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Cattle Manure Amendments Can Increase the pH of Acid Soils

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ABSTRACT

Crop production on acid soils can be improved greatly by adjusting the pH to near neutrality. While soil acidity is commonly corrected by liming, there is evidence that animal manure amendments can increase the pH of acid soils. The effect of fresh cattle manure on soil acidity and nutrient availability was determined in the laboratory for two acid soils from Beaverlodge and Fort Vermillion in the Peace River region of Alberta, Canada. The effect of manure on soil pH was immediate and persisted during an 8-wk incubation. Manure-amended soil had significantly higher pH than unamended soil, and the highest rate (40 g manure kg^{-1}, dry weight basis) increased the pH of Beaverlodge and Fort Vermillion soils from 4.8 to 6.0 and 5.5 to 6.3, respectively. The higher pH in manure-amended than unamended soils was attributed to buffering from bicarbonates and organic acids in cattle manure. Mineral N (NH$_4$–N + NO$_3$–N), available P, K, Ca, and Mg increased immediately after manure application, and available P and K remained significantly higher in manure-amended than unamended soil after the 8-wk incubation. Soils amended with 40 g manure kg^{-1} had three to four times more plant-available P and K than unamended soils after incubation. Available S concentrations did not differ significantly in manure-amended and unamended soils. Extractable Al and Fe declined slightly after manure application, but did not differ in manure-amended or unamended soils after incubation. No change in the cation-exchange capacity (CEC) of manure-amended soils compared to unamended soils was observed in this study, and it appears that appreciable changes in Al, Fe, and CEC from manure application do not occur in the short-term (weeks). Our results indicate that, in the short-term, cattle manure amendments can increase the pH and the quantity of plant-available P and K in acid soils.

IT IS WELL ESTABLISHED that crop production on acid soils can be improved greatly when soil pH is adjusted to near neutrality. Soil pH affects nutrient solubility, and influences the sorption or precipitation of nutrients with Al and Fe (Hue, 1992). Increasing the pH of acidic soils improves plant-availability of macronutrients while reducing the solubility of elements such as Al and Mn (O'Hallorans et al., 1997; Hue and Licudine, 1999). Soil acidity problems in North America are commonly corrected by applying limestone or gypsum. However, there is evidence that organic residues from green and animal manures can increase the pH of acid soils and improve soil fertility by supplying nutrients for crop production (Hue, 1992; Warren and Fonteno, 1993; Iyamuremye et al., 1996; O'Hallorans et al., 1997; Wong et al., 1998). The effect of animal manure on soil pH may persist over several years. Bickelhaupt (1989) found that the application of composted lime-treated horse manure to a slightly acidic soil (pH 5.7) increased soil pH to between 6.7 and 7.3, and the effect was undiminished 12 yr after manure application.

Intensive confined beef cattle production has been increasing in Alberta for 20 years and feedlots containing more than 50 000 animals are now common (Chang and Janzen, 1996). Since production efficiency is improved with concentrated animal production, the trend towards intensive production units is likely to continue. The potential for contamination of ground and surface waters through improper handling and disposal of animal manure from cattle feedlots is considerable because most feedlots have a relatively small land base and transportation costs are high (Chang et al., 1998). If cattle manure can be substituted economically for lime to increase the pH of acid soils, farm managers

may consider transporting manure from feedlots for land application.

The objectives of this study were to determine (i) whether cattle manure could increase the pH of acid soils; (ii) the effect of manure on extractable soil nutrients, including N, P, K, S, Ca, Mg, Al and Fe; and (iii) the effect of manure on the CEC and buffering capacity (carbonate and bicarbonate concentrations) of acid soils.

MATERIALS AND METHODS

Soils used in this experiment were collected from the top 15 cm of two agricultural sites in the Peace River region of northern Alberta, Canada, after wheat harvest in the fall of 1998. The soils were a Hazelmere silt loam from Beaverlodge, Alberta, and a Davis silt loam from Fort Vermillion, Alberta. The Beaverlodge soil is a Gray Luvisol (fine-loamy, mixed, frigid Typic Hapludalf) containing 220 g sand kg^{-1}, 580 g silt kg^{-1} and 200 g clay kg^{-1} with 28 g organic C kg^{-1} and pH 4.8. The Fort Vermillion soil is an Orthic Gray Luvisol (fine-loamy, mixed, frigid Typic Hapludalf) containing 250 g sand kg^{-1}, 630 g silt kg^{-1} and 120 g clay kg^{-1} with 34 g organic C kg^{-1} and pH 5.6. Additional information on these soils has been reported by Franzluebbers and Arshad (1997) and Soon (1994).

