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Effects of Long-Term Fertilization for Cassava Production on Soil Nutrient Availability as Measured by Ion Exchange Membrane Probe and by Corn and Canola Nutrient Uptake

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ABSTRACT : The effects of long-term fertilization on soil properties and nutrient availability are not well documented for cassava cultivation in Vietnam. In 1990, a field research plots were established with 12 treatments to test the effect of different rates of nitrogen (N), phosphorus (P) and potassium (K) on soil properties in Acrisols at Thai Nguyen University in Northern Vietnam. In 1999, composite soil samples (0 to 20 cm depth) were collected from eight selected plots for measurements of nutrient supply rates by ion exchange membrane probes and for growing corn and canola in a growth chamber with and without added lime. Generally, long-term nitrogen (N) fertilization increased available N supply rates but decreased available potassium (K) and magnesium (Mg). Long-term phosphorus (P) applications increased canola N, calcium (Ca) and Mg uptake. Canola P uptake increased with increased P rates only when lime was added. Long-term K applications increased canola N, K, Ca, Mg uptake but only significantly increased corn N uptake. Liming significantly increased uptake of N, P, K, Ca, Mg and S for both corn and canola. However, NH_4-N, K and Mg soil supply rates were reduced when lime was added, due to competition between Ca from the added lime and other nutrients.

Keywords: cassava, long-term fertilization, resin membrane, soil nutrient.

Cassava (*Manihot esculenta* Crantz.) is the third most important food crop after rice and maize in Vietnam, and one of the most efficient producers of carbohydrate in the sloping infertile soils common in the northern hill region of Vietnam. However, soil degradation and long-term cassava yield decreases have been observed without fertilization in continuous cassava cropping systems (Wargiono *et al.*, 1997). These reductions are either due to nutrient extraction in the harvested product, resulting in nutrient depletion, or due to severe erosion under cassava production (Puttacharoen *et al.*, 1998). Fertilizer additions have been reported to significantly increase cassava yields (Howeler & Cadavid, 1990). As well, by promoting vegetation growth, fertilizer additions may be associated with reduced soil erosion.

Application of nitrogen, phosphorus and potassium fertilizers for several years can have significant effects on soil chemical and physical properties such as pH, total nutrient content and nutrient availability (McAndrew & Malhi, 1992; Steffens, 1994; Richards *et al.*, 1995). However, the effect of repeated additions of NPK fertilizers on soil properties and nutrient availability has not been well documented for cassava production systems in steeply sloping lands.

The objective of the study was to assess the influence of long-term application of N, P and K for cassava production on the nutrient availability of the soils using nutrient supply rates as measured by ion exchange membrane probes, and corn and canola nutrient uptake under unlimed and limed conditions in a growth chamber experiment.

MATERIALS AND METHODS

Long-term fertilizer trial description for study sample collection

In 1990, field experimental plots were established on Acrisols (FAO-UNESCO Soil Classification) at the experimental station at Thai Nguyen University in Northern Vietnam to examine effects of four rates of N, P and K alone, or in combination on cassava yield and soil properties over time. The field experiment was designed as a randomized complete block design with 12 treatments and four blocks. Cassava has been grown in plots of 40.3 m^2 in February with a density of 14,000 plants ha^{-1}. Nitrogen (urea), P (single super phosphate) and K (potassium chloride) fertilizers were applied annually from 1990 to 1999. In 1995 and 1996, all treatments received the same addition of 50 kg ha^{-1} of magnesium sulfate ($MgSO_4$). All P was applied at planting time, while N and K applications were split, with half applied at planting time and the other half in two months later. Table 1 shows that the soil at the research site would be

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Table 1. Characteristics of a soil profile at the research site.

Soil characteristics	Soil depths (cm)		
	0-20	20-45	45-100
pH	4.3	4.4	4.3
Organic C (g kg^{-1})	10.1	5.1	3.6
Total N (g kg^{-1})	0.55	0.23	0.16
Total P (g kg^{-1})	0.12	0.08	0.08
Total K (g kg^{-1})	0.80	0.90	1.39
Total S (g kg^{-1})	0.09	0.12	0.12
Exchangeable (mg kg^{-1})			
NH_4-N	1.98	0.95	1.45
NO_3-N	<LD>^{x}	<LD>	<LD>
K	8.0	11.5	6.9
SO_4-S	9.6	8.5	13.4
Ca	37.0	27.0	37.0
Mg	3.0	2.0	<LD>
Al	24.3	24.9	28.3

^{x}<LD> is lower than detection limit.

classified as acidic and low or very low in nutrients according to the nutritional requirements of cassava (Howeler, 1998). The general characteristics of experimental site were presented in Table 1.

