Cattle manure and lime amendments to improve crop production of acidic soils in northern Alberta

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Whalen, J. K., Chang, C. and Clayton, G. W. 2002. **Cattle manure and lime amendments to improve crop production of acidic soils in northern Alberta**. Can. J. Soil Sci. **82**: 227–238. Crop production on acid soils can be improved greatly by adjusting the pH to near neutrality. Although soil acidity is commonly corrected by liming, there is evidence that animal manure amendments can increase the pH of acid soils. Fresh cattle manure and agricultural lime were compared for their effects on soil acidity and the production of canola (*Brassica napus* L.) and wheat (*Triticum aestivum* L.) in a greenhouse study. Canola and wheat yield, the nutrient content of grain and straw, and selected soil properties were determined on a Gray Luvisol (pH 4.8) from the Peace Region of Alberta. Soil pH increased with lime and manure applications, and canola and wheat yields were higher in limed and manure-amended soils than unfertilized, unlimed soils. Macronutrient uptake by canola and wheat was generally improved by liming and manure applications, and micronutrient uptake was related to the effects of lime and manure on soil pH. An economic analysis compared the costs of using cattle manure and lime to increase soil pH to 6.0. The costs of applying lime and fresh cattle manure to increase soil pH were compared, based on the fees for purchasing and applying lime or loading, hauling and applying manure. The nutrient value of manure was calculated based on the quantities of plant-available N, P and K in fresh manure. At distances less than 40 km, it is economical to substitute fresh cattle manure for agricultural lime to increase soil pH of acidic soils. However, good manure management practices should be followed to minimize the risk of nutrient transport and environmental pollution from agricultural land amended with cattle manure.

Key words: Agricultural economics, canola production, cattle manure, lime, soil pH, wheat production

Whalen, J. K., Chang, C. et Clayton, G. W. 2002. **L'amélioration de rendement dans les sols acides au nord de l'Alberta avec du fumier bovin et de la chaux**. Can. J. Soil Sci. **82**: 227–238. Il a été établi que les cultures en sols acides peuvent être améliorées en applicant un élément alcanisant, principalement de la chaux agricole, afin d'approcher le seuil de la neutralité. Or, si la chaux demeure assez populaire, il a déjà été suggéré que l'application de fumier peut aussi augmenter le pH du sol. L'expérience présentée dans cet article consistait à comparer l'impact d'un fumier frais de bovin sur le pH, ainsi que les cultures du canola (*Brassica napus L.*) et du blé (*Triticum aestivum L.*) à celui de la chaux. Les cultures étaient effectuées en serre sur un Luvisol gris (pH 4.8) de la région de Peace River en Alberta. Le pH du sol a augmenté avec l'application de la chaux et du fumier. Non seulement il est démontré qu'en general, les récoltes de blé et de canola sont plus abondantes sur les sols traités avec de la chaux ou du fumier que sur ceux traités seulement aux engrais chimiques, mais également que les deux traitements permettent une meilleure absorption des macronutriments par les racines. L'absorption des micronutriments restait pourtant le paramètre le plus intéressant pour l'experience, car il est relié au pH du sol, par conséquent à l'effet alcanisant de la chaux et du fumier. Nous avons comparé les coûts necessaire pour augmenter le pH du sol a 6.0 en utilisant le fumier ou la chaux. La valeur du fumier a été calculée basée sur les quantities de N, P et K disponible aux plantes. Considerant les coûts d'achat, d'entreposage et d'application de chacun des traitements, pour des distances de moins de 40 km, le fumier frais de bovin s'avère une solution aussi économiquement rentable que l'application de chaux. Toutefois, il demeure important de bien gérer l'application de fumier afin de réduire la contamination des sols par la perte de nutriments causée par ce genre d'élément.

Mots clés: Chaux agricole, culture de blé, culture de canola, économie agricole, fumier de bovin

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 agricultural limestone. 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 pH of acidic soils increases following beef cattle manure applications, which may be due to calcium carbonates and organic acids in the manure that buffer soil acidity (Eghball 1999; Whalen et al. 2000). Therefore, animal manure could be substituted for agricultural lime to improve production on acidic soils.

The 4800 cattle (*Bos taurus*) feedlots operating in Alberta have the capacity to feed 1.2 million cattle per year. The

Table 1 Properties of cattle manure used in this study[z]

Parameters	Mean value	Method used
Moisture content (kg kg^{-1})	0.45	Oven-dried, 105ºC for 48 h
pH	6.8	1:2 manure:water slurry
Electrical conductivity (dS m^{-1})	29.2	1:2 manure:water slurry
Organic C (g kg^{-1})	249.3	Carlo-Erba C and N analyzer (Milano, Italy).
Total N (g kg^{-1})	22.8	Carlo-Erba C and N analyzer (Milano, Italy).
Total P (g kg^{-1})	7.0	H_2O_2/H_2SO_4 digest, molybdate-ascorbic acid method
Total K (g kg^{-1})	22.2	H_2O_2/H_2SO_4 digest, AAS
Available NH_4 + NO_3 (g kg^{-1})	2.9	2M KCl extract, phenate/Cd reduction methods
Available P (g kg^{-1})	5.2	$NaHCO_3$-soluble P, molybdate-ascorbic acid method
Available K (g kg^{-1})	21.5	Saturated paste extract, AAS
Available S (mg kg^{-1})	4.9	Saturated paste extract, methylthymol blue
Available Ca (cmol kg^{-1})	1.4	Saturated paste extract, AAS
Available Mg (cmol kg^{-1})	5.8	Saturated paste extract, AAS

[z]Values are the means of at least 15 determinations. Nutrient analyses are expressed on a per-kg of manure (dry weight) basis.

majority of these feedlots are located in southern Alberta (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. It is often not economical to broaden the land base by hauling manure long distances (Freeze et al. 1999; McKenzie et al. 2000). Improper handling and disposal of manure have resulted in nutrient accumulation, particularly nitrogen and phosphorus, in soils and nutrient transport to ground and surface waters (Paterson and Lindwall 1992; Chang and Janzen 1996). Consequently, there is interest in siting new cattle feedlot operations in north-central and northern Alberta because few cattle feedlots operate in these regions currently. There are an estimated 1.2 million ha of acidic (pH < 6.0) agricultural soils in the Peace Region of northern Alberta that could benefit from lime application (Soon 1992; Arshad et al. 1997). A laboratory study that demonstrated an increase in soil pH from cattle manure applications to acidic soils from northern Alberta (Whalen et al. 2000) indicated cattle manure could be substituted for agricultural lime. However, that study did not evaluate crop production on acidic soils amended with cattle manure, nor did it consider the economics of substituting cattle manure for agricultural lime.

The objectives of this study were to determine (1) the yield and nutrient content of wheat and canola on acid soils from the Peace Region of Alberta amended with lime or cattle manure; and (2) the costs of using cattle manure and lime to increase soil pH and improve crop production on acid soils from the Peace Region of Alberta.

METHODS AND MATERIALS

Soils used in this experiment were collected in May 1999 from the top 15 cm of an unlimed agricultural field under barley (*Hordium vulgare* L.) production in the Peace Region of northern Alberta, Canada. The soil was a Hazelmere silt loam (Gray Luvisol) from Beaverlodge, Alberta 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 lime requirement of the soil was determined using the *p*-nitrophenol-H_3BO_3-KCl buffer (pH 8.0) method (McKeague 1978), and the amount of $CaCO_3$ required to raise soil pH to 6.5 was 4.5 Mg ha^{-1} or about 2 g lime kg^{-1} in small pots. Additional information on this soil has been reported by Franzluebbers and Arshad (1997) and Whalen et al. (2000).

