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Nitrogen and phosphorus mineralization potentials of soils receiving repeated annual cattle manure applications

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Abstract Manure application rates are generally calculated to balance nutrient inputs with crop requirements, based on a projected crop yield and estimates of nutrient release from recently applied manure during a growing season. Often, the contribution to plant nutrition of manure applied in the past is not considered explicitly. We obtained archived soil samples collected every 5 years during a 25-year period (1973–1998) from a long-term study in Lethbridge, Alberta, Canada to evaluate the effects of long-term manure applications on soil N and P mineralization potentials (N_{max} and P_{max}, respectively). Soils from experimental plots receiving 0, 30, 60, 90, 120 and 180 Mg manure (wet weight) ha^{-1} year^{-1} were incubated aerobically for 20 weeks under four different combinations of soil temperature (10°C and 20°C) and moisture [50% and 75% of field capacity (FC)] conditions. N_{max} and P_{max} were fit using a first-order rate equation. N_{max} and P_{max} were related linearly to the cumulative amount of N and P applied in manure, suggesting long-term manure applications increased the proportion of potentially mineralizable N and P in soils. Soil storage and handling in the laboratory (e.g., weekly rewetting during incubations) affected the slopes of the regression equations describing N_{max} and P_{max}. The slopes of regression lines relating N_{max} and P_{max} to cumulative manure applications were highest when soils were incubated at 20°C and 75% of FC. Adjusting manure application rates on agricultural land with a history of manure amendments, based on the increase in potentially mineralizable N and P from past manure applications, could help minimize nutrient export and environmental pollution from manure-amended soils.

Keywords Nitrogen · Phosphorus · Mineralization potential · Calcareous soil · Cattle manure

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Introduction

The application of manure to agricultural land has been viewed as an excellent way to recycle nutrients and organic matter that can support crop production and maintain or improve soil quality. However, in areas where many intensive livestock operations exist, disposal of manure is often limited to land in the vicinity of the operations, with the result that manure is often applied at a high frequency and high rates. As a result, the nearest land may be amended with large quantities of manure on a continual basis. Manure applications must be managed carefully to minimize nutrient export from agricultural systems into adjacent ecosystems, including aquatic ecosystems and the atmosphere. The export of N from manure-amended soils through greenhouse gas emissions and transport processes, such as leaching, surface runoff and erosion, have been well documented (Adams et al. 1994; Chang and Janzen 1996; Goss and Goorahoo 1995; Zebarth et al. 1999). Migration of P from manure-amended soils to ground and surface waters has been linked to eutrophication of aquatic systems (Daniel et al. 1994; Sharpley et al. 1994; Heathwaite 1997).

Manure application rates are generally calculated to balance N inputs with crop requirements, based on a projected crop yield and estimates of N release from recently applied manure during a growing season (King 1984). Often, the contribution to plant nutrition of manure applied in the past is not considered explicitly. Yet, in soils with a history of annual manure applications, the pool of nutrients available for crop uptake during a growing season is:

$$\text{Available nutrients} = k_y M_y + k_{y-1} M_{y-1} + k_{y-2} M_{y-2} \dots + k_{y-n} M_{y-n} \quad (1)$$

where k is the availability factor in the growing season for manure applied from a given year, M is the amount of manure nutrient applied, and y is the year of manure application. Numerous studies have investigated N release, and, to a lesser extent, P release from manure in the first weeks to several months after manure application (Castellanos and Pratt 1981; Bitzer and Sims 1988; Mafongoya et al. 2000; Zaman et al. 1998). However, there is limited information on how nutrient mineralization in soils is affected by long-term applications of manure. Soil chemical, physical and biological properties are altered by manure applications (Hafez 1974; Chang et al. 1991; Haynes and Naidu 1998), and it seems possible that long-term manure applications could change nutrient release patterns significantly. Measurement of nutrient mineralization and immobilization over the longer term is required to improve models of nutrient availability and provide management guidelines for manure use on agricultural land.

The objective of this study was to determine the N and P mineralization potentials (N_{max} and P_{max}, respectively) of soil that received different rates of cattle manure annually for up to 25 years. We also assessed the effect of temperature and moisture on N_{max} and P_{max}.

Materials and methods

Site description

Soils used in this study were from research plots located at the Agriculture and Agri-Food Research Centre in Lethbridge, Alberta, Canada. Since 1973, solid cattle manure has been applied annually to non-irrigated and irrigated soils in a split-plot experiment. The soil in the study area is a well-drained calcareous Orthic Dark Brown Chernozemic (Typic Haploboroll) clay loam. Both non-irrigated and irrigated soils were seeded to six-row feed barley (*Hordeum vulgare* L. cvs. Galt, Leduc, Virden, and Duke) from 1974 to 1995 and canola (*Brassica rapa* L. cv. Tobin) in 1996. The non-irrigated soils were seeded to six-row feed barley (*H. vulgare* L. cv. Duke) in 1997 and triticale (*X Triticosecale wittmack* cv. Pronghorn) in 1998. The irrigated soils were seeded to corn (*Zea mays* L. cv. Pioneer Hybrid 3957) in 1997 and 1998. 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. 1991; Chang and Janzen 1996; Whalen and Chang 2001). Some information is provided on initial soil properties (Table 1) and characteristics of the manure applied from 1973 to 1997 (Table 2).

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

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

Experimental design

Cattle manure was applied each year after crop harvest (September to October) beginning in 1973 and incorporated immediately after application by one of three methods: plough, rototiller and cultivator plus disk. Within each tillage treatment (main plot), manure was applied to subplots (7.5×15 m) at the following rates: 0, 30, 60 and 90 Mg ha^{-1} (wet weight) in non-irrigated soils and 0, 60, 120 and 180 Mg ha^{-1} (wet weight) in irrigated soils. Main and subplot treatments were arranged in a split-plot design with three replicates. Recommended annual manure applications in this area were 22–27 Mg (wet weight) ha^{-1} for non-irrigated soils and 56–67 Mg ha^{-1} (wet weight) for irrigated soils at the initiation of the experiment (Alberta Environment and Alberta Agriculture 1973). Soil properties and crop production were not affected significantly by tillage (Sommerfeldt et al. 1988) and since 1986, manure has been incorporated in all subplots with a cultivator, which increased the number of replicate manure treatments to nine. Manure applied in this study came from an open, unpaved commercial cattle feedlot, contained no bedding, and was stored for 1 to 2 years before application (Table 2). 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).

N and P mineralization study

Soil samples were collected annually after crop harvest prior to manure application by extracting two cores from each plot. Soil cores were subdivided by depth into six segments (0 to 15 cm, 15 to 30 cm, 30 to 60 cm, 60 to 90 cm, 90 to 120 cm, and 120 to150 cm), composited, oven-dried (60°C), and ground (<2 mm mesh). Soil samples from the top increment (0–15 cm depth) have been archived every 5 years since 1973. Samples used in this study were collected in 1978, 1983, 1988, 1993 and 1998, and have been stored in tightly sealed glass jars in the dark since they were archived.

Table 2 Characteristics of manure applied in the field study between 1973 and 1997. Nutrient analyses are expressed on a per kilogram of manure (dry weight) basis. At least five manure subsamples were analysed each year to generate a mean value (±SE) for manure characteristics

Parameters	Mean value	Method used
Moisture content (kg kg^{-1})	32.8±2.2	Oven-dried, 105°C for 48 h
pH	7.1±0.1	1:2 Manure:water slurry
Electrical conductivity (dS m^{-1})	23.4±1.6	1:2 Manure:water slurry
Na adsorption ratio	20.6±1.2	Saturated paste extracts, analysed by AAS
Organic C (g kg^{-1})	267±17	Carlo-Erba C and N analyzer (Milan)
Total N (g kg^{-1})	15.9±0.9	Carlo-Erba C and N analyzer (Milan)
Total P (g kg^{-1})	6.1±0.3	H_2O_2/H_2SO_4 digest, molybdate-ascorbic acid method
Available NH_4-N (g kg^{-1})	1.3±0.2	2 M KCl extract, phenate method
Available NO_3-N (g kg^{-1})	0.21±0.05	2 M KCl extract, Cd reduction-diatotization method
Available P (g kg^{-1})	2.3±0.2	$NaHCO_3$-soluble P, molybdate-ascorbic acid method
Available S (g kg^{-1})	0.53±0.09	Saturated paste extract, methylthymol blue

A composite sample of surface (0–15 cm) soils was made by combining archived soil from each manure and irrigation treatment each year (4 manure rates×2 irrigation levels×5 years=40 soil samples). The water retention capacity at –20 kPa [field capacity (FC) for this soil, Oosterveld and Chang 1980] was determined on a few samples from each manure and irrigation treatment using the moisture retention plate method (Topp et al. 1993). Duplicates of each composite soil sample were weighed into 120-ml specimen cups, packed to approximately 1 g cm^{-3} (field bulk density for this soil, Oosterveld and Chang 1980), and moistened to 50% or 75% of FC. Soils were then placed in sealed 950-ml jars and incubated aerobically in the dark at 10°C or 20°C for up to 20 weeks. Soils were aerated weekly by removing lids from jars for between 10 and 15 min to re-establish ambient conditions.