Treatment selection, soil sampling and liming

The eight selected treatments used in a growth chamber experiment are shown in Table 2. Composite soil samples were taken from the 32 plots (0 to 20 cm depth) in June 1999. Each composite sample was comprised of 20 bulked cores taken between the rows of cassava plants in each plot. The samples were air-dried for study. The air-dried samples were received two levels of lime: 1) no lime (control) and 2) 2.5 g $CaCO_3$ kg^{-1} soil. The soils then were incubated for three weeks before experiment.

Determination of nutrient supply rate

Soil nutrient supply rates of NH_4-N, NO_3-N, P, SO_4-S were measured using anion exchange membrane and K, Ca, Mg by cation exchange membrane (Plant Root Simulator^{TM}) probes (Qian *et al.*, 1996). Prior to use, cation exchanger was saturated with H^+ cation by immersion in 0.5 M HCl whereas anion exchanger was saturated with anion HCO_3^- using 0.5 M $NaHCO_3$. One cation probe in H^+ form and one anion probe in HCO_3^- form were placed in approximately 120 g soil in 30-dram plastic vials in the laboratory. After the probes were placed in soil, the soils were brought to field capacity with deionized water. The probes were allowed to remain in the soils for one week. The probes were then removed from the vials, and washed free of soil with deionized water. Each probe was then eluted using 20 ml of 0.5 M HCl for 1 h. After elution, ions in the eluted solution were analyzed using automated colorimetry for NO_3-N, NH_4-N and PO_4-P, inductively coupled plasma for SO_4-S and AA/FE for K, Ca, and Mg.

Table 2. Treatments used in the experiment.

Treatment	Rates
1	$N_0P_0K_0$
2	$N_0P_{40}K_{80}$
3	$N_{80}P_{40}K_{80}$
4	$N_{160}P_{40}K_{80}$
5	$N_{80}P_0K_{80}$
6	$N_{80}P_{80}K_{80}$
7	$N_{80}P_{40}K_0$
8	$N_{160}P_{80}K_{160}$

Note: number following N, P and K indicates the amount of N, P_2O_5 and K_2O (kg/ha), respectively, applied annually during the nine years from 1990 to 1998.

Plant culture and analysis

Corn and canola were grown without fertilizers in pots with 1200 g of the soils in the growth chambers that were set at temperature of 25°C for corn and 20°C for canola throughout the experiment. All pots were watered once a day to keep soil moisture at about 90% of field capacity.

Corn was harvested three weeks after planting because severe K deficiency symptoms were developed. It is suggested that corn, which has coarse roots, has limited capacity to access K from these soils and, as a result, the data for corn growth and plant nutrient composition is likely not sufficient to evaluate the effect of soil N and P residual effects in the experiment. Canola, which has finer roots and can better extract soil K, may be better in detecting the soil N and P residual effects under conditions of K deficiency. Consequently, canola was grown in the pots for five weeks after corn was harvested.

After harvesting, corn and canola dry matter yields were determined and then the harvested plant materials were ground for analysis. The ground samples were digested in concentrated H_2SO_4 and H_2O_2 using a temperature-controlled block. Then the digested solutions were analyzed using automated colorimetry for N and P, inductively coupled plasma for S, and AA/FE for K, Ca, and Mg.

RESULTS AND DISCUSION

Data on nutrient supply rates of soils in which cassava was grown for nine years with different fertilization treatments are presented in Tables 3, while growth increment, nutrient concentrations and, total nutrients uptake of corn and canola grown on that soil without fertilization in Table 4 and 5.

Table 3. Effects of long-term fertilization for cassava and liming on soil nutrient supply rates.