Experimental Design

About 1500 g (oven-dried basis) of air-dried coarsely sieved (< 25 mm) soil was packed into pots (20-cm tall × 10-cm diameter) at approximately field bulk density (1 g cm^{-3}). Pots were amended with either fresh cattle manure or agricultural lime. The manure, taken from a beef cattle feedlot with straw bedding, was coarsely ground (<32 mm) and stored at –20°C for several weeks prior to this experiment. Some physical and chemical properties of the cattle manure used in the study are given in Table 1. Fresh cattle manure was added at rates of 0, 10, 20, 30 and 40 g (oven-dry basis) manure kg^{-1}, which corresponds to approximately 0, 30, 60, 90 and 120 Mg ha^{-1} of manure containing 0.45 kg water kg^{-1}. Agricultural lime was applied at rates of 0, 0.75, 1.5, 3 and 4 g $CaCO_3$ kg^{-1}, which is equivalent to field applications of 0, 1.7, 3.4, 6.7 and 9 Mg lime ha^{-1}. Each rate of manure and lime was applied to eight replicate pots. The pots that received 0 g manure kg^{-1} were designated unfertilized controls (0) and those that received 0 g $CaCO_3$ kg^{-1} were the fertilized controls (0 + NP). With the exception of the unfertilized controls (0 g manure kg^{-1} treatment), all pots received 70 mg N kg^{-1} from KNO_3 and 25 mg P kg^{-1} from KH_2PO_4, and all amendments were mixed thoroughly in the top 10 to 15 cm of potted soil.

Soils were moistened, and four replicate pots were planted with Polish canola (*Brassica napus* L. cv. Horizon) whereas the other four replicate pots were planted with hard red spring wheat (*Triticum aestivum* L. 'Katepwa'). After establishment, wheat was thinned to five plants per pot and canola was thinned to six plants per pot. Pots were placed in a controlled climate chamber at 20°C under full light intensity (about 350 mmoles m^{-2} s^{-1}, 12 h photoperiod) and watered regularly to prevent moisture stress. Additional N fertilizer (70 mg N kg^{-1} from KNO_3) was added to canola in fertilized control, lime-amended and manure-amended pots 16, 41, 76 and 99 d after seeding. Wheat in fertilized control, lime-amended and manure-amended pots received additional N fertilizer (70 mg N kg^{-1} from KNO_3) 20 and 53 days after seeding.

Plant Analysis

At maturity (116 d after seeding canola, 68 d after seeding wheat), plants were harvested. The aboveground portion was separated into grain and straw, and roots were separated from bulk soil. Grain and straw were oven-dried (70°C for 48 h), finely ground (< 1 mm mesh screen) and analyzed for total C and N using a Carlo-Erba C and N analyzer (Milan, Italy). Total macronutrients (P, K, Ca, Mg, S) and micronutrients (Fe, Cu, Mn, Zn, Al, Na, B, and Mo) in finely ground grain and straw samples were analyzed in HNO_3 digests (Jones and Case 1990) using a Spectro Ciros CCD inductively coupled argon plasma emission spectrometer (Spectro Analytical Instruments, Kieve, Germany). Nutrient uptake of canola and wheat was calculated for each replicate treatment, and was the sum of nutrient uptake (yield × nutrient concentration) in the grain and straw of the crops.

Soil Analysis

At plant harvest, soils from each pot were separated from plant roots, homogenized, sieved (< 2 mm mesh) and air-dried. Moist soil samples for mineral N analysis were weighed immediately after sieving and stored in a refrigerator at 4°C overnight. Soil pH was determined on air-dried soils using 1:2 soil:0.01 M $CaCl_2$ slurries after a 30-min equilibration. Mineral N (NH_4-N and NO_3-N) was determined on moist soil samples in 2 M KCl extracts [1:5 soil (dry weight basis):extractant] and measured colorimetrically using the phenate and cadmium reduction-diazotization methods (Maynard and Kalra 1993) with a Technicon II flow-injection autoanalyzer (Technicon Industrial Systems, Tarrytown, NY). Available P was determined in Kelowna (0.015 M NH_4F + 0.25 M CH_3COOH) soil extracts (1:10 air-dried soil:extractant) following the procedure of Ashworth and Mrazek (1995), and was measured colorimetrically by the ammonium molybdate-ascorbic acid method (Murphy and Riley 1962) using a Technicon IV autoanalyzer (Technicon Industrial Systems, Tarrytown, NY).

Statistical Analysis

Data were log transformed to equalize variance and evaluated statistically by ANOVA in a general linear model (GLM) using SAS software (SAS Institute, Inc. 1990). The interaction between treatment (type and rate of amendment added to pots) and crop (canola, wheat) was statistically significant ($P < 0.001$) for most soil and plant parameters evaluated. The effects of treatments were compared statistically for each crop species with a t-test (LSD) at the 95% confidence level (Steel and Torrie 1980). Linear regressions of the relationship between soil pH and crop yield were fit with the SAS/INSIGHT function of SAS software (version 6.12). Values presented in tables and figures are arithmetic means.

RESULTS

Grain and Straw Yields

Canola straw yields were between 2.99 and 16.09 g dry matter pot^{-1}, and grain yields ranged from 0.65 to 4.01 g dry matter pot^{-1} (Fig. 1A). Total canola production (grain plus straw) was significantly higher in pots amended with lime, and in manure-amended pots receiving rates of 20 g manure kg^{-1} or higher, than fertilized controls (Fig. 1A). Lime and manure-amended pots produced significantly more canola than unfertilized controls, and pots receiving 30 g manure kg^{-1} produced significantly more canola than lime-amended pots (Fig. 1A.). Wheat straw production ranged from 2.37 to 3.91 g dry matter pot^{-1} whereas wheat grain yields were between 0.84 and 1.28 g dry matter pot^{-1} (Fig. 1B). Total wheat production was significantly higher in lime and manure-amended pots than unfertilized controls, and significantly higher in pots receiving 4 g lime kg^{-1} and 40 g manure kg^{-1} than the fertilized controls (Fig. 1B). Pots receiving 40 g manure kg^{-1} produced significantly more wheat than pots amended with 0.75 to 3 g lime kg^{-1} (Fig. 1B).

Plant Nutrient Analysis

The concentration of most macronutrients in the grain and straw of canola and wheat tended to be greater in pots that received lime or manure than in unfertilized controls. The N, K, S, Ca and Mg removal in canola grain plus straw was significantly higher in lime- and manure-amended pots than in fertilized controls, whereas the canola harvested from lime- and manure-amended pots removed significantly higher quantities of all macronutrients than unfertilized controls (Table 2). Although P uptake in wheat grain plus straw was significantly greater in manure-amended pots than fertilized controls, the S and Mg uptake was significantly higher in lime-amended pots than fertilized controls. Pots receiving 3 and 4 g lime kg^{-1} removed significantly more Ca than fertilized controls. The N, K, Ca and Mg removal in wheat was significantly higher in lime- and manure-amended pots than unfertilized controls. Wheat uptake of P was significantly greater in manure-amended pots and pots receiving more than 0.75 g lime kg^{-1}. Wheat S uptake was significantly greater in lime-amended pots and the 40 g manure kg^{-1} treatment than unfertilized controls (Table 3).

Canola grain plus straw grown on soils amended with lime and manure removed significantly more Na, B and Mo than unfertilized controls, and manure-amended pots had significantly higher Zn uptake than unfertilized controls (Table 4). There were few differences in the micronutrient uptake of canola from lime-amended, manure-amended and fertilized control pots (Table 4). Canola grown in pots receiving lime and more than 20 g manure kg^{-1} removed significantly more Al than unfertilized controls, although Al uptake did not differ in lime-amended, manure-amended and fertilized controls (Table 4). The mean Al concentration ranged from 11.6 to 41.0 μg g^{-1} in canola grain and from 1233 to 3515 μg g^{-1} in canola straw. The Mn uptake in canola was significantly greater in manure-amended than in fertilized and unfertilized control pots (Table 4). However, Mn uptake in canola grown on lime-amended soils was significantly greater in pots receiving 0.75, 3 and 4 g lime kg^{-1} than in unfertilized control soils, but did not differ among lime-amended and fertilized control soils (Table 4). The mean Mn concentration was between 0.113 and 0.258 μg g^{-1} in canola grain and 94.2 to 220.1 μg g^{-1} in canola straw.

Wheat grown on most manure-amended soils removed significantly more Fe, Na, Zn, B and Mo in grain and straw

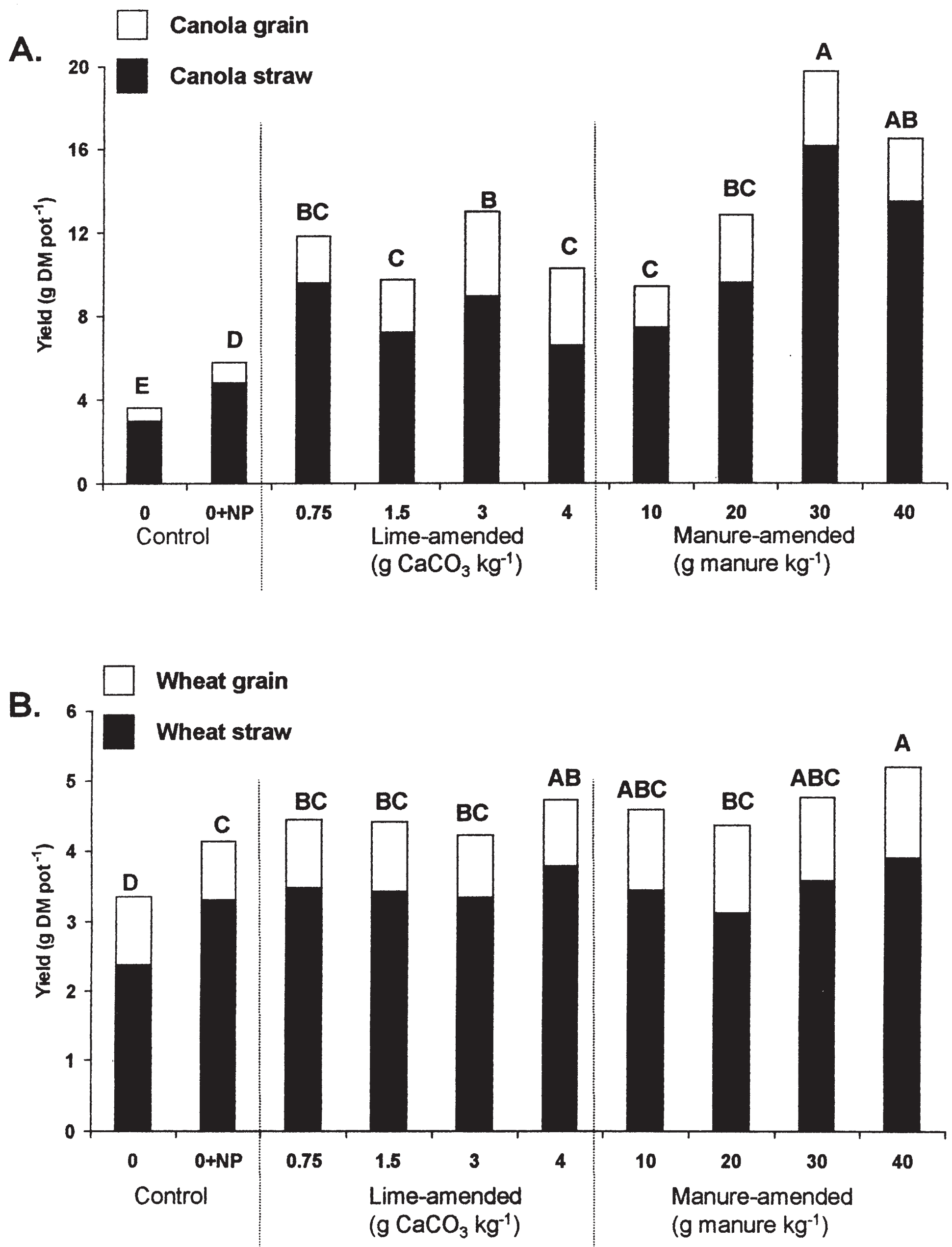

Fig. 1. Effect of limestone and cattle manure amendments on grain and straw yields (g dry matter pot^{-1}) of (A) canola and (B) wheat. Bars with the same letter indicate mean total yield (grain + straw) values are not significantly different ($P < 0.05$, LSD).

than wheat grown on unfertilized controls (Table 5). Lime-amended soils produced wheat with significantly more Fe, Zn, B and Mo than the unfertilized controls (Table 5). There were few differences in the micronutrient uptake of wheat from lime-amended, manure-amended and fertilized control pots (Table 5). Wheat grown in pots receiving manure or 4 g lime kg^{-1} had significantly higher Al uptake than unfertilized controls, but there was no difference in the Al uptake of wheat grown on lime-amended, manure-amended and fertilized control pots (Table 5). The mean Al concentration ranged from 16.7 to 24.5 µg g^{-1} in wheat grain and 817 to 1200 µg g^{-1} in wheat straw. The Mn uptake was significantly greater in manure-amended than lime-amended, fertilized and unfertilized controls (Table 5). The mean Mn concentration was between 4.0 and 16.4 µg g^{-1} in wheat grain and 196 to 802 µg g^{-1} in wheat straw.

Soil pH and Soil Available Nutrients

The pH of unfertilized and fertilized control soils did not vary significantly after canola and wheat harvest (Figs. 2A, 2B). However, soil pH after canola harvest was significantly greater in lime-amended pots receiving more than 0.75 g lime kg^{-1}, and in manure-amended pots receiving rates of 20 g manure kg^{-1} or higher compared to the controls (Fig. 2A). After wheat harvest, soil pH was significantly higher in pots amended with 3 g lime kg^{-1} or more than manure-amended

Table 2. Macronutrient uptake of canola grown on lime- and manure-amended soils

Treatment	Rate	N	P	K	S	Ca	Mg
		(mg pot^{-1})					
Control	0	49.3*e*	3.2*e*	23.0*e*	6.3*c*	31.1*b*	5.4*e*
	0+NP	103.2*d*	5.4*d*	45.9*d*	9.0*c*	44.6*b*	9.3*d*
Lime	0.75	181.2*bc*	12.5*cd*	114.6*bc*	23.7*ab*	125.6*a*	24.0*bc*
	1.5	153.4*c*	10.0*d*	100.8*c*	17.9*b*	85.5*a*	16.4*c*
	3	174.6*bc*	11.9*cd*	97.4*c*	21.4*b*	139.5*a*	21.4*bc*
	4	147.5*c*	9.8*d*	112.8*bc*	20.6*b*	113.0*a*	16.8*c*
Manure	10	162.8*c*	16.3*bc*	118.0*bc*	23.3*ab*	100.4*a*	19.1*bc*
	20	209.6*b*	22.8*b*	141.2*ab*	29.2*ab*	127.2*a*	25.2*b*
	30	271.7*a*	39.2*a*	191.0*a*	34.2*ab*	147.3*a*	41.4*a*
	40	275.2*a*	35.0*a*	188.3*a*	39.6*a*	134.7*a*	34.2*ab*

a–e Mean values within a column followed by the same letter are not significantly different ($P < 0.05$, LSD).

Table 3. Macronutrient uptake of wheat grown on lime- and manure-amended soils

Treatment	Rate	N	P	K	S	Ca	Mg
		(mg pot^{-1})					
Control	0	35.0*c*	8.3*e*	50.7*d*	5.3*c*	6.0*d*	3.7*c*
	0+NP	74.0*a*	8.8*de*	87.5*b*	6.9*b*	11.0*bc*	5.7*b*
Lime	0.75	78.0*a*	9.8*cde*	96.3*ab*	8.6*a*	12.2*ab*	6.8*a*
	1.5	82.5*a*	10.5*cd*	94.6*ab*	8.4*a*	12.4*ab*	6.6*a*
	3	79.8*a*	10.1*cd*	93.2*ab*	8.9*a*	13.4*a*	6.7*a*
	4	81.3*a*	11.0*c*	104.4a	8.9*a*	14.2*a*	6.8*a*
Manure	10	60.7*b*	11.2*bc*	86.6*b*	5.7*c*	10.0*bc*	5.8*b*
	20	58.3*b*	13.2*ab*	73.7*c*	5.8*c*	9.3*c*	5.4*b*
	30	63.6*b*	13.5*ab*	82.9*bc*	5.4*c*	10.5*bc*	6.1*ab*
	40	83.3*a*	15.9*a*	95.2*ab*	7.0*b*	11.4*bc*	7.3*a*

a–e Mean values within a column followed by the same letter are not significantly different ($P < 0.05$, LSD).

Table 4. Micronutrient and Na uptake of canola grown on lime- and manure-amended soils

Treatment	Rate	Fe	Al	Na	Mn	Cu	Zn	B	Mo
		(mg pot^{-1})				(µg pot^{-1})			
Control	0	0.70*a*	7.0*b*	5.2*e*	0.37*c*	39.5*d*	93.8*e*	62.8*e*	6.1*e*
	0+NP	1.68*a*	14.6*a*	9.3*d*	0.79*bc*	68.7*cd*	203.1*de*	93.2*d*	17.2*d*
Lime	0.75	3.46*a*	17.6*a*	23.4*c*	1.37*ab*	167.4*ab*	502.7*abc*	211.1*abc*	8.7*abc*
	1.5	1.03*a*	13.5*a*	19.3*c*	0.57*bc*	85.0*bc*	259.8*cd*	152.6*c*	29.7*bc*
	3	2.63*a*	13.2*a*	24.3*c*	1.12*ab*	131.5*abc*	417.9*bc*	195.9*bc*	43.3*ab*
	4	2.43*a*	12.1*a*	17.3*c*	1.11*ab*	77.9*bcd*	369.6*bcd*	158.5*c*	20.6*cd*
Manure	10	1.73*a*	9.8*ab*	27.1*bc*	1.53*a*	79.0*bcd*	291.5*bcd*	182.3*bc*	20.1*cd*
	20	2.39*a*	9.0*ab*	39.8*ab*	1.84*a*	120.5*bc*	447.4*bc*	229.9*ab*	33.7*b*
	30	3.70*a*	20.1*a*	44.7*a*	2.06*a*	267.2*a*	863.6*a*	291.9*a*	65.6*a*
	40	3.87*a*	12.7*a*	53.8*a*	1.67*a*	149.8*ab*	628.0*ab*	256.2*ab*	52.7*ab*

a–e Mean values within a column followed by the same letter are not significantly different ($P < 0.05$, LSD).

pots, and the pH was significantly higher in lime- and manure-amended pots than the fertilized and unfertilized controls (Fig. 2B). The relationships between soil pH and yield for canola and wheat were described for manure-amended and lime-amended soils (Fig. 3A, 3B). The slopes of the regressions were between 2.8 and 2.9 times greater for manure-amended than lime-amended soils, and the R^2 values of the regressions were greater for manure-amended than lime-amended soils for both crops (Fig. 3A, 3B).

Mineral N (NH_4-N + NO_3-N) concentrations found in pots following canola harvest ranged from less than 1 to 28 mg N kg^{-1}, and there was significantly more mineral N in the fertilized control pots than unfertilized control, lime-amended or manure-amended pots (data not shown). The mineral N content of soils following wheat harvest was between 2 and 44 mg N kg^{-1}, and unfertilized control pots had significantly less mineral N than the fertilized control, lime-amended and manure-amended pots (data not shown). Available P concentrations after harvest were significantly ($P < 0.05$, LSD) higher in manure-amended than lime-amended or control soils (Figs. 4A, 4B). Soil available P

Table 5. Micronutrient and Na uptake of wheat grown on lime- and manure-amended soils

Treatment	Rate	Fe	Al	Na	Mn	Cu	Zn	B	Mo
		(mg pot^{-1})				(μg pot^{-1})			
Control	0	0.26*c*	0.74*b*	0.16*e*	173.3*de*	40.3*ab*	135.4*d*	23.5*c*	1.2*d*
	0+NP	0.41*a*	0.78*ab*	0.23*de*	209.4*d*	33.1*b*	187.8*c*	31.3*ab*	1.8*d*
Lime	0.75	0.37*ab*	0.79*ab*	0.20*de*	202.7*d*	33.4*b*	199.3*bc*	30.2*ab*	2.5*c*
	1.5	0.38*ab*	0.79*ab*	0.19*de*	196.1*d*	42.0*ab*	185.0*bc*	31.3*ab*	3.0*c*
	3	0.42*ab*	0.67*b*	0.19*de*	180.5*de*	38.8*ab*	172.7*c*	30.4*ab*	3.1*c*
	4	0.39*ab*	0.93*a*	0.32*d*	160.0*e*	38.5*ab*	165.1*c*	29.0*b*	3.4*c*
Manure	10	0.33*bc*	0.92*a*	0.55*c*	298.8*c*	37.0*ab*	187.8*bc*	23.2*c*	9.0*b*
	20	0.37*ab*	0.98*a*	1.14*b*	375.3*b*	44.6*ab*	200.2*bc*	23.4*c*	12.4*ab*
	30	0.41*ab*	0.98*a*	1.30*a*	526.0*a*	41.1*ab*	228.3*b*	27.7*b*	16.1*a*
	40	0.49*a*	0.94*a*	1.16*ab*	654.8*a*	49.8*a*	299.3*a*	34.6*a*	13.5*ab*

a–e Mean values within a column followed by the same letter are not significantly different ($P < 0.05$, LSD).

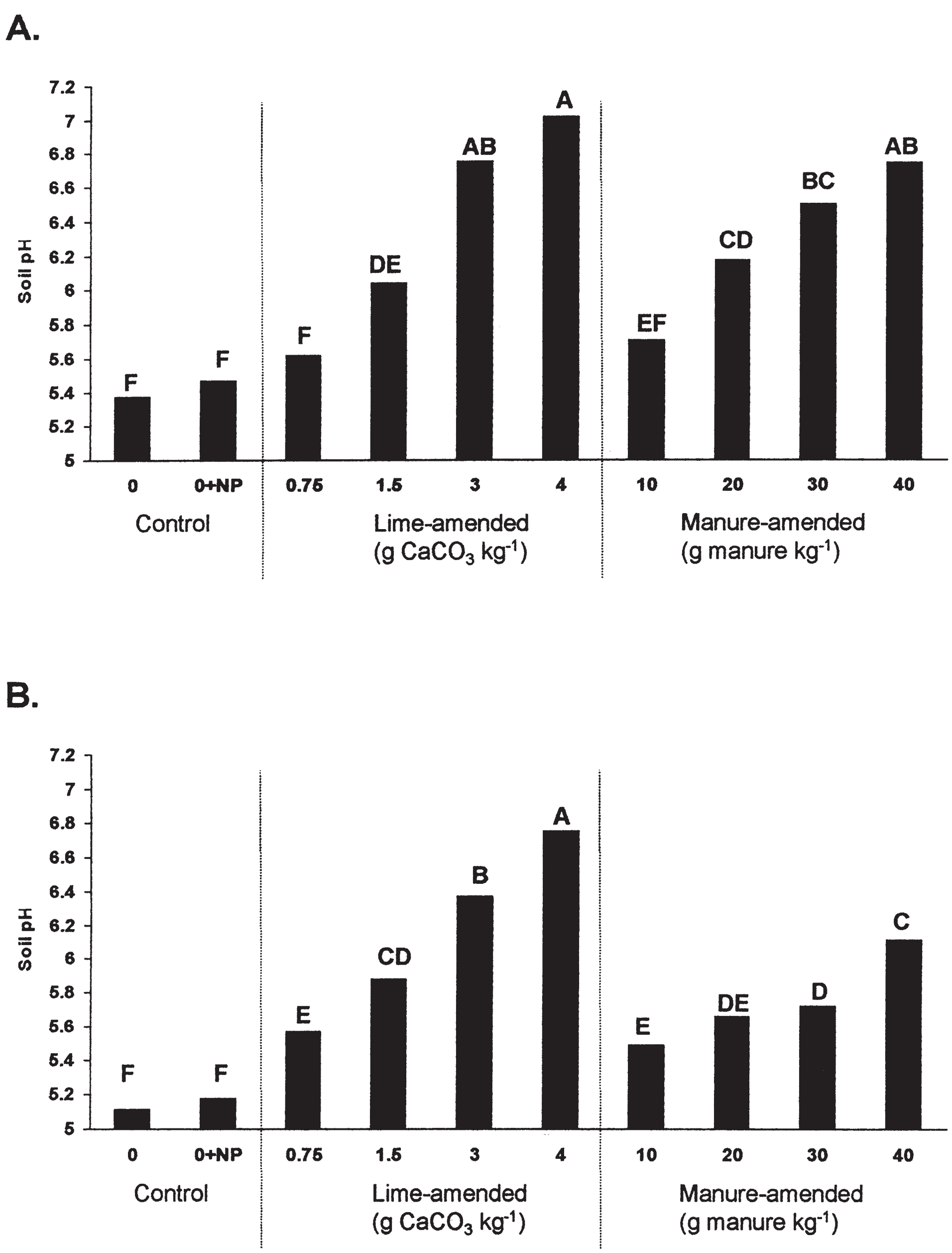

Fig. 2. Effect of limestone and cattle manure amendments on soil pH after harvest of (A) canola and (B) wheat. Bars with the same letter indicate mean values are not significantly different ($P < 0.05$, LSD).

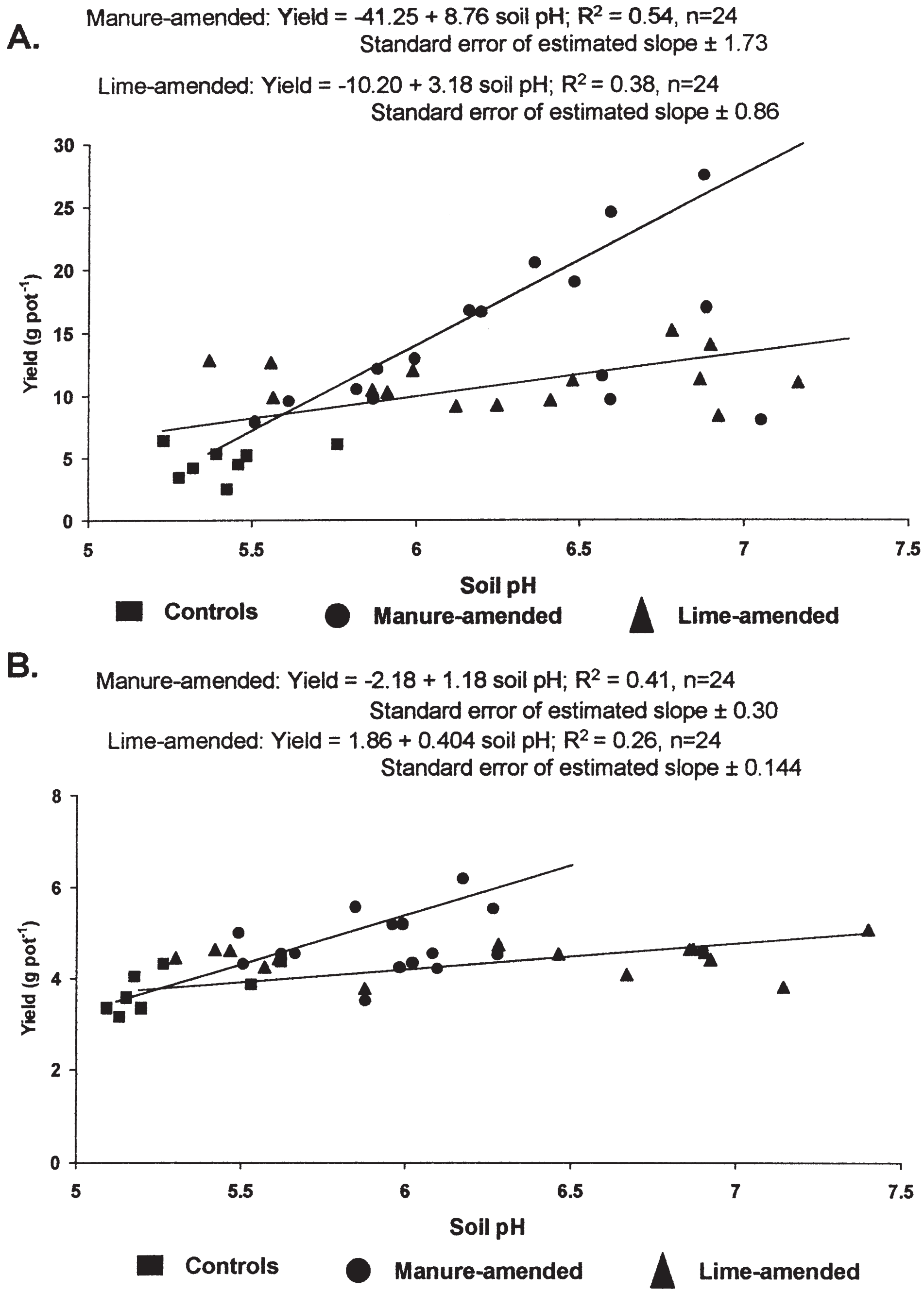

Fig. 3. Relationship between soil pH and yield of (A) canola and (B) wheat in acidic soils that received limestone or cattle manure. Regressions included fertilized and unfertilized controls.

was highest in soils that received the largest manure application under canola and wheat production (Figs. 4A, 4B).

DISCUSSION

Canola and wheat are considered moderately tolerant to soil acidity, but do respond to liming. Limed soils in the Peace Region of Alberta support higher canola and wheat yields than unlimed soils (Hoyt et al. 1974; Arshad et al. 1997). Manure amendments had a positive effect on canola production, and rates of more than 10 g manure kg^{-1} increased grain plus straw yields relative to soils that received fertilizer only. Lime applications of 0.75 g $CaCO_3$ kg^{-1} and higher improved canola production relative to soils that received fertilizer only. Wheat grain plus straw production were lower in unfertilized soils than in soils that received lime and manure applications, but only the highest lime and manure application rates (4 g $CaCO_3$ kg^{-1} and 40 g manure kg^{-1}) produced more wheat than fertilized soils. Crops vary in their tolerance to soil acidity, and hence in their response to the amelioration of soil acidity. Canola and wheat yield increased linearly with soil pH, but the slopes of regression lines relating yield to soil pH indicate a nearly threefold improvement in yield of

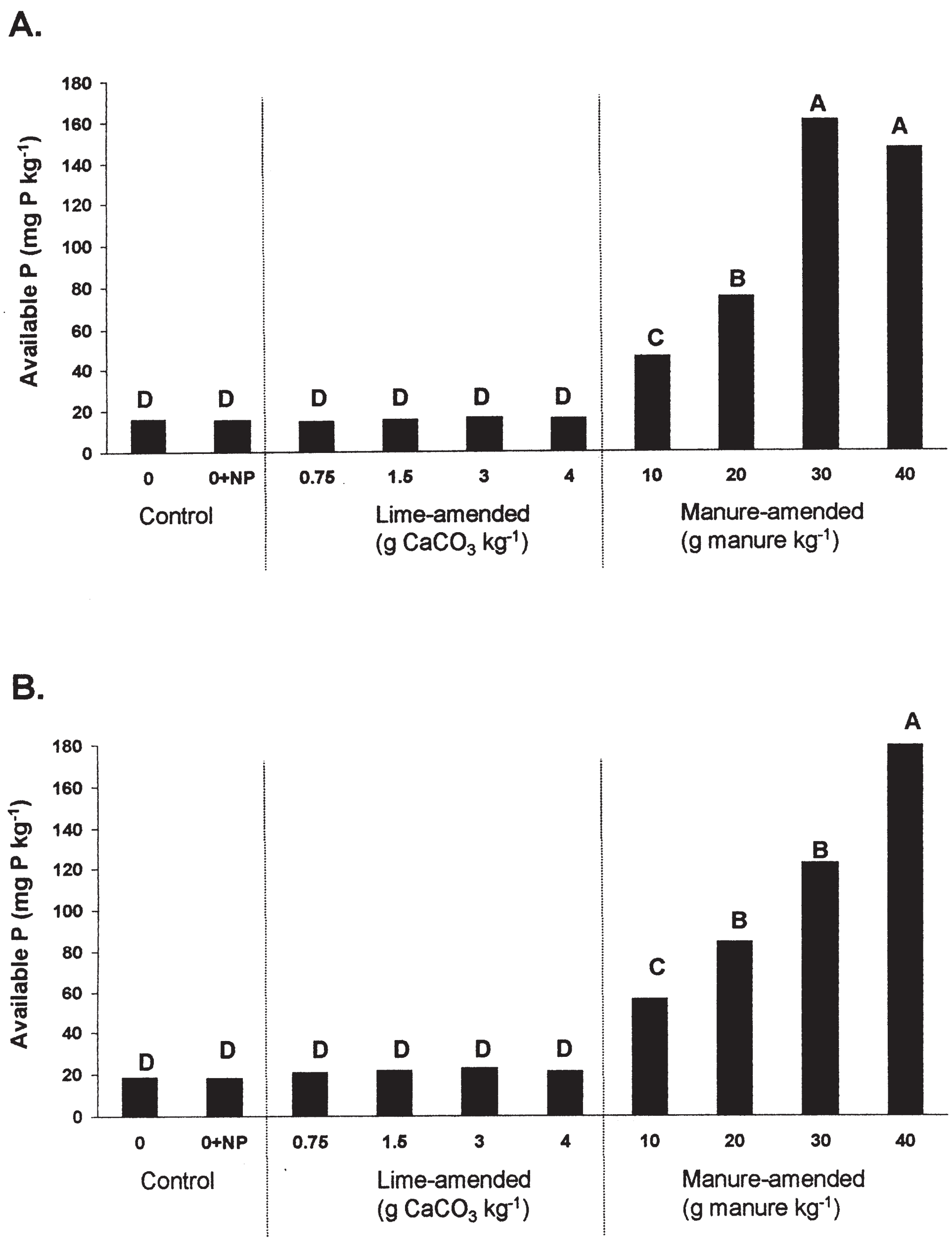

Fig. 4. Effect of limestone and cattle manure amendments on soil available P concentrations after harvest of (A) canola and (B) wheat. Bars with the same letter indicate mean values are not significantly different ($P < 0.05$, LSD).

manure-amended than lime-amended soils with an equal increase in soil pH. This result suggests that increasing soil pH is only partly responsible for improving crop production on acid soils, and manure applications promote plant growth by buffering soil acidity and by providing plant-available nutrients. In our greenhouse study, greater yield improvements were observed for canola than wheat, and this possibility should be investigated under field conditions.

The most important growth-limiting factor in acid soils is believed to be Al toxicity because high levels of soluble and/or exchangeable Al, combined with low levels of Ca, impair plant root development and limit water and nutrient uptake by plants (Adams 1984). The uptake of N, K, S, Ca and Mg in canola grain and straw was greater from soils receiving lime and manure than fertilized soils, and the P uptake was higher in manure-amended soils than in soils that received lime or fertilizer only. The P uptake in wheat was greater in manure-amended soils than in fertilized or lime-amended soils, and S, Ca and Mg uptake were greater in some lime-amended soils than manure-amended and fertilized soils. Green and animal manures can increase P availability in soils and consequently improve P uptake by crops (Ohno and Crannell 1996). Although the macronutrient content of plant parts tended to be the same or slightly higher in lime- and manure-amended soils than in fertilized and unfertilized soils, macronutrient uptake, which includes yield and nutrient content, was generally highest in the pots with the highest yields.

Field studies in the Peace Region of Alberta that evaluated the beneficial effects of liming on crop production have focused mainly on crop yields, and less attention has been paid to nutrient uptake by crops. Our results suggest that canola grown on soils similar to the one investigated in this study would likely remove more macronutrients when soils were limed or amended with manure than when they received fertilizer only. Interestingly, macronutrient uptake by wheat appeared to be similar whether acid soils receive lime and inorganic fertilizer, manure, or inorganic fertilizer only, suggesting that liming agents did not improve macronutrient use by wheat significantly. However, positive effects of liming and green manure on field-scale cereal production in the Peace Region of Alberta have been demonstrated (Arshad and Gill 1997; Arshad et al. 1999). We harvested wheat early (maturity for this cultivar is between 90 and 100 days), so we did not account for differences among the treatments during the later development stages (e.g., grain filling) of wheat. Research should be conducted to determine macronutrient uptake by canola and wheat in limed and manure-amended soils under field conditions.

The uptake of some micronutrients by canola and wheat was improved by lime and manure amendments, compared to unfertilized soils, but generally there was no difference in the micronutrient uptake of soils that received lime, manure or inorganic fertilizer only. Liming is well known to increase the availability of certain micronutrients for plant uptake (Adams 1984). The higher removal of B and Mo in canola and wheat grown on most lime- and manure-amended soils than unfertilized and fertilized soils was likely due to an increase in plant-available B and Mo. These micronutrients become more available for plant uptake as soil pH increases (Barber 1984).

Micronutrient cations such as Fe, Cu and Zn become less available to plants as soil pH increases (Barber 1984). Although canola and wheat grown on soils receiving the highest rates of manure tended to remove more Fe, Cu and Zn than fertilized and unfertilized soils, only some of these differences were significant. The uptake of Fe, Cu and Zn may have been higher in manure-amended than fertilized soils because of higher canola and wheat yields on some manure-amended than fertilized soils, or because levels of plant-available micronutrients were higher in manure-amended than fertilized soils. After 13 yr of lime and fertilizer treatments, Cummings and Xie (1995) found higher Cu and Zn concentrations in leaves, shoots and trunks of peach trees fertilized with poultry manure than with inorganic N fertilizers, which they attributed to plant-available micronutrients contained in the poultry manure. Other agents in manure (e.g., organic acids and chelating agents) may have altered micronutrient availability in the manure-amended soils. Evans (1991) found simple organic acids increased soil exchangeable Zn concentrations and Zn uptake by wheat, and concluded that organic acids influenced the availability of Zn to plants. The Na uptake in canola and wheat was higher in most manure-amended soils than the other treatments. Manure applied to pots contained, on average, 12.7 ± 0.4 mg Na g^{-1}, and it appears that canola and wheat readily assimilated this element.

There was no difference in the Al uptake of canola and wheat grown on lime-amended, manure-amended and fertilized soils, and there was generally no difference in the Mn uptake of canola and wheat grown on lime-amended and fertilized soils. The availability of Al and Mn decreases as soil pH increases (Barber 1984), and it appeared that lime applications may have interfered with Al and Mn uptake through their effects on soil pH. Reduction in Al and Mn availability to plants through the precipitation of Al- and Mn-hydroxyl compounds is thought to be the single greatest benefit of liming (Adams 1984). Manure applications appeared to reduce Al availability to plants, but enhanced Mn availability to canola and wheat. There was more Mn removed in canola and wheat grown on manure-amended than fertilized and unfertilized soils. In contrast to our findings, Warman and Cooper (2000) found tissue Mn concentrations in forages were lower when soils were amended with composted or fresh poultry manure than when soils received inorganic fertilizers. The levels of Al and Mn assimilated by canola and wheat did not produce visual toxicity symptoms. Organic residues such as compost and animal manure are believed to alter micronutrient availability through the formation of complexes with organic matter decomposition products, adsorption of positively charged cations on organic matter surfaces, and formation of precipitates with hydroxy compounds released from redox and ligand exchange reactions (Hue 1992; Van den Berghe and Hue 1999). Our results indicate that cattle manure and lime altered Al and Mn availability to plants, but we did not investigate the specific mechanisms responsible for these effects.

The pH of the acidic Grey Luvisol soil used for the greenhouse study was higher in pots amended with fresh cattle manure and agricultural lime after canola and wheat harvest. Fresh cattle manure applications of 20 to 30 g manure kg^{-1} or lime applications of 1.5 g CaO_3 kg^{-1} were sufficient to raise soil pH to 6.0. Other studies have reported an increase in the pH of acidic soils after application of fresh or composted animal manure (Warren and Fonteno 1993; Iyamuremye et al. 1996; Cooper and Warman 1997; O'Hallorans et al. 1997; Whalen et al. 2000). Calcium carbonates and organic acids in the manure may buffer soil acidity (Eghball 1999; Whalen et al. 2000), and the hydrolysis of sodium released from exchange sites or solubilized from manure can also increase soil pH (Wolt 1994). However, the long-term effect of animal manure on soil pH may depend on the manure source and soil characteristics. The pH of acidic soils (pH 5.4) receiving low and medium applications of swine lagoon effluent annually for 11 yr increased by 0.4 to 0.5 units, whereas the pH of soils receiving high annual applications of effluent declined by 0.3 units (King et al. 1990). Soil pH in unfertilized bulk soils after harvest tended to be lower under wheat (pH = 5.15) than canola (pH = 5.37). Plant roots can affect soil pH because cation uptake is balanced by the release of H^+ ions from root surfaces, and the effect of roots on soil pH is influenced by root architecture (Barber 1984). Our results suggest that this effect is greater in acid soils under wheat than canola production, but further research is required to determine whether these effects are observed under field conditions.

Canola and wheat received N fertilizer periodically during the study to prevent N deficiencies. The variation in soil mineral N (NH_4-N plus NO_3-N) concentrations at harvest were likely influenced by differences in N use efficiency between the crops and the length of time between N fertilization and harvest. Soil-available P concentrations were greater in manure-amended plots than lime-amended plots or the control pots, which may have led to the higher P content in canola grain, canola straw and wheat straw of the treatments receiving manure. In a long-term study on feedlot cattle manure applications, about 42% of the total P in cattle manure was $NaHCO_3$-extractable, and between 50 and 66% of the total P in soils that received manure applications for 16 yr was $NaHCO_3$-extractable (Whalen and Chang 2001). These results indicate a large proportion of the P in cattle feedlot manure is in forms available for plant uptake, and cattle manure may contribute to the formation of a large pool of plant-available P in soils (Whalen and Chang 2001). There was no difference in the available P concentration of lime-amended and unfertilized control pots at harvest, despite the fact that inorganic P fertilizer was added to the lime-amended pots at seeding. The P content of grain and straw harvested from lime-amended pots also did not differ from unfertilized control pots. The lack of differences among these treatments may have been due to stabilization of inorganic P fertilizers in forms not available to plants.

Although manure can provide sufficient plant-available P to support canola and wheat production, the accumulation of plant-available P in the manure-amended treatments relative to lime-amended treatments could have negative environmental consequences. The risk of pollution of surface water bodies with P originating from agricultural land is known to be greater in soils with more, than less, plant-available P, but depends on many factors including climate, soil type and hydrology, agronomic practices and landscape position (Lemunyon and Gilbert 1993; Heathwaite 1997). Therefore, any plans to substitute animal manure for agricultural lime in the Peace Region of Alberta should follow nutrient management guidelines to minimize the risk of nutrient transport and environmental pollution from agricultural land.

Comparison of Costs for Animal Manure and Lime Applications to Correct Soil Acidity

It is evident that soil acidity problems can be corrected by amending acid soils with lime or cattle manure. The application of lime or manure to acid soils can also improve canola and wheat production under greenhouse conditions, compared to soils that receive no liming agents or fertilizer. Field studies have not yet been conducted in the Peace Region of Alberta to assess the economic feasibility of adjusting soil pH under field conditions with animal manure compared to liming. The following discussion estimates the costs of using cattle manure and lime to ameliorate soil acidity and improve canola and wheat production in the Peace Region of Alberta.

The major assumption in this analysis is that canola and wheat production in the field will increase appreciably if producers can raise the soil pH to at least 6.0. This assumption is supported by field experiments that demonstrated liming improved growth and yields of several cereal, oilseed and forage crops in the Peace Region (Hoyt et al. 1974; Penney et al. 1977; Arshad and Gill 1997; Arshad et al. 1997). The quantity of lime ($CaCO_3$) required to increase soil pH to 6.0 was 1.5 g kg^{-1}, which is approximately 3.4 Mg lime ha^{-1}. The quantity of manure required to raise soil pH to 6.0 was 20 g kg^{-1} under canola and 30 g kg^{-1} under wheat. For the purposes of this analysis, we will assume the quantity of manure required to increase soil pH to 6.0 is about 30 g manure (dry wt) kg^{-1}, which corresponds to 60 Mg manure (wet wt) ha^{-1}.

Costs associated with purchasing and applying lime, and manure loading, hauling and application are reported in Table 6. The cost of liming a soil with a lime requirement of 3.4 Mg lime ha^{-1} would be \$257.18 ha^{-1}, based on the known purchase, shipping and application costs (Table 6). Manure application costs depend on labor costs as well as hauling distance. If manure is hauled 5 km for application, the cost of applying 60 Mg ha^{-1} range from \$285.00 to \$312.60, depending on labor costs (Table 6).

Although it appears to be more expensive to correct the pH of acid soils with manure than lime application, animal manure contains large quantities of plant-available nutrients. Freeze et al. (1999) calculated the value of N and P in manure, based on inorganic fertilizer costs, to be \$0.71 kg^{-1} N and \$0.67 kg^{-1} P. Fertilizer prices have increased since Freeze et al. (1999) conducted their analysis, and updated values of N, P and K in manure, based on the cost of inorganic fertilizers, are reported in Table 7. The nutrient value of the cattle manure we applied in our study was \$13.43 Mg^{-1} fresh manure, based on the quantities of plant-available N, P and K in fresh manure (Table 7). The value of applying 60 Mg ha^{-1} of fresh cattle manure (\$805.80 ha^{-1}) with a similar composition to the manure we used would outweigh the costs of hauling manure distances of 5 km and 12.6 km from feedlots. Manure application costs would be between \$805.80 and 900.00 ha^{-1} if manure was hauled 40 km from the feedlot, and the break-even distance (costs = benefits) for manure application is 40 km when labor costs are \$8 per hour.

We have given value only to available N, P and K pools in manure because they are readily available for plant uptake, and have not given a value to the N, P and K not readily available for plant uptake, other macro- and micronutrients, or the organic matter in manure. We have also assumed no loss of plant-available N from manure during handling and land application. Through best management practices, producers may be able to minimize N losses via ammonia volatilization, denitrification and leaching from fresh manure. Although most of the total K in manure is readily available for plant uptake, a large proportion of the N and P in cattle manure is in organic forms and is released slowly as manure decomposes. Organic N and P pools have the potential to contribute to soil fertility and plant nutrition in the longer-term (i.e., years). It is common for producers to purchase N, P and K fertilizers, but they tend to apply other macro- and micronutrients less often to agricultural soils. Cattle manure generally contains all the macro- and micronutrients required for crop production, and so the

Table 6. Costs associated with lime and animal manure applications including hauling costs of manure to field sites for $12 h^{-1} and $8 h^{-1} labor rates

		Manure (labor = $12 h^{-1})			Manure (labor = $8 h^{-1})		
Cost ($ Mg^{-1})	Lime ($CaCO_3$)	5 km	12.6 km	40 km	5 km	12.6 km	40 km
Purchase[z]	65.00						
Application[z]	10.64						
Loading[y]		3.81	3.81	3.81	3.51	3.51	3.51
Hauling and Application[y]		1.40	3.53	11.19	1.24	3.16	9.92

[z]Lime purchase price includes delivery costs. Application costs include machinery operating, depreciation and investment costs. Lime costs were provided by Peter Darbyshire, Greymont Western Ltd. (formerly Continental Lime Ltd.) in April, 2000.
[y]Manure loading, hauling and application costs are from Freeze et al. (1999) and include machinery operating, depreciation and investment costs.

Table 7. Value of N, P, and K in cattle manure based on inorganic fertilizer costs

	Inorganic fertilizer source		
Parameter	N (46-0-0)	P (11-52-0)	K (0-0-61)
Fertilizer price ($ Mg-1)[z]	455	485	305
Fertilizer nutrient value ($ kg^{-1} nutrient)[y,x]	0.99	1.66	0.60
	Fresh cattle manure[w]		
	Available N	Available P	Available K
Nutrient concentration (g kg^{-1} dry manure)	2.9	5.2	21.5
Nutrient value ($ Mg^{-1} dry manure)	2.87	8.63	12.90
Nutrient value ($ Mg^{-1} wet manure)[v]	1.58	4.75	7.10

[z]Price at fertilizer plant, provided by Greg Haney, Belcan, in November 2001.
[y]The fertilizer P value was calculated after subtracting the fertilizer N value from the price of 11-52-0, and converting from P_2O_5 to P (kg $P_2O_5 \times 0.4369$ = kg P).
[x]The fertilizer K value was calculated after converting from K_2O to K (kg $K_2O \times 0.8302$ = K).
[w]Available N, P and K refer to forms of these nutrients readily-available for plant uptake (see Table 1 for information on assessment of available nutrients).
[v]Wet manure contained 45% water and 55% dry matter.

value we placed on manure is an underestimate of its true fertilizer value. Cattle manure is also a source of organic matter, which can improve soil physical, chemical and biological properties and potentially lead to better conditions for crop production. More study is needed to quantify the effects of organic matter on crop production so a value could be placed on the organic matter in cattle manure. Due to these limitations, we believe our economic assessment has underestimated the value of cattle manure.

Our results indicate that the cost of correcting soil acidity in the Peace Region of Alberta could be less with cattle manure than lime if the source of manure was less than 40 km of the target agricultural field. Locating feedlots in acid soil areas would diversify the farm operation and increase productivity of land nearby. Further research is needed to determine what values are appropriate for pools of non-extractable N and P, other macronutrients and micronutrients, and organic matter in cattle manure. Depending on the value of these other components of manure, it may be feasible to haul manure greater distances to correct soil acidity and improve soil fertility. However, any attempt to substitute cattle manure for agricultural lime should be part of a balanced nutrient management plan to minimize the risk of environmental pollution from manure.

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