Soils were extracted 0, 2, 4, 8, 12, 16 and 20 weeks after the incubation started to assess N and P mineralization. The total number of extractions was 2,000 [40 composite samples×2 replicates=80 extractions at week 0+(40 composite soils×2 replicates×2 moisture levels×2 temperatures×6 extractions)]. We did not have enough jars to incubate 80 soil samples separately under all moisture and temperature conditions for each extraction date. Instead, we weighed 100 g of each composite soil sample into 16 replicate cups, and removed subsamples of soil at 3 extraction times. Therefore, four replicates were prepared for each set of soil temperature and moisture conditions, two cups containing soil analysed after 2, 4 and 8 weeks and the other two containing soil analysed after 12, 16 and 20 weeks.

The N_{max} and P_{max} of soils collected in 1978, 1983 and 1988 were determined in a study that ran from October 1991 to March 1992. Soils collected in 1993 and 1998 were incubated from April–September 1999 to assess N_{max} and P_{max}. The conditions during the laboratory incubations were virtually identical except that soils incubated during the 1991–1992 study were rewetted to 50% FC or 75% FC every week, whereas soils incubated during the 1999 study were not. In the 1999 study, 10 ml water was placed in the bottom of each jar to maintain soil humidity.

Mineral N (NH_4-N and NO_3-N) was determined in 0.01 M $CaCl_2$ extracts (1:8 soil:extractant) and measured colorimetrically using the phenate and cadmium reduction-diatotization methods with a Technicon II autoanalyzer (Technicon Industrial Systems, Tarrytown, N.Y.). Available P was determined in the same 0.01 M $CaCl_2$ extracts (1:8 soil:extractant), and ortho-phosphate was measured colorimetrically by the ammonium molybdate-ascorbic acid method using a Technicon IV autoanalyzer (Technicon Industrial Systems).

Calculations

The N_{max} (mg N kg^{-1}) of unamended and manure-amended soils was calculated from the first-order equation

$$N_{\mathrm{i}} = N_{\max} + k_{\mathrm{N}} e^{-t} \qquad (2)$$

where N_i is the mineral N concentration (mg N kg^{-1}), k_N is the rate constant ($week^{-1}$) and t is the incubation time (week). The P_{max} (mg P kg^{-1}) was calculated by substituting inorganic P for mineral N data in Eq. 2.

Statistical analysis

The main effects on N and P dynamics were evaluated by ANOVA using a general linear model (GLM) using SAS software (SAS Institute 1990). The concentration of N and P in soil extracts was affected significantly ($P<0.001$) by manure treatments, irrigation, the year that soil was collected, the length of incubation, and the temperature and moisture content of incubated soils. However, there was no significant effect ($P>0.05$) of irrigation on the N and P concentrations in soils with a similar history of manure applications when incubated under the same temperature and moisture conditions in the laboratory, so we combined data from the non-irrigated and irrigated blocks in the analysis. N_{max} and P_{max} and associated rate constants were calculated from a nonlinear least square regression analysis using the PROC NLIN function of SAS (SAS Institute 1990). Linear regressions were fit using the SAS/INSIGHT function of SAS software (version 6.12).

Results

N and P dynamics after 5, 10 and 15 annual manure applications (incubation 1)

Mineral N (NH_4-N+NO_3-N) concentrations in soils collected after five annual manure applications and incubated at 20°C tended to increase during the first 4 weeks of incubation, decline between week 4 and week 8, and then increase after week 8 of the incubation (Fig. 1a, b). The highest mineral N concentrations were measured at weeks 16 and 20 in soils incubated at 50% FC, and there was no difference [$P>0.05$, least significant difference (LSD)] in the mineral N concentrations in extracts from week 16 and week 20 (Fig. 1a). In soils incubated at 75% FC, mineral N concentrations were

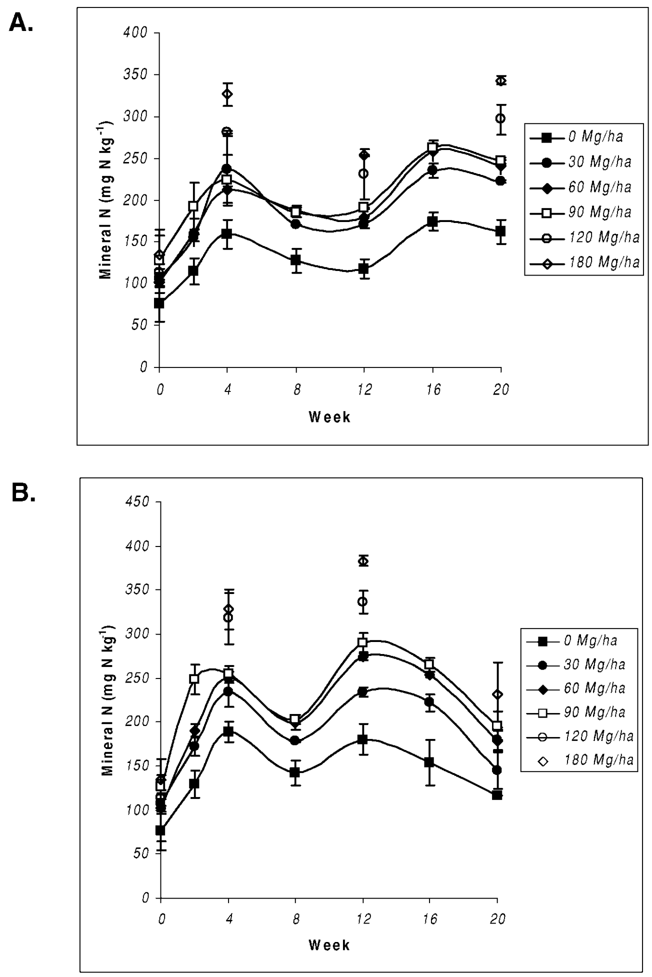

Fig. 1 N dynamics of soils collected after five annual manure applications and incubated for 20 weeks at 20°C and **a** 50% of field capacity (FC) or **b** 75% of FC. Values are means and *vertical bars* indicate SEs

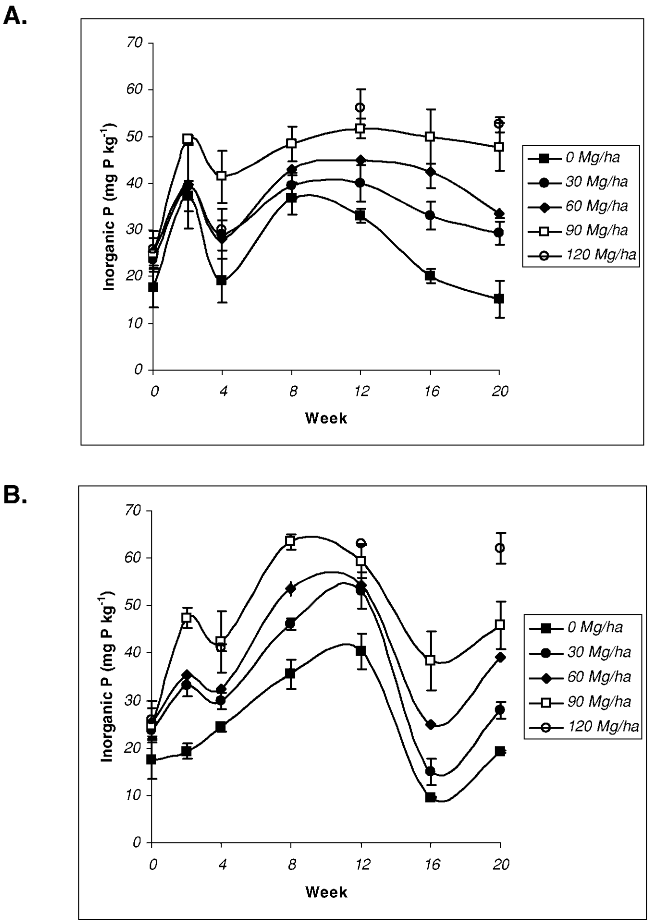

Fig. 2 P dynamics of soils collected after five annual manure applications and incubated for 20 weeks at 20°C and **a** 50% of FC or **b** 75% of FC. Values are means and *vertical bars* indicate SEs

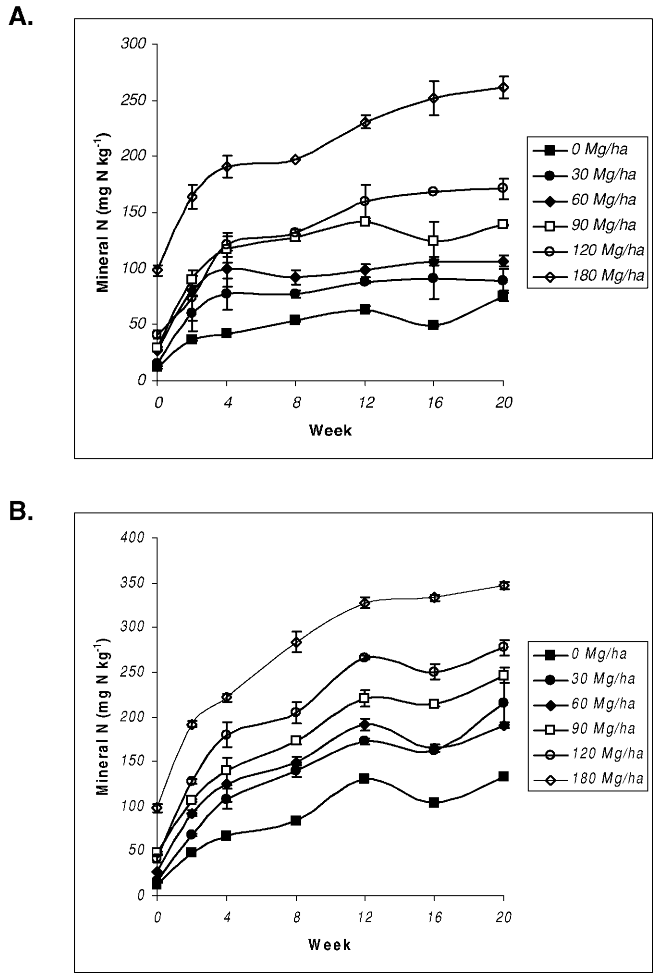

Fig. 3 N dynamics of soils collected after 20 annual manure applications and incubated for 20 weeks at 20°C and **a** 50% of FC or **b** 75% of FC. Values are means and *vertical bars* indicate SEs

highest at week 12, and there was a significant (P<0.05, LSD) decline in mineral N concentrations between week 12 and week 20. The trend observed in Fig. 1 was also found in soils collected after five annual manure applications that were incubated at 10°C, and in soils collected after ten and 15 annual manure applications (data not shown).

The inorganic P concentration of soils collected after 5 annual manure applications and incubated at 20°C increased between week 0 and week 12, and declined significantly (P<0.05, LSD) between week 12 and week 16 when the moisture content was 50% FC and 75% FC (Fig. 2a, b). Similar results were observed for samples incubated at 10°C, and for soils collected after 10 and 15 annual manure applications (data not shown).

N and P dynamics after 20 and 25 annual manure applications (incubation 2)

Mineral N (NH_4-N+NO_3-N) concentrations in soils collected after 20 annual manure applications and incubated at 20°C were highest after 20 weeks of incubation when maintained at 50% or 75% FC (Fig. 3a, b). The inorganic P concentration in soils collected after 20 annual manure applications and incubated at 20°C increased between week 0 and week 12, and declined between week 12 and week 16 in samples maintained at 50% and 75% FC (Fig. 4a, b). The mineral N and inorganic P dynamics were similar in soils collected after 25 annual manure applications (data not shown).

N_{max} and P_{max} from incubations 1 and 2

N_{max} and P_{max} were related linearly to the cumulative manure N and P (manure$_{TN}$ and manure$_{TP}$, respectively) applied to soils (Fig. 5a, b). Regression equations relating N_{max} and manure$_{TN}$ after 5, 10 and 15 annual manure applications (incubation 1) had R^2 values ranging from 0.25 to 0.97 (Table 3). The slopes of the regression lines tended to be higher for soils collected after 5 than 10 or 15 annual manure applications (Table 3). Incubation temperature and moisture also affected the slopes of the

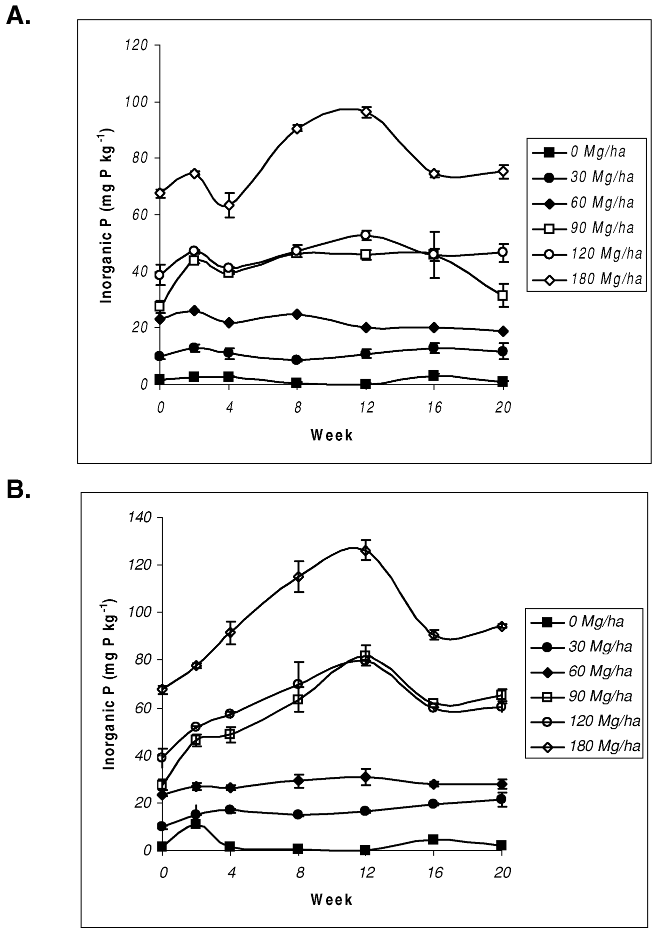

Fig. 4 P dynamics of soils collected after 20 annual manure applications and incubated for 20 weeks at 20°C and **a** 50% of FC or **b** 75% of FC. Values are means and *vertical bars* indicate SEs

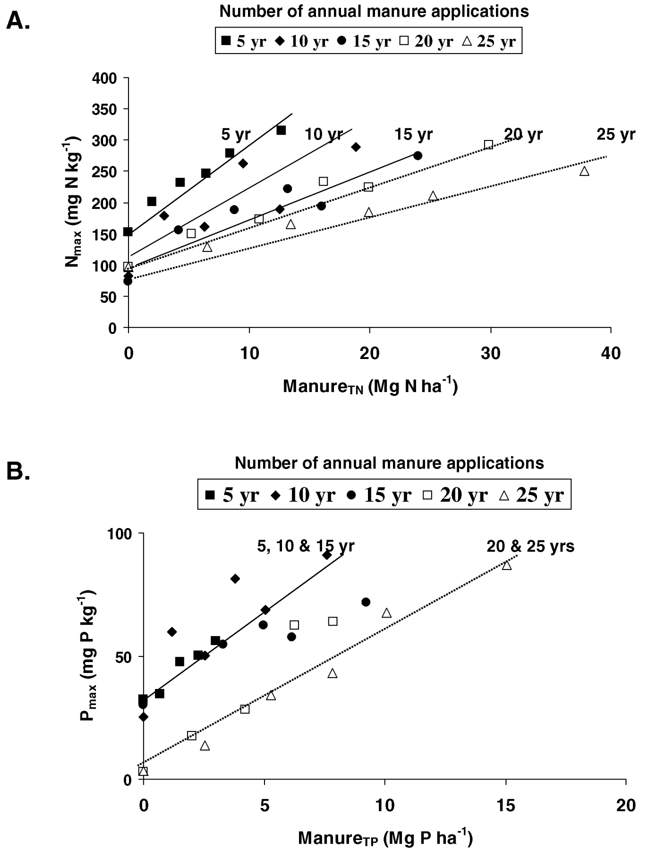

Fig. 5 Relationship between **a** the N mineralization potential and cumulative total N added in manure (*$Manure_{TN}$*) after up to 25 annual manure applications, and **b** the P mineralization potential and cumulative total P added in manure (*$Manure_{TP}$*) after up to 25 annual manure applications. Mineralization potentials were calculated using a nonlinear least squares method for soils incubated at 20°C and 75% of FC. *yr* Year

Table 3 Effect of incubation temperature and moisture on linear relationships between N mineralization potential (N_{max}) and cumulative total N added in cattle feedlot manure ($manure_{TN}$) and P mineralization potential (P_{max}) and cumulative total P added in cattle feedlot manure ($manure_{TP}$) after 5, 10 and 15 annual manure applications (incubation 1). *FC* Field capacity

Number of annual manure applications	Regression equation	R^2	Regression equation	R^2
10°C and 50% FC				
5	N_{max}=160.88+7.681 $manure_{TN}$	0.78	P_{max}=30.19+6.977 $manure_{TP}$	0.99
10	N_{max}=138.33+4.397 $manure_{TN}$	0.25	P_{max}=38.67+5.737 $manure_{TP}$	0.72
15	N_{max}=111.56+4.326 $manure_{TN}$	0.48	P_{max}=36.88+3.041 $manure_{TP}$	0.80
10°C and 75% FC				
5	N_{max}=169.02+9.987 $manure_{TN}$	0.82	P_{max}=36.02+5.706 $manure_{TP}$	0.94
10	N_{max}=115.96+6.552 $manure_{TN}$	0.44	P_{max}=41.51+5.528 $manure_{TP}$	0.68
15	N_{max}=112.86+4.720 $manure_{TN}$	0.57	P_{max}=38.81+2.376 $manure_{TP}$	0.65
20°C and 50% FC				
5	N_{max}=160.49+11.866 $manure_{TN}$	0.94	P_{max}=33.03+6.249 $manure_{TP}$	0.97
10	N_{max}=113.30+7.676 $manure_{TN}$	0.62	P_{max}=39.35+6.126 $manure_{TP}$	0.67
15	N_{max}=112.46+4.898 $manure_{TN}$	0.66	P_{max}=35.92+3.559 $manure_{TP}$	0.85
20°C and 75% FC				
5	N_{max}=168.18+12.257 $manure_{TN}$	0.97	P_{max}=31.63+8.323 $manure_{TP}$	0.95
10	N_{max}=116.80+9.172 $manure_{TN}$	0.71	P_{max}=37.59+7.470 $manure_{TP}$	0.76
15	N_{max}=112.95+5.839 $manure_{TN}$	0.76	P_{max}=35.24+4.236 $manure_{TP}$	0.88

Table 4 Effect of incubation temperature and moisture on linear relationships between N_{max} and $manure_{TN}$ and P_{max} and $manure_{TP}$ after 20 and 25 annual manure applications (incubation 2). For abbreviations, see Table 3

Number of annual manure applications	Regression equation	R^2	Regression equation	R^2
10°C and 50% FC				
20	N_{max}=39.98+3.753 $manure_{TN}$	0.93	P_{max}=-0.613+5.986 $manure_{TP}$	0.99
25	N_{max}=40.50+2.119 $manure_{TN}$	0.92	P_{max}=-0.190+5.080 $manure_{TP}$	0.97
10°C and 75% FC				
20	N_{max}=56.06+4.307 $manure_{TN}$	0.99	P_{max}=1.423+7.540 $manure_{TP}$	0.99
25	N_{max}=54.51+2.727 $manure_{TN}$	0.97	P_{max}=1.184+6.287 $manure_{TP}$	0.97
20°C and 50% FC				
20	N_{max}=53.19+5.133 $manure_{TN}$	0.96	P_{max}=–1.815+6.665 $manure_{TP}$	0.99
25	N_{max}=52.31+2.898 $manure_{TN}$	0.92	P_{max}=–1.814+5.772 $manure_{TP}$	0.96
20°C and 75% FC				
20	N_{max}=108.13+6.315 $manure_{TN}$	0.97	P_{max}=0.737+8.443 $manure_{TP}$	0.98
25	N_{max}=102.86+4.085 $manure_{TN}$	0.99	P_{max}=1.860+5.822 $manure_{TP}$	0.98

regression lines, and the slope of the regression lines tended to be higher as soil temperature and moisture content increased (Table 3). Regression equations relating P_{max} and $manure_{TP}$ after 5, 10 and 15 annual manure applications (incubation 1) had R^2 values ranging from 0.65 to 0.99, and the slopes of the regression lines tended to be higher for soils collected after 5 than 10 or 15 annual manure applications (Table 3).

The slopes of the lines relating N_{max} to $manure_{TN}$ and P_{max} to $manure_{TP}$ (incubation 2) were higher for soils collected after 20 than 25 annual manure applications (Table 4). Although the slope of the lines for N_{max} and $manure_{TN}$ tended to be higher for warmer, moister soils than cooler, drier soils, similar trends were not observed for the slope of the lines relating P_{max} to $manure_{TP}$ (Table 4).

Discussion

The differences in incubation 1 and 2, described in the Materials and methods, affected N dynamics. There was a significant decline in mineral N concentrations of soils moistened to 75% FC after week 12 in incubation 1, but not in incubation 2. It seems likely that part of the mineral N was lost from rewetted soils in incubation 1 through gaseous emissions (e.g., denitrification, volatilization). Periodic rewetting stimulated N and P mineralization, and N_{max} and P_{max} were higher in soils from incubation 1 than incubation 2. Therefore, it was not possible to compare N_{max} and P_{max} from the two studies.

Storage also affected N_{max} and P_{max}, and soils that had been stored longer before analysis tended to have higher N_{max} and P_{max} values than soils that were not stored as long. For instance, soils collected after five annual manure applications (1978) were stored for 13 years, whereas soils collected after 15 annual manure applications (1988) were stored for only 3 years before soil samples were incubated in 1991. The higher N_{max} and P_{max} values of stored soils suggests that organic N and organic P compounds in soil became readily mineralizable after longer storage. This result was surprising because we assumed that constant storage conditions (oven-dried, ground soil samples were stored in sealed glass jars in the dark) would limit soil microbial and enzymatic activity. However, soil N_{max} and P_{max} were sufficiently different due to storage that we could not combine data from soils collected in different years. The study would have been improved had we measured N_{max} and P_{max} at the time soils were collected rather than on archived soil samples. Other steps we would take in the future to improve measurement of N_{max} and P_{max} would be to use discrete replicate soil samples rather than composite soil samples from manure-amended plots. We would also prepare more replicate samples for incubation at each soil temperature and moisture to allow destructive soil sampling at each sampling date, and ensure that all samples were incubated under identical conditions.