Treatment	Nutrient supply rates (0.1 µ g cm^{-2} $week^{-1}$)					
	NH_4-N	NO_3-N	K	Ca	Mg	SO_4-S
			Without lime addition			
1. $N_0P_0K_0$	118	176	145	702	151	90
2. $N_0P_{40}K_{80}$	129	270	193	654	141	121
3. $N_{80}P_{40}K_{80}$	228	237	127	669	99	94
4. $N_{160}P_{40}K_{80}$	81	210	105	607	93	70
5. $N_{80}P_0K_{80}$	124	261	249	463	104	90
6. $N_{80}P_{80}K_{80}$	50	236	97	669	104	77
7. $N_{80}P_{40}K_0$	103	252	85	535	96	96
8. $N_{160}P_{80}K_{160}$	111	218	254	739	110	127
Contrast						
– N linear (2 vs. 3 vs. 4)	NS	NS	NS	NS	<0.01	0.02
N quadratic	NS	NS	NS	NS	NS	NS
– P linear (5 vs. 3 vs. 6)	NS	NS	0.03	NS	NS	NS
P quadratic	NS	NS	NS	NS	NS	NS
– No K vs. K (7 vs. 3)	0.06	NS	NS	0.05	NS	NS
– NPK linear (1 vs. 3 vs.8)	NS	NS	0.08	NS	<0.01	0.08
NPK quadratic	NS	NS	NS	NS	0.01	NS
			With 2.5 g $CaCO_3$ kg^{-1}			
1. $N_0P_0K_0$	7.4	120	7.7	1883	19.5	165
2. $N_0P_{40}K_{80}$	6.0	195	6.6	1856	19.8	271
3. $N_{80}P_{40}K_{80}$	2.7	209	4.2	1845	14.6	207
4. $N_{160}P_{40}K_{80}$	3.1	163	2.3	1822	12.1	183
5. $N_{80}P_0K_{80}$	2.8	152	5.3	1869	17.6	144
6. $N_{80}P_{80}K_{80}$	1.4	220	3.4	1913	15.6	94
7. $N_{80}P_{40}K_0$	3.3	145	2.1	1948	13.3	252
8. $N_{160}P_{80}K_{160}$	1.3	245	5.6	1889	15.5	177
Contrast						
– N linear (2 vs. 3 vs. 4)	NS	NS	NS	NS	0.01	NS
N quadratic	NS	NS	NS	NS	NS	NS
– P linear (5 vs. 3 vs. 6)	NS	NS	NS	NS	0.06	NS
P quadratic	NS	NS	NS	NS	NS	NS
– No K vs. K (7 vs. 3)	NS	NS	NS	NS	NS	NS
– NPK linear (1 vs. 3 vs.8)	0.07	0.03	NS	NS	NS	NS
NPK quadratic	NS	NS	NS	NS	NS	NS
No lime vs. lime	<0.01	0.01	<0.01	<0.01	<0.01	<0.01

[x] NS: not significant.

Effect of long-term nitrogen application

The nutrient supply rate as measured by ion exchange membrane provides an indication of the potential nutrient supply to a plant root surface. N application and cassava cultivation for nine years tended to decrease the supply rates of K, Mg and S with increasing N under both limed and unlimed conditions, showing statistically significant decrease in Mg and S (Table 3). The reductions in the supply rates of these nutrients with added N indicate that long-term application of N without adequate supply of these elements in cassava production resulted in the depletion of their availability. N (NH_4 + NO_3) supply rate was lowest at the highest N rate (160 kg N ha^{-1}) among N fertilization plots with 40 kg P_2O_5 ha^{-1} and 80 kg K_2O ha^{-1}. Unfortunately, soil P supply rates could not be determined because P concentration in the eluent solution from the membranes was below the detection limit of the automated colorimetry. In a tropical soil such as the present experimental soil with low pH (4.4 to 4.5), the content of soluble P forms is very low compared to temperate soils such as those studied by Qian and Scjoenau (2000). Moreover, high soil positive charge due to low soil pH may restrict the P anion from moving in the soil by diffusion. Further method development is required in order to use the resin membranes effectively in high P fixing and low P content soils such as these. The availability of P, K, and Mg in

Table 4. Effects of long-term fertilization for cassava and liming on corn growth, nutrient tissue concentration and uptake.

Treatment	Shoot dry wt (mg pot^{-1})	Nutrient concentration g kg^{-1}					Total nutrient uptake mg pot^{-1}				
		N	P	K	Ca	Mg	N	P	K	Ca	Mg
					Without lime addition						
1. $N_0P_0K_0$	510	25	1.0	10.9	6.4	3.0	12.6	0.47	6.2	3.2	1.46
2. $N_0P_{40}K_{80}$	498	25	0.9	10.7	5.8	2.3	12.6	0.45	5.3	3.0	1.19
3. $N_{80}P_{40}K_{80}$	471	30	1.0	9.9	6.0	2.2	14.6	0.47	4.8	2.8	1.05
4. $N_{160}P_{40}K_{80}$	415	26	1.1	6.0	7.2	2.4	10.5	0.45	2.5	2.9	0.97
5. $N_{80}P_0K_{80}$	492	26	1.1	11.4	5.0	2.1	12.6	0.51	5.6	2.6	1.04
6. $N_{80}P_{80}K_{80}$	467	26	1.1	7.8	8.7	3.3	12.3	0.49	3.7	4.1	1.52
7. $N_{80}P_{40}K_0$	359	29	1.3	5.9	6.7	2.6	10.2	0.46	2.1	2.4	0.92
8. $N_{160}P_{80}K_{160}$	480	26	0.9	14.5	6.0	1.9	12.6	0.42	7.3	2.8	0.88
Contrast:											
– N linear (2 vs. 3 vs. 4)	NS[x]	NS	0.08	NS	NS	NS	NS	NS	NS	NS	NS
N quadratic	NS	0.07	NS	NS	NS	NS	0.08	NS	NS	NS	NS
– P linear (5 vs. 3 vs. 6)	NS	NS	NS	0.08	NS	NS	NS	NS	NS	NS	NS
P quadratic	NS	0.08	NS	NS	NS	NS	0.08	NS	NS	NS	NS
– No K vs. K (7 vs. 3)	NS	NS	0.02	NS	NS	NS	0.03	NS	NS	NS	NS
– NPK linear (1 vs. 3 vs.8)	NS	NS	NS	NS	NS	0.10	NS	NS	NS	NS	0.08
NPK quadratic	NS	0.09	NS	NS	NS	NS	NS	NS	NS	NS	NS
					With 2.5 g $CaCO_3$ kg^{-1}						
	469	33	1.3	9.2	15.8	3.4	14.9	0.56	4.7	7.2	1.53
1. $N_0P_0K_0$	448	34	1.1	10.7	14.1	3.2	14.7	0.46	5.1	6.1	1.42
2. $N_0P_{40}K_{80}$	538	34	1.1	9.5	15.7	2.4	18.0	0.57	5.3	8.3	1.29
3. $N_{80}P_{40}K_{80}$	413	34	1.1	6.5	17.7	2.5	14.0	0.45	2.7	7.2	1.03
4. $N_{160}P_{40}K_{80}$	453	25	0.8	7.9	11.0	2.1	10.7	0.33	3.6	4.7	0.92
5. $N_{80}P_0K_{80}$	453	35	1.4	6.6	19.7	3.2	15.9	0.61	3.1	8.8	1.39
6. $N_{80}P_{80}K_{80}$	416	36	1.4	6.1	18.0	2.8	15.0	0.59	2.6	7.5	1.15
7. $N_{80}P_{40}K_0$	609	29	0.9	13.9	14.0	2.5	17.6	0.53	8.5	8.5	1.49
8. $N_{160}P_{80}K_{160}$											
Contrast	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
– N linear (2 vs. 3 vs. 4)	0.07	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
N quadratic	NS	NS	0.08	0.01	0.06	0.06	NS	NS	NS	0.07	0.05
– P linear (5 vs. 3 vs. 6)	0.08	NS	NS	NS	NS	NS	0.02	NS	NS	0.05	NS
P quadratic	0.08	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
– No K vs. K (7 vs. 3)	0.05	NS	NS	NS	NS	NS	NS	NS	0.04	NS	NS
– NPK linear (1 vs. 3 vs.8)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
NPK quadratic											
– No lime vs. lime	NS	< 0.01	NS	NS	NS	NS	<0.01	<0.01	NS	<0.01	NS

[x] NS: not significant.

the soil of long-term N fertilization was reported to decrease by Darusman *et al.* (1991) and McAndrew and Malhi (1992).

Corn and canola were grown with the soils subjected to different fertilization for cassava production over the nine-year period and not applied with fertilizers. N uptake by corn tended to increase in the soil with N fertilizer application of 80 kg N ha^{-1} compared to the control, but the increase was significant only in unlimed condition (Table 4). N uptake was not different between the highest rate (160 kg N ha^{-1}) and the control. An increase in N uptake at 80 kg N ha^{-1} but no increase at the highest rate (160 kg N ha^{-1}) suggests that there was accumulation of residual N over nine years of application but at the highest rate an imbalance of nutrients may be responsible for the depressed N uptake. It should be noted that, in the experiment, corn was harvested on three weeks after planting. At two weeks after planting, severe K deficiency symptoms were observed in corn leaves in all treatments. For this reason soil nutrient availability effects associated with long-term N additions cannot be precisely assessed by corn growth and nutrient uptake due to the severe K limitation. The severe K deficiency noted in the

Table 5. Effects of long-term fertilization for cassava and liming on canola growth, tissue nutrient concentration and total nutrient uptake.

Treatment	shoot dry wt (mg pot^{-1})	Tissue nutrient concentration g kg^{-1}					Total nutrient uptake mg pