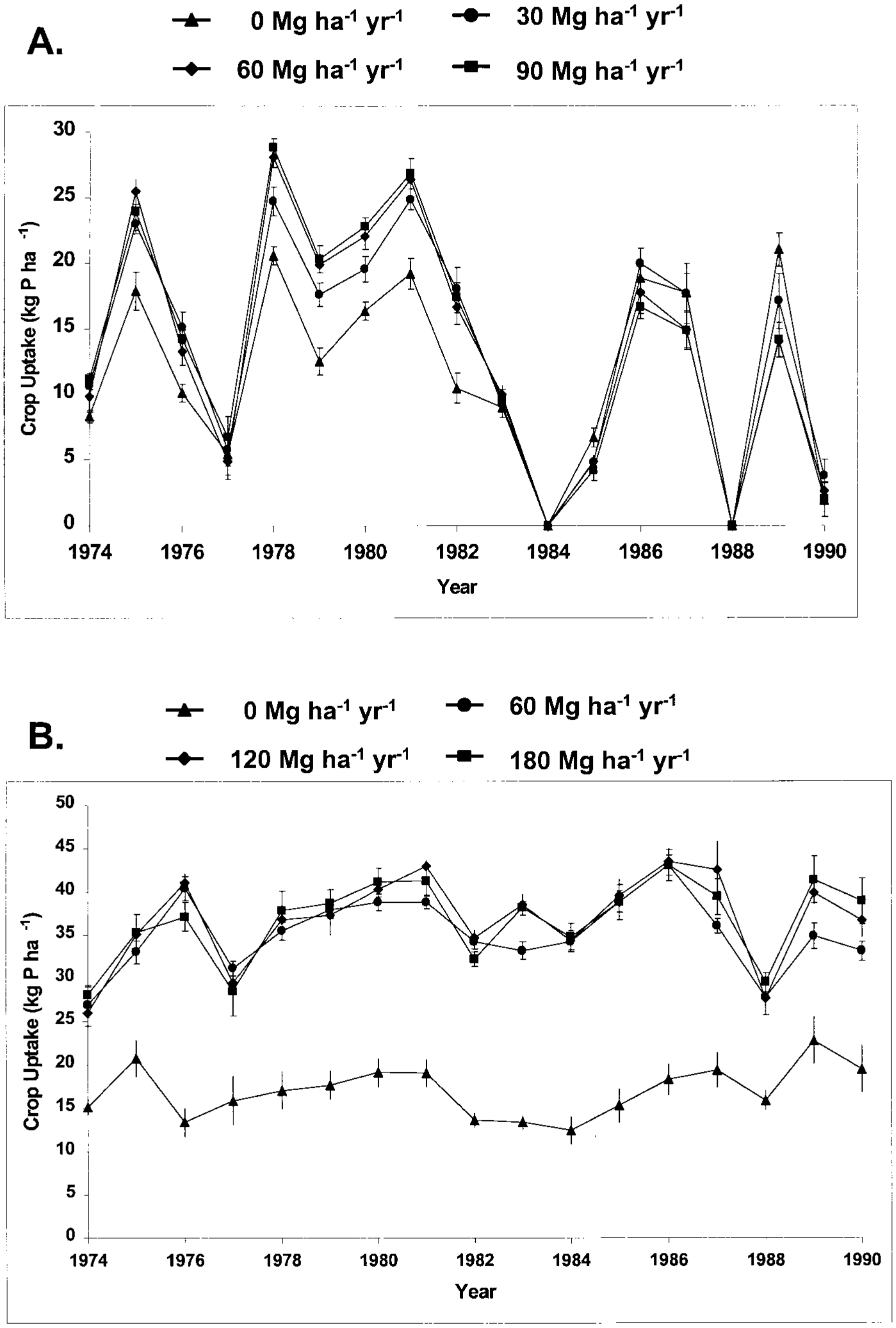

Fig. 1. Annual P uptake by barley grown on soil amended annually with various rates of feedlot manure under (*A*) nonirrigated and (*B*) irrigated conditions. Values are means (±standard errors).

RESULTS AND DISCUSSION

Phosphorus Input

In nonirrigated plots, the cumulative P input from manure between 1973 and 1990 was 1.6, 3.4, and 5.1 Mg P ha^{-1} in plots amended with 30, 60, and 90 Mg ha^{-1} yr^{-1}, respectively. Irrigated plots amended with 60, 120, and 180 Mg ha^{-1} yr^{-1} had a cumulative P input of 3.4, 6.3, and 9.4 Mg P ha^{-1}, respectively, between 1973 and 1990. The mean N to P ratio of manure applied during the 16-yr study was 2.6:1, which is lower than the N to P ratios of 4.2:1 to 5.4:1 reported for cattle feedlot manure in Alberta by the Intensive Livestock Operations Committee (1995). About 42% of manure P was NaH CO$_3$–extractable before application, indicating that nearly half of the manure P was in forms available for plant uptake (Tiessen et al., 1983).

Phosphorus Output

Annual P uptake in aboveground crop biomass (grain plus straw) ranged from 2 to 25 kg P ha^{-1} yr^{-1} in manure-amended nonirrigated plots and 22 to 38 kg P ha^{-1} yr^{-1} in manure-amended irrigated plots between 1974 and

1990. Crop yield was more variable in nonirrigated than irrigated plots, and crop failure on nonirrigated plots occurred in 1984 and 1988 due to drought (Fig. 1A,B). Cumulative P uptake by barley ranged from 0.21 Mg P ha^{-1} in nonirrigated plots to 0.63 Mg P ha^{-1} in irrigated plots during the 16-yr period examined. Greater P uptake by barley in irrigated than nonirrigated plots was due to higher yield and N uptake by the crop (Chang and Janzen, 1996). The amount of P removed in barley grain and straw in the nonirrigated plots during the 16-yr period was between 5 and 15% of the cumulative manure P applied. In irrigated plots, the amount of P removed by crop uptake ranged from 7 to 18% of the cumulative manure P applied.

Soil Phosphorus Pools and Phosphorus Balance

Total and available P levels increased greatly in all plots amended with manure annually for 16 yr (Fig. 2A,B and 3A,B). By 1990, total P in nonirrigated soil to the 150-cm depth was 1.2 to 3.8 Mg P ha^{-1} greater in manure-amended than control plots, while the total P in irrigated soils was 1.9 to 5.2 Mg P ha^{-1} greater than control plots (Fig. 2A,B). The available P in nonirrigated soils to the 150-cm depth was 0.8 to 1.9 Mg P ha^{-1}

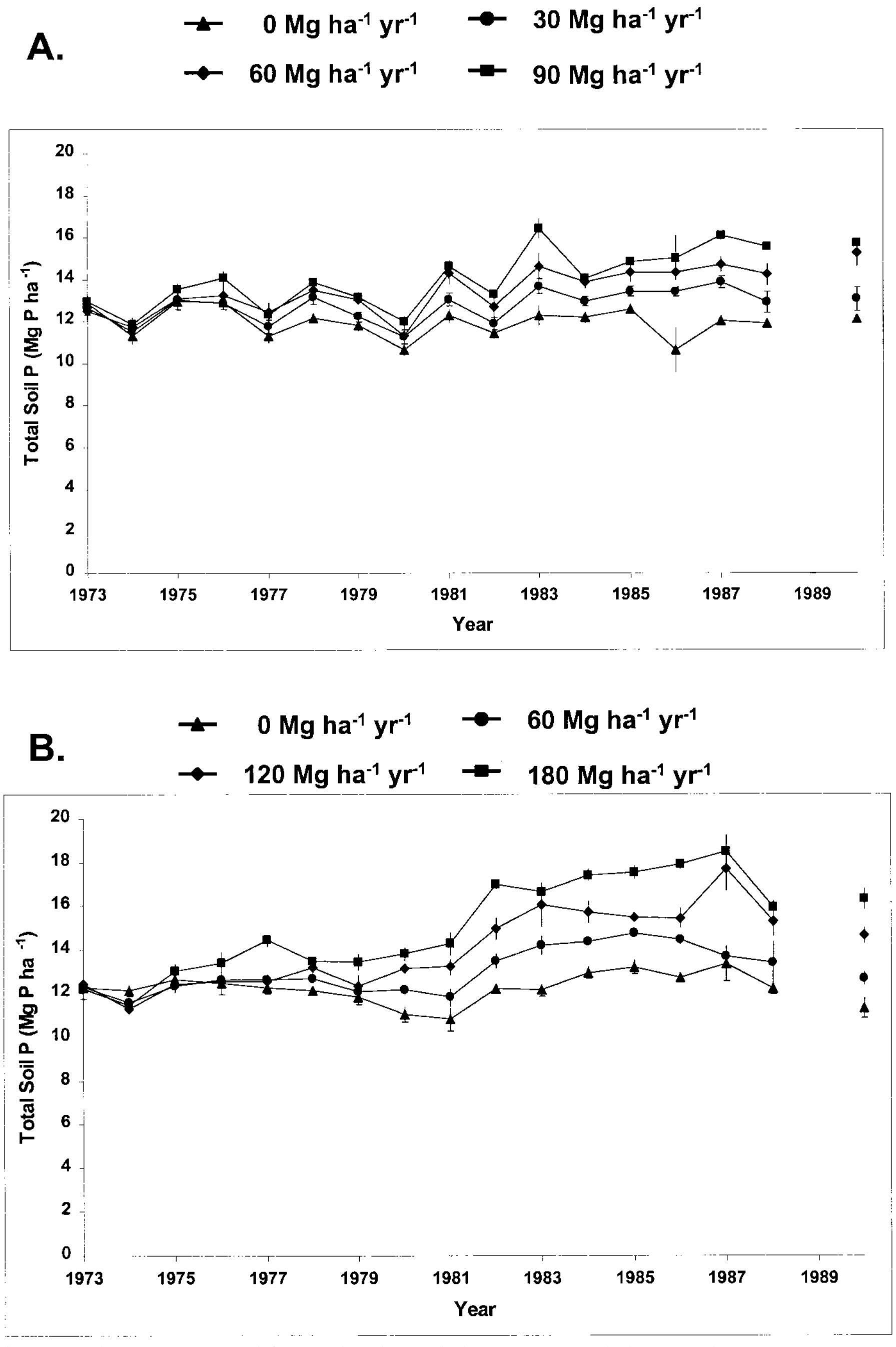

Fig. 2. Annual changes in total soil P to a depth of 150 cm in (*A*) nonirrigated and (*B*) irrigated soils amended annually with different rates of feedlot manure. Values are means (±standard errors).

higher in manure-amended than control soils, whereas available P in irrigated soils was 1.2 to 2.9 Mg P ha^{-1} higher in manure-amended than control soils by 1990 (Fig. 3A,B). Available P accounted for 50 to 66% of the total P accumulated in nonirrigated soils, and 56 to 63% of the total P in irrigated soils.

Virtually all manure P applied to nonirrigated soils was recovered in soil and crop P pools (Fig. 4A,B,C). The proportion of manure P recovered in topsoil (0 to 15 cm) tended to decline, while the amounts of manure P recovered in the 15- to 60- and 60- to 150-cm depths tended to increase from 1974 to 1990 (Fig. 4A,B,C). There was an apparent balance between P applied in manure and P recovered in soil and crop pools, which suggests that losses of P through surface runoff or erosion in nonirrigated plots were negligible. The rooting zone of barley in nonirrigated plots may extend to 60 cm, which suggests that soil P in the 15- to 60-cm depth could be assimilated by the crop. Repeated annual manure applications have increased soil total and available P levels at depths exceeding 60 cm, particularly in plots receiving the higher rates of manure (Table 3). It seems possible that P could be leached past 150 cm if annual manure applications are continued.

In irrigated plots, an average of 93, 88, and 85% of manure P applied was recovered in soil and crop P pools of plots amended with 60, 120, and 180 Mg ha^{-1} yr^{-1} between 1974 and 1990 (Fig. 5A,B,C). During the 16 yr

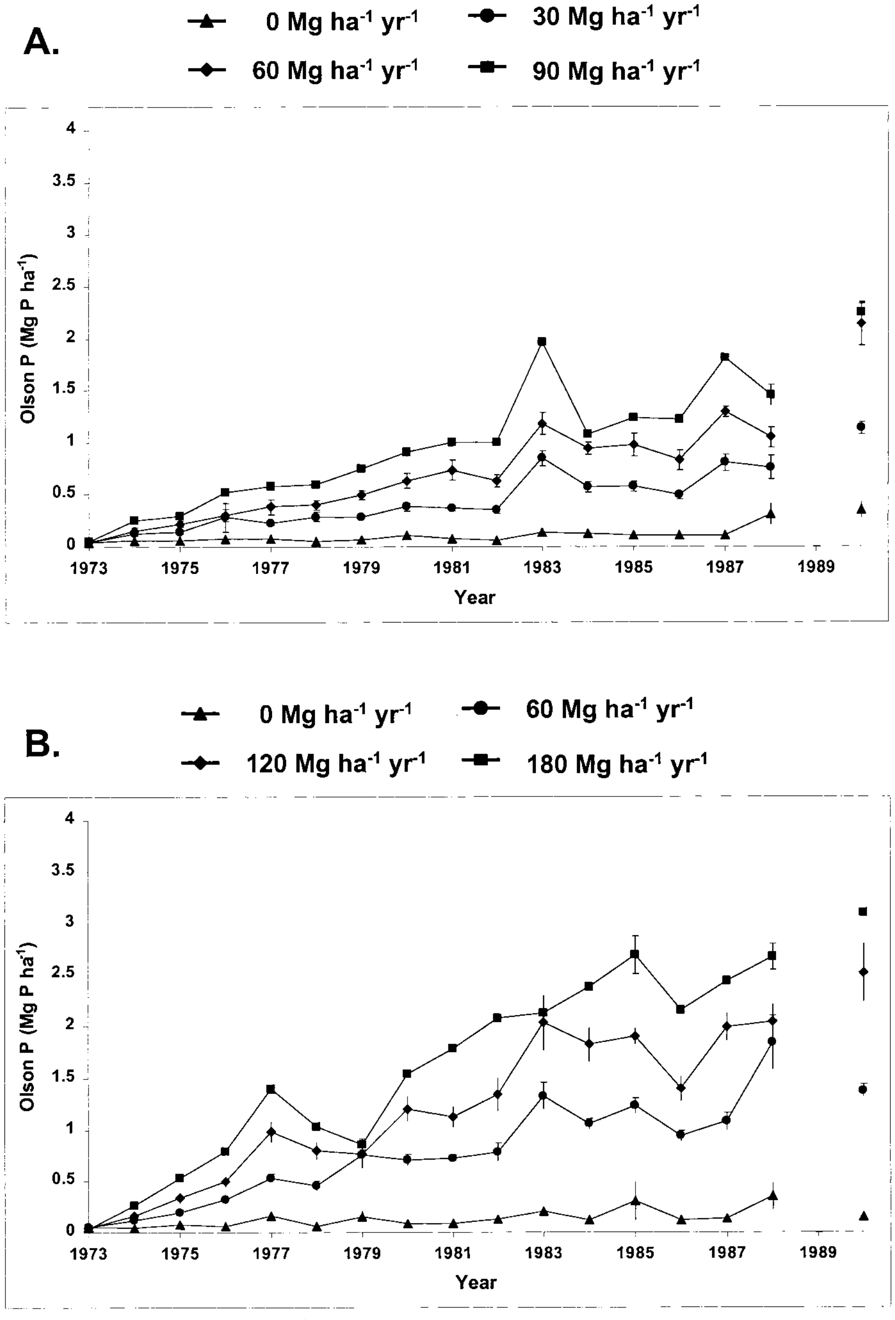

Fig. 3. Annual changes in available soil P to a depth of 150 cm in (*A*) nonirrigated and (*B*) irrigated soils amended annually with different rates of feedlot manure. Values are means (±standard errors).

Table 3. Influence of 16 yr of annual manure applications on total P and Olsen P concentration in cultivated soils. Data are means (±standard errors) for soils collected in 1990 from nonirrigated plots.

	Total P				Available P			
	Manure Rate (Mg ha^{-1} yr^{-1}, wet weight)							
Soil Depth	0	30	60	90	0	30	60	90
cm	g P kg^{-1}				mg P kg^{-1}			
0 to 15	1.06 ± 0.12	1.50 ± 0.10	1.96 ± 0.19	2.24 ± 0.10	141 ± 42	317 ± 40	538 ± 66	606 ± 20
15 to 30	0.84 ± 0.04	1.12 ± 0.10	1.58 ± 0.15	1.66 ± 0.17	62 ± 16	176 ± 42	389 ± 61	378 ± 49
30 to 60	0.60 ± 0.01	0.72 ± 0.04	0.68 ± 0.02	0.76 ± 0.05	11 ± 6	30 ± 11	35 ± 8	59 ± 15
60 to 90	0.62 ± 0.02	0.54 ± 0.07	0.66 ± 0.02	0.70 ± 0.03	5 ± 1	12 ± 3	23 ± 3	22 ± 5
90 to 120	0.60 ± 0.01	0.62 ± 0.04	0.70 ± 0.03	0.68 ± 0.02	6 ± 2	11 ± 3	26 ± 4	18 ± 3
120 to 150	0.66 ± 0.02	0.60 ± 0.08	0.66 ± 0.02	0.74 ± 0.02	13 ± 4	13 ± 3	33 ± 5	36 ± 5

Table 4. Influence of 16 yr of annual manure applications on total P and Olsen P concentration in cultivated soils. Data are means (±standard errors) for soils collected in 1990 from irrigated plots.

	Total P				Available P			
	Manure Rate (Mg ha^{-1} yr^{-1}, wet weight)							
Soil Depth	0	60	120	180	0	60	120	180
cm	g P kg^{-1}				mg P kg^{-1}			
0 to 15	0.92 ± 0.12	1.76 ± 0.10	2.80 ± 0.12	3.75 ± 0.13	95 ± 41	452 ± 25	736 ± 36	964 ± 33
15 to 30	0.64 ± 0.02	1.11 ± 0.08	1.76 ± 0.14	2.02 ± 0.14	21 ± 6	229 ± 37	517 ± 40	612 ± 48
30 to 60	0.57 ± 0.02	0.67 ± 0.03	0.80 ± 0.04	0.93 ± 0.05	4 ± 1	30 ± 3	99 ± 19	176 ± 40
60 to 90	0.60 ± 0.03	0.54 ± 0.04	0.63 ± 0.02	0.65 ± 0.02	3 ± 1	5 ± 1	18 ± 4	26 ± 6
90 to 120	0.61 ± 0.03	0.60 ± 0.01	0.61 ± 0.01	0.65 ± 0.02	3 ± 1	6 ± 1	20 ± 5	21 ± 3
120 to 150	0.60 ± 0.02	0.60 ± 0.01	0.66 ± 0.03	0.67 ± 0.02	5 ± 1	10 ± 2	32 ± 5	48 ± 7

that irrigated plots received annual manure applications, there was a trend of greater manure P recovery in subsurface (>15 cm) than topsoil (0 to 15 cm) layers (Fig. 5A,B,C). By 1990, there was more total and available P in the profile of manure-amended than unamended soils (Table 4). Manure P not recovered in soil and crop P pools of irrigated plots may have been lost through surface runoff or leached through the soil profile to depths greater than 150 cm. Ground water levels under irrigated plots varied through the year, and water table levels ranged from about 50 to 250 cm, indicating that P leached to depths greater than 150 cm could eventually be transported to ground water. The ground water levels in nonirrigated plots are always greater than 150 cm. After 16 yr of continuous annual manure application, about 7 to 15% of P applied to irrigated plots could not be accounted for in the crop and soil to the 150-cm depth.

Other studies that have investigated the long-term effects of manure on soil P dynamics have observed P accumulation and movement through the profile. After 11 yr of annual application, King et al. (1990) found that swine lagoon effluent increased levels of available P at a depth of 75 cm, but they predicted further downward migration of P would be slow due to increasing clay content and decreasing pH below 75 cm. Available P levels to a depth of 60 cm in loamy and clayey soils from Alabama were more than six times greater in soils amended annually with poultry litter for 15 to 28 yr than unamended soils (Kingery et al., 1994).

Our study shows elevated extractable and total P concentrations at depths up to 150 cm. Substantial P movement through the profile was unexpected at this site because it was thought that the soil (calcareous clay loam) would have considerable capacity to adsorb P applied in excess of plant P requirements. Lutwick and Graveland (1978) found the phosphorus adsorption capacity was related to clay content, cation exchange capacity, and ammonium acetate-extractable Ca and Mg in Orthic Brown and Orthic Dark Brown Chernozemic soils from southern Alberta. The phosphorus adsorption capacity of silty clay and silty clay loam soils ranged from 236 to 950 mg P kg^{-1} soil at sampling depths from 0 to 150 cm. It was estimated that soils with a clayey texture could receive annual applications of 40 kg P ha^{-1} in sewage effluent for 120 to 153 yr before the P adsorption capacity of the profile was saturated (Lutwick and Graveland, 1978). Similarly, James et al. (1996) reported that calcareous soils in Utah had an exceedingly large capacity to retain P from turkey (*Meleagris gallopavo*) and beef manure, and indicated that P contamination of ground water was not likely. However, Eghball et al. (1996) demonstrated that P from beef manure could move through soil layers with high calcium carbonate contents and could eventually reach ground water, especially in areas with shallow water tables.

Our results support findings by Eghball et al. (1996) since up to 1.4 Mg P ha^{-1} was not accounted for in irrigated plots receiving 180 Mg manure ha^{-1} yr^{-1} after 16 yr of continuous manure application. The mechanisms responsible for P movement through calcareous soils are not known. Feedlot manure contains appreciable quantities of soluble salts, and after eleven annual applications of feedlot manure, soluble Na had increased at depths below 120 cm in irrigated plots, and there had been displacement of Ca and Mg on the exchange complex by Na (Chang et al., 1991). Reduction in the quantities of exchangeable Ca after repeated application of feedlot manure and irrigation, or colloid-mediated transport of P due to increased soil dispersion with increasing Na saturation, could partially explain the apparent movement of P in irrigated soils (Parfitt, 1978). Other anions, such as fluoride and sulfate, are adsorbed on mineral surfaces and can compete for binding sites with P, while P solubilization from mineral

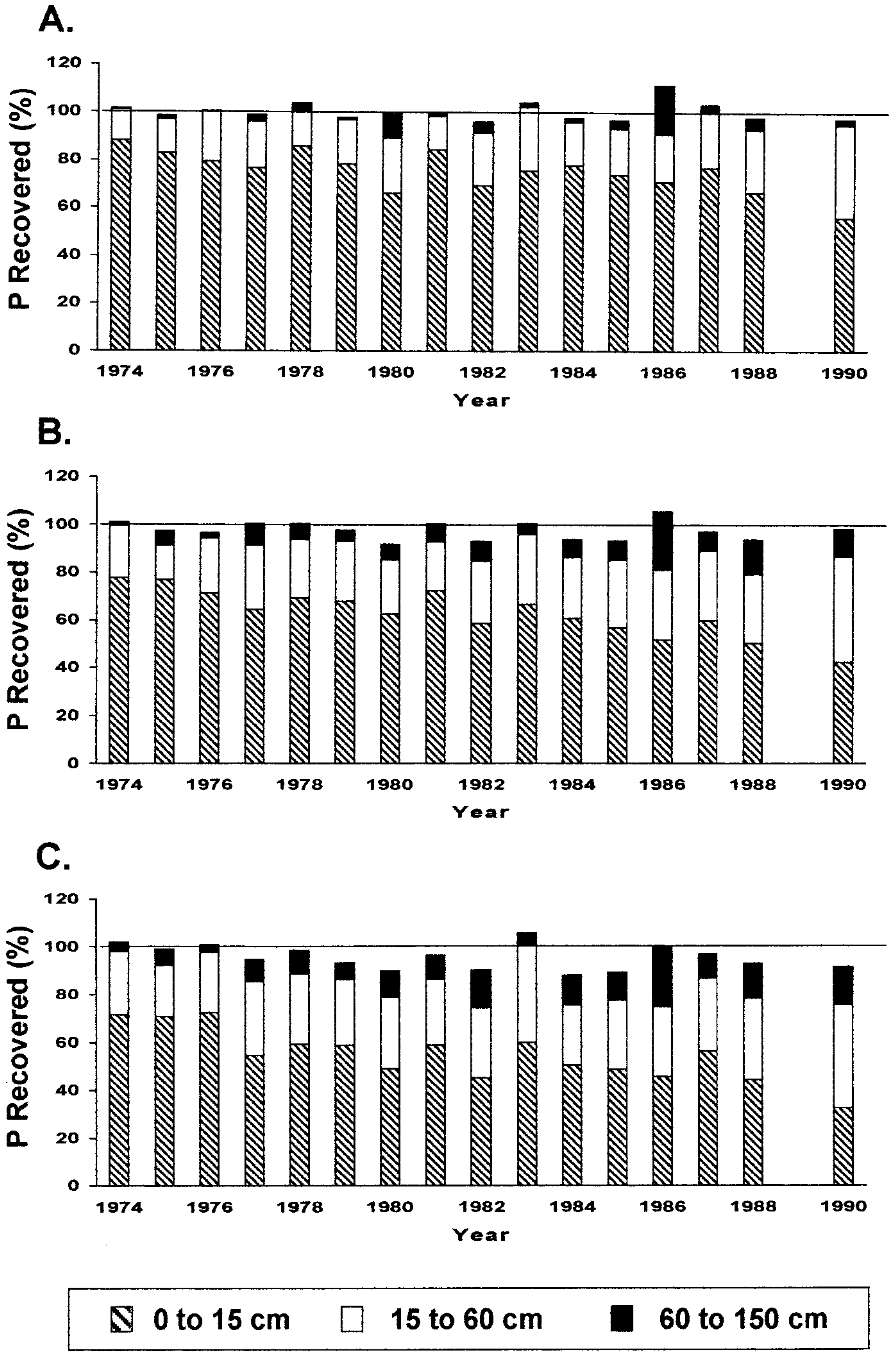

Fig. 4. Recovery of P from manure in crop and soil P (to the 150-cm depth) pools in nonirrigated plots receiving annual manure applications of (*A*) 30, (*B*) 60, and (*C*) 90 Mg ha^{-1}.

surfaces can be increased by organic acids present in animal manure (Fox et al., 1990; Violante and Gianfreda, 1993; Iyamuremye et al., 1996; Ohno and Crannell, 1996). Finally, the transport of mobile inorganic P and dissolved organic P compounds through the profile may have been enhanced by irrigation. We did not conduct experiments to investigate these mechanisms, and further studies are needed to research possible explanations of the data.

This study demonstrated risk to ground water from P movement through calcareous fine-textured (clay) soils that have received annual feedlot manure applications. A possible solution to this problem is applying feedlot manure based on crop P rather than crop N requirements. The maximum recommended P fertilizer rates for barley production are 25 kg P ha^{-1} on nonirrigated and 45 kg P ha^{-1} on irrigated Orthic Brown Chernozemic soils (Alberta Agriculture, 1997). The quantity of manure that could be applied on soils from this study to support crop production, based on a mean total manure P content of 6.2 g P kg^{-1}, would be 6 Mg manure ha^{-1} (wet wt.) on nonirrigated plots and 10 Mg ha^{-1} on irrigated plots. This would supply 69 g N kg^{-1} to nonirrigated plots and 115 g N kg^{-1} to irrigated plots, but Chang and Janzen (1996) found that only 56% of the N applied in cattle feedlot manure was mineralized in the long term (nearly 20 yr). Therefore, the N supplied in manure would be insufficient for crop production,

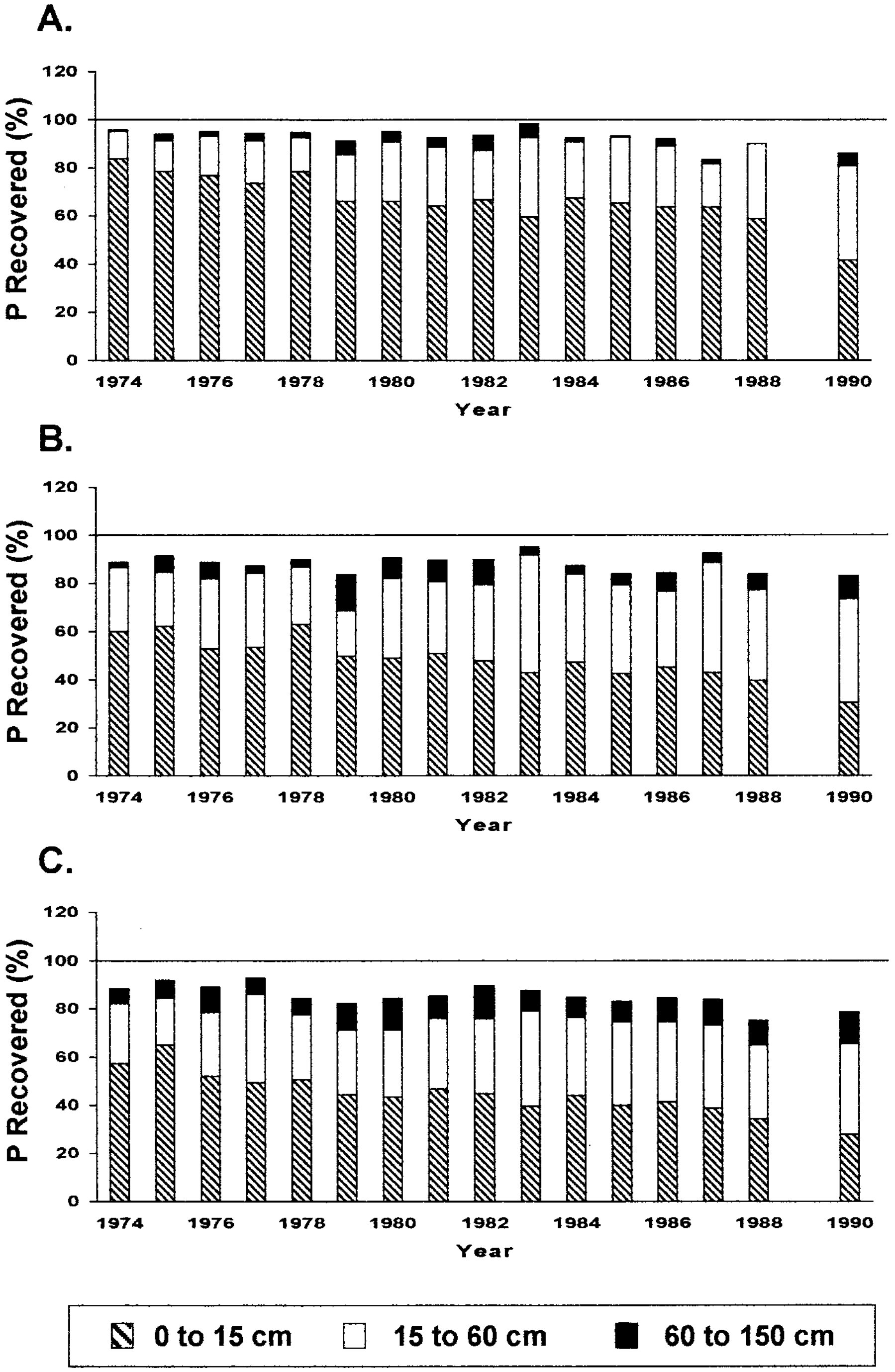

Fig. 5. Recovery of P from manure in crop and soil P (to the 150-cm depth) pools in irrigated plots receiving annual manure applications of (*A*) 60, (*B*) 120, and (*C*) 180 Mg ha^{-1}.

based on maximum fertilizer N recommendations of 73 kg N ha^{-1} for nonirrigated and 146 kg N ha^{-1} for irrigated soils (Alberta Agriculture, 1995), and supplemental N fertilizer would be required.

Based on the observation that 50 to 66% of the total P in manure-amended soils was Olsen P, we could assume that manure provides about 50% of the P for plant uptake during the growing season and the remainder is derived from the soil P pool. The manure application rate of 30 Mg ha^{-1} to nonirrigated soils would provide 67 kg P ha^{-1} of plant-available P, whereas an application of 60 Mg ha^{-1} to irrigated soils would provide 134 kg P ha^{-1} of plant-available P. Therefore, the manure applications provided nearly three times as much plant-available P that was required for barley production based on recommended inorganic P fertilizer rates (Alberta Agriculture, 1997). If we assumed that all of the manure P would eventually be available for plant uptake, and chose application rates that balanced total P inputs with total P removal in the crop, then manure applications of 30 Mg ha^{-1} and 60 Mg ha^{-1} provided five to six times more P than was recommended for barley production.

However, in semi-arid climates where crop production and nutrient uptake depends on rainfall, P uptake by barley was seldom equivalent to the maximum fertilizer rates of 25 kg P ha^{-1} on nonirrigated and 45 kg P ha^{-1} on irrigated plots from 1974 to 1990. Attempts to devise farm-level nutrient balances will require knowledge of the P content of manure, crop, and soil pools as well as manure application and crop production rates.

CONCLUSIONS

Repeated manure applications at rates based on crop N requirements have led to P accumulation in cropped soils. About 42% of manure P was available for crop uptake prior to application, and up to 15% of the manure P applied during the 16-yr period was removed in barley grain and straw. Total P concentrations increased with soil depth with repeated manure applications and much of the P from manure (50 to 66%) was in plant-available forms. In nonirrigated plots, all of the P applied in manure was accounted for in crop removal and total soil P pools. Manure application rates were greater on irrigated than nonirrigated plots, and substantial P losses were observed after 16 yr of repeated annual manure applications. There is a risk of ground water contamination with P from manure in irrigated plots receiving high (>60 Mg ha^{-1}) annual manure applications. In addition, P could be lost from surface soils through water and wind erosion. If manure applications were made to balance total P inputs with total P removal in the crop, then manure application rates of 30 Mg ha^{-1} and 60 Mg ha^{-1} provided five to six times more P than was recommended for barley production on nonirrigated and irrigated soils.

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