Experimental Design

One-hundred grams (oven-dried basis) of air-dried sieved (<2 mm) soil were mixed with fresh cattle manure at the rate of 0, 10, 20, 30, and 40 g (oven-dry basis) manure kg^{-1}. Some physical and chemical properties of the cattle manure used in the study are outlined in Table 1. Soil–manure mixtures were placed in cups without drains to prevent nutrient leaching, moistened to between 70 and 75% of soil field capacity, covered, and incubated at 25°C ($\pm$ 1°C) in a controlled climate room. The effects of cattle manure on soil acidity and fertility were determined by destructively sampling four replicate soil–manure mixtures of each soil type at 0, 2, 4, and 8 weeks after the beginning of the experiment.

Soil Analysis

Soil pH was determined on 1:2 soil/0.01 M CaCl$_2$ slurries after a 30-min equilibration. The lime requirement of soils used in this study was determined using the p-nitrophenol-H$_3$BO$_3$–KCl buffer (pH 8.0) method. The amount of CaCO$_3$ required to raise soil pH to 6.5 was 4.5 Mg ha^{-1} for the Beaverlodge soil and 2.3 Mg ha^{-1} for the Fort Vermillion soil. Mineral N (NH$_4$–N and NO$_3$–N) was determined in 2 M KCl extracts (1:5 soil/extractant) and measured colorimetrically using the phenate and cadmium reduction–diatotization methods with a Technicon II flow-injection autoanalyzer (Technicon Industrial Systems, Tarrytown, NY). Available P, K, S, Ca, and Mg were determined in Kelowna (0.015 M NH$_4$F + 0.25 M CH$_3$COOH) soil extracts (1:10 soil/extractant). Orthophosphate and sulfate were measured colorimetrically by the ammonium molybdate–ascorbic acid method and the methylthymol blue method, respectively, using a Technicon IV flow-injection autoanalyzer (Technicon Industrial Systems, Tarrytown, NY). Available K, Ca, and Mg in Kelowna extracts were analyzed by AAS. Ammonium oxalate–extractable Al and Fe were determined using the method of McKeague and Day (1966) and analyzed by AAS. The CEC was measured using BaCl$_2$ as an index ion (Hendershot and Duquette, 1986). Since there was insufficient soil in each replicate sample for analysis, soil samples were composited by treatment and sampling time and carbonate and bicarbonate concentrations were

Table 1. Properties of cattle manure used in this study.†

Moisture content (kg kg^{-1})	45
pH (1:2 manure/water)	6.8
Electrical conductivity (dS m^{-1})	29.2
Total C (g kg^{-1})‡	249.3
Total N (g kg^{-1})‡	22.8
Total P (g kg^{-1})§	7.0
Available N (NH$_4$–N + NO$_3$–N) (g kg^{-1})¶,‡‡	2.9
Available P (g kg^{-1})#,‡‡	5.2
Available K (g kg^{-1})††,§§	21.5
Available S (mg kg^{-1})††,§§	4.9
Available Ca (cmol$_c$ kg^{-1})††,§§	1.4
Available Mg (cmol$_c$ kg^{-1})††,§§	5.8
Bicarbonate (g kg^{-1})††	2.9
Carbonate (g kg^{-1})††	0

† Values are the means of at least 15 determinations. Nutrient analyses are expressed on a per kg of manure (dry weight) basis.
‡ Analyzed using Carlo-Erba C and N analyzer (Milano, Italy).
§ H$_2$O$_2$/H$_2$SO$_4$ digests.
¶ 2 M KCl extracts (1:5 manure/extractant).
# Kelowna (NH$_4$F + CH$_3$COOH) extracts (1:10 manure extractant).
†† Saturated paste extracts.
‡‡ Analyzed by autoanalyzer (Technicon Industrial Systems, Tarrytown, NY).
§§ Analyzed by AAS (Perkin-Elmer Corp., Norwalk, CT).

determined on saturated paste extracts by potentiometric titration to pH 8.0 (CO$_3$) and pH 4.0 (HCO$_3$) (Eaton et al., 1995).

Statistics

Data were log transformed to equalize variance and evaluated statistically by two-factor ANOVA in a general linear model (GLM) using SAS software (SAS Institute Inc., 1990). The effects of manure rate, incubation time, and the interaction between these variables on soil pH and fertility parameters were evaluated. Variables that significantly affected soil
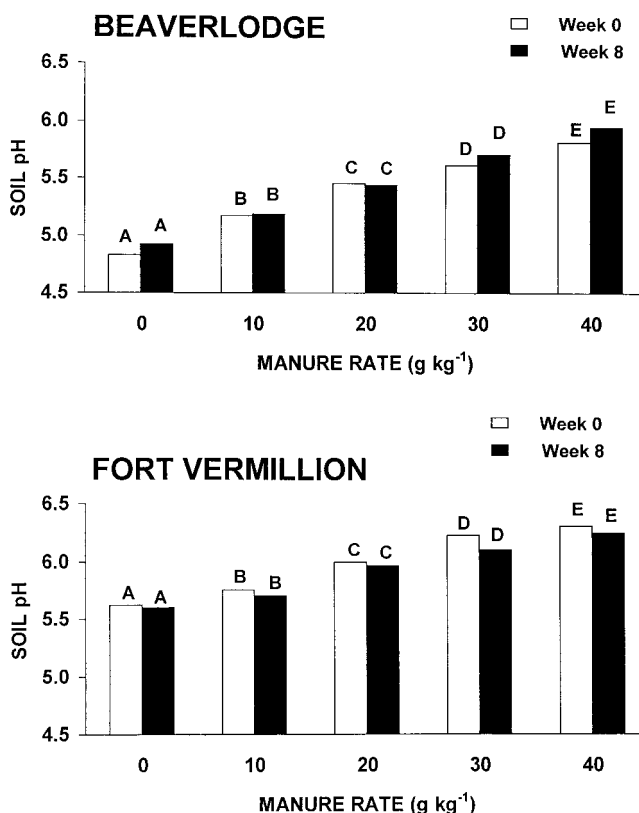

Fig. 1. Changes in soil pH immediately (Week 0) and 8-wk after application of cattle manure to Beaverlodge and Fort Vermillion soils. Bars followed by the same letter are not statistically significantly different ($P < 0.05$, Tukey-Kramer test).

pH and fertility parameters were analyzed statistically using a Tukey-Kramer test at the 95% confidence level.

RESULTS

The application of cattle manure to acid soils had an immediate effect on soil pH. The pH of manure-amended soils was significantly higher ($P < 0.05$, Tukey-Kramer test) than unamended soils, and the effect persisted during the 8-week incubation (Fig. 1a and 1b). The application of 40 g manure kg^{-1} provided the highest buffering capacity of the manure rates examined and increased the pH of Beaverlodge and Fort Vermillion soils from 4.8 to 6.0 and 5.5 to 6.3, respectively (Fig. 1a, 1b).

Immediately after manure application, mineral N (NH_4–N + NO_3–N) concentrations were greater in amended than unamended soils, and NH_4–N concentrations in soils receiving 20, 30, or 40 g manure kg^{-1} were significantly higher ($P < 0.05$, Tukey-Kramer test) than unamended soils from the Beaverlodge and Fort Vermillion sites (Tables 2 and 3). The nitrate and ammonium concentrations in manure-amended soils from the Beaverlodge site declined after the 8-wk incubation, likely due to immobilization and/or denitrification (Table 2). However, in soils from the Fort Vermillion site, there was a net increase in NO_3–N after incubation (Table 3). There was no effect of manure application on mineral N concentrations after the 8-wk incubation for either soil (Tables 2 and 3).