Soil temperature and moisture effects on N_{max} and P_{max}

The N dynamics differed in incubation 1 and 2 because of periodic rewetting of soils in incubation 1 that likely led to N losses through gaseous emissions. Since we could not accurately quantify the mineral N pool in soils from incubation 1, the N_{max} values of soils collected after 5, 10 and 15 annual manure applications are probably underestimated. The slopes of regression lines relating N_{max} to $manure_{TN}$ were highest when soils were incubated at 20°C and 75% of FC, regardless of the year that soils were collected. The Q_{10} values of soils incubated at 50% of FC ranged from 1.13 to 1.75, whereas soils incubated at 75% of FC had Q_{10} values between 1.23 and 1.50. These results are consistent with those of other studies that report higher microbial activity and greater N_{max} in hotter, wetter soils than cooler, drier soils (Sierra and Marban 2000; Clough et al. 1998).

The P dynamics of soils were similar in incubations 1 and 2, and the highest inorganic P concentrations in soil extracts were measured at week 12 of the incubation. It is believed that P mineralization proceeds generally through biochemical, rather than biological, pathways through the action of extracellular phosphatases (McGill and Cole 1981). This hypothesis suggests that P mineralization dynamics should be different from organic matter decomposition and N mineralization patterns because as inorganic P accumulates in soil solution, extracellular enzyme production slows and P mineralization is suppressed (McGill and Cole 1981; Tarafdar and Claassen 1988). Our data would support this hypothesis if the decline in inorganic P concentrations after week 12 of the incubation could be attributed to P incorporation in microbial biomass and a decline in soil phosphatase activity. Since we did not measure these parameters, we suggest future experimentation to investigate this possibility.

The slopes of regression lines relating P_{max} to $manure_{TP}$ were highest when soils were incubated at 20°C and 75% of FC, regardless of the year that soils were collected. The Q_{10} values of soils incubated at 50% of FC ranged from 0.90 to 1.17, whereas soils incubated at 75% of FC had Q_{10} values between 0.93 and 1.78. There is limited information on the effect of soil temperature and moisture on P_{max}. Although extracellular phosphatases have an important role in P mineralization, inorganic P may have been removed from soil solution through sorption on soil surfaces and precipitation with secondary minerals (e.g., Fe, Al and Ca) as well as immobilization in microbial biomass. Our results, which should be investigated further, suggest P_{max} increased with increasing soil temperature in some soils incubated at 75% of FC, but was not affected by soil temperature at 50% of FC.

Effect of manure applications on N_{max} and P_{max}

N_{max} and P_{max} increased linearly with increasing $manure_{TN}$ and $manure_{TP}$. These results indicate that long-term manure applications can increase the proportion of potentially mineralizable N and P in soils. These results differ from those found in short-term studies of N mineralization from manure-amended soils under laboratory conditions where N immobilization can be greater in soils that receive higher, rather than lower, rates of manure (Zaman et al. 1998). The N release from manure in short-term laboratory studies is affected by manure characteristics, such as the C/N ratio of the manure, lignin and carbohydrate content, as well as the manure application rate, characteristics of the soil mixed with manure, and incubation conditions (Bitzer and Sims 1988; Zaman et al. 1998; Mafongoya et al. 2000). The increase in N_{max} and P_{max} with increasing manure applications may be related to greater plant growth, soil microbial and enzymatic activity (Oberson et al. 1996). Higher N_{max} and P_{max} values in manure-amended than unamended soils may also be related to changes in soil organic matter quality, and our results suggest more organic N and organic P compounds that are susceptible to decomposition exist in manure-amended soils.

The greater potential mineralization of N and P as manure applications increase was detected at the field scale by comparing extractable nutrient concentrations in manure-amended and unamended soils. Chang et al. (1991) reported that accumulation of NO_3-N and available PO_4 in the soil profile (to 150 cm depth) increased with cumulative manure applications in soils that received annual applications for 11 years. While virtually all of the N and P in manure applied to dryland plots for 20 to 25 years was recovered in soil and crops, measurable quantities of N and P were lost from irrigated plots through denitrification and leaching (Chang and Entz 1996; Chang et al. 1998; Whalen and Chang 2001).

Clearly, it is critical that producers who have applied manure to agricultural land for many years adjust spreading rates each year to account for the nutrients that will be released from partially decomposed manure applied in the past. Since producers may not routinely test all their fields prior to spreading manure, it may be necessary to implement regional guidelines that limit manure applications to soils that have received manure for many years to protect air and water resources. Controlled laboratory incubations suggest that the potential for nutrient release from partially decomposed manure increases with continued manure application. Nutrient mineralization potentials of new and partially decomposed manure from different sources is expected to differ following land application due to variation in the chemical characteristics of the manure, soil properties and soil biota, agricultural and cropping practices, and environmental conditions. Further studies at the field scale will be required to quantify the impact of these findings on nutrient cycling in manure-amended soils and to develop new guidelines for the efficient management of manure and other organic wastes.

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