Available P, K, Ca, and Mg were higher in manure-amended soils than unamended soil from the Beaverlodge and Fort Vermillion sites immediately after manure application (Tables 2 and 3). Available S concentrations did not differ in manure-amended and unamended soils from either site (Tables 2 and 3). Available P, Ca, and Mg concentrations were significantly higher ($P < 0.05$, Tukey-Kramer test) in soils receiving 20, 30, or 40 g manure kg^{-1} while available K levels were significantly higher ($P < 0.05$, Tukey-Kramer test) in soils amended with 30 or 40 g manure kg^{-1} than unamended soils at both sites (Tables 2 and 3). After incubation, available P levels remained significantly higher ($P < 0.05$, Tukey-Kramer test) in soils amended

with 20, 30, or 40 g manure kg^{-1} and available K levels were significantly higher ($P < 0.05$, Tukey-Kramer test) in soils amended with 30 or 40 g manure kg^{-1} than unamended soils (Tables 2 and 3). Available S concentrations in manure-amended and unamended soils did not differ after incubation (Tables 2 and 3). In Beaverlodge soils, available Ca and Mg concentrations after incubation were significantly higher ($P < 0.05$, Tukey-Kramer test) in soil amended with 40 g manure kg^{-1} than unamended soils (Table 2B), while unamended soil from the Fort Vermillion site had among the highest levels of available Ca and Mg after incubation (Table 3B).

Immediately after manure application, oxalate-extractable Al concentrations were significantly lower ($P < 0.05$, Tukey-Kramer test) in soils receiving 30 and 40 g manure kg^{-1} than unamended soils, and oxalate-extractable Fe concentrations were significantly lower ($P < 0.05$, Tukey-Kramer test) in soil amended with 30 g manure kg^{-1} than unamended soils from the Beaverlodge site (Table 2A). There was no difference in oxalate-extractable Al and Fe levels of manure-amended and unamended soils at either site before or after incubation (Tables 2 and 3). The CEC of Beaverlodge and Fort Vermillion soils ranged from 36.8 to 40.8 and 57.4 to 59.1, respectively, during the study but were not affected significantly by manure amendments (Tables 2 and 3). Carbonates were not detected in fresh manure (Table 1) or soil from either site. Due to insufficient sample size, carbonate and bicarbonate concentrations were measured on soil samples composited by manure treatment for each site. Since there were large differences in the HCO_3 concentrations of manure-amended samples, there is strong evidence for the following results, even though we were unable to perform statistical tests. The HCO_3 concentration was higher in manure-amended than unamended soils from both sites immediately after manure application, however the difference in HCO_3 levels between manure-amended and unamended soils decreased after the 8-wk incubation (Tables 2 and 3). The HCO_3 concentration in soil from the Beaverlodge site amended with 40 g manure kg^{-1} was 70 and 47% higher than unamended soil after manure application and after 8-wk incubation, respectively

Table 2. Effect of cattle manure on extractable nutrients and cation-exchange capacity (CEC) of Beaverlodge soil immediately after application and after an 8-wk incubation.†

Manure rate	NH_4–N	NO_3–N	P	K	S	Ca	Mg	Al	Fe	CEC	HCO_3‡
g kg^{-1}			mg kg^{-1}					cmol$_c$ kg^{-1}			mg kg^{-1}
					Immediately after application						
0	12.7b	277.2a	51.8c	19.5c	6.5a	2.5d	1.1d	4.5a	13.1a	38.2a	104
10	15.5b	356.8a	93.6c	45.9bc	6.5a	3.2c	1.4c	4.5a	12.5ab	38.7a	172
20	20.5a	592.3a	153.6b	59.9bc	8.0a	3.9b	1.8b	4.3ab	12.0ab	38.0a	212
30	25.6a	490.6a	205.7a	75.6ab	7.2a	4.0b	1.6b	4.1b	11.3b	40.0a	271
40	24.2a	308.4a	236.1a	96.7a	7.3a	4.8a	2.1a	4.1b	12.0ab	40.8a	361
					After an 8-wk incubation						
0	1.7a	276.8a	65.3d	29.4c	9.4a	3.6b	1.5b	4.6a	15.4a	37.5a	202
10	1.8a	216.9a	101.3c	44.6bc	10.1a	4.5ab	1.8b	4.4a	14.0a	37.7a	258
20	1.0a	204.1a	162.8ab	65.4bc	9.6a	4.2b	1.8b	4.4a	13.4a	38.8a	333
30	1.4a	173.6a	155.4b	91.9ab	12.4a	4.2b	1.8b	4.4a	14.8a	36.8a	382
40	1.9a	173.5a	209.3a	126.4a	11.2a	5.5a	2.3a	4.3a	15.3a	40.4a	381

† Means followed by the same letter within a column are not statistically significantly different ($P < 0.05$, Tukey-Kramer test).
‡ Single determination on composited soil sample.

(Table 2). A similar trend was observed in soil from the Fort Vermillion site where soil amended with 40 g manure kg^{-1} had 43 and 21% more HCO_3 than unamended soil after manure application and after 8-wk incubation, respectively (Table 3).

DISCUSSION

There was an immediate increase in the pH of two acid soils after application of fresh cattle manure, and the effect persisted during an 8-wk incubation of soil–manure mixtures. Other studies have reported a similar effect on soil pH after application of fresh or composted animal manure (Bickelhaupt, 1989; Warren and Fonteno, 1993; Cooper and Warman, 1997; Iyamuremye et al., 1996; O'Hallorans et al., 1997; Eghball, 1999). However, soil pH has been shown to decline in some manure-amended soils. Soil pH in the top 15 cm of calcareous soils (pH 7.8) amended with cattle manure annually for 11-yr declined by 0.3 to 0.7 units, and the decline was greatest in plots receiving three times the recommended rates for manure application (Chang et al., 1990). The pH of soils (pH 5.4, top 15 cm) receiving low and medium applications of swine lagoon effluent annually for 11-yr increased by 0.4 to 0.5 units, while the pH of soils receiving high annual applications of effluent declined by 0.3 units (King et al., 1990). While we have shown that cattle manure amendments can increase the pH of acid soils, the effects of manure on soil pH will depend on the manure source and soil characteristics.

It has been proposed that changes in the pH of soils amended with cattle manure are due to buffering from $CaCO_3$ since much of the $CaCO_3$ added to cattle diets may be excreted in manure (Eghball, 1999). We did not detect carbonate in either the manure or soils examined in this study, although large quantities of bicarbonate were present in fresh cattle manure, and manure-amended soils had higher levels of bicarbonate than unamended soils. The higher soil pH in manure-amended than unamended soils may have been partially, although not totally, due to buffering from bicarbonates. The pH of soil from the Beaverlodge site amended with 40 g manure kg^{-1} after incubation was

6.0, and the lime requirement to achieve pH 6.0 was 3.4 Mg $CaCO_3$ ha^{-1}, or 3400 mg $CaCO_3$ kg^{-1} (assuming a furrow layer of 1 ha to a depth of 20 cm). The application of 40 g manure kg^{-1} added 257 mg HCO_3 kg^{-1} to the soil. Since bicarbonate is only half as reactive as carbonate, the application of 40 g manure kg^{-1} would have added approximately 129 mg CO_3 kg^{-1}, or about 5% of the carbonate required to adjust soil pH to 6.0. It seems likely that compounds other than carbonates and bicarbonates, such as organic acids with carboxyl and phenolic hydroxyl groups, have an important role in buffering soil acidity and increasing the pH of acid soils amended with manure.

Mineral N concentrations tended to be greater in manure-amended than unamended soils immediately after application of fresh manure. Ammonium levels in manure-amended and unamended soils from the Beaverlodge and Fort Vermillion sites declined significantly ($P < 0.001$) in the first 2 wk of incubation, and remained below 2 mg NH_4–N kg^{-1} from Weeks 2 to 8 (data not shown). There was at least a 50% reduction in the NO_3–N concentrations of manure-amended soils from the two sites by Week 2 of the incubation, followed by an increase in NO_3–N levels from Weeks 2 to 8 (data not shown). The net decline in the mineral N concentration of manure-amended soils from the Beaverlodge site during incubation may have been due to immobilization or stabilization of N in non-extractable chemically or physically protected pools, and possibly gaseous losses. It seems possible that manure applications stimulated microbial activity, either by increasing soil pH or providing readily available C substrates for microbial growth, which may have resulted in net N immobilization after the 8-wk incubation. Conversely, incubation of manure-amended and unamended soils from the Fort Vermillion site produced a net increase in the mineral N pool, which suggests conditions were more favorable for microbial growth and activity in soils from the Fort Vermillion than Beaverlodge site. Available P and K concentrations were greater in manure-amended than unamended soils throughout the study, which suggests that much of the P and K added in cattle manure remains in a pool that is readily available for plant uptake. Despite the addition of Ca and Mg from cattle manure to

Table 3. Effect of cattle manure on extractable nutrients and cation-exchange capacity (CEC) of Fort Vermillion soil immediately after application and after an 8-wk incubation.†

Manure rate	NH_4–N	NO_3–N	P	K	S	Ca	Mg	Al	Fe	CEC	HCO_3‡
g kg^{-1}			mg kg^{-1}					cmol$_c$ kg^{-1}			mg kg^{-1}
					Immediately after application						
0	7.1c	13.4a	8.7d	49.0c	5.4a	5.4d	2.1c	4.0a	32.4a	59.0a	400
10	10.2bc	11.1a	22.2cd	78.1bc	4.7a	7.5a	2.9a	4.1a	34.8a	59.1a	439
20	14.7b	10.6a	35.6c	107.3b	5.6a	7.0ab	2.8ab	3.8a	31.7a	58.9a	495
30	17.4b	8.2a	59.4b	128.9ab	5.9a	6.4bc	2.5b	3.7a	31.8a	58.3a	496
40	23.8a	10.9a	78.1a	177.5a	6.7a	6.2c	2.5b	3.4a	27.9a	57.4a	700
					After an 8-wk incubation						
0	1.5a	65.7a	12.3c	65.2c	8.5a	7.4ab	3.0a	4.7a	45.1a	59.0a	513
10	0.9a	56.7a	21.3bc	80.6bc	8.1a	6.5bc	2.5ab	4.5a	41.8a	58.6a	516
20	1.4a	66.6a	30.0b	106.5b	8.6a	6.0c	2.5ab	4.8a	44.6a	58.6a	572
30	1.2a	45.0a	39.8ab	130.2ab	8.9a	5.6c	2.2b	4.5a	42.4a	59.0a	649
40	9.7a	55.1a	50.0a	174.0a	9.9a	7.6a	3.0a	4.5a	43.8a	58.4a	651

† Means followed by the same letter within a column are not statistically significantly different ($P < 0.05$, Tukey-Kramer test).
‡ Single determination on composited soil sample.

soil–manure mixtures, quantities of plant-available Ca and Mg were greater only in soils amended with the highest manure rate than unamended soils from both sites after the 8-wk incubation.

Soil extraction with acid ammonium oxalate measures noncrystalline inorganic and organic–complexed Al and Fe that can contribute to soil acidity and bind P, in particular, as well as other nutrients. It has been suggested that organic amendments such as manure may react similarly to $CaCO_3$ by precipitating Al and Fe or may form humic complexes with Al and Fe (Iyamuremye et al., 1996). We did not find a significant reduction in extractable Al and Fe concentrations of manure-amended than unamended soils from either site after incubation. Although repeated manure amendments have been shown to increase soil CEC (Ndayegamiye and Côté, 1989; Gao and Chang, 1996), we found no change in the CEC of manure-amended soils compared to unamended soils in this study. It appears that appreciable changes in Al, Fe, and CEC from manure applications do not occur in the short term (weeks).

Our results indicate that, in the short-term (weeks), cattle manure amendments can increase soil pH and supply considerable quantities of plant-available nutrients. We would caution against applying manure rates from this laboratory study at the field scale since the rates we have used could result in application of N and P in excess of crop requirements and could pose a threat to soil and environmental quality. We are currently investigating the effect of manure and lime amendments on crop growth and nutrition of wheat (*Triticum aestivum* L.) and canola (*Brassica rapa* L.). We anticipate that our current research will provide information on the rates of cattle manure and lime required to improve nutrient acquisition and yield of crops grown in acidic soils, and we will compare the cost of using cattle manure or lime to correct soil acidity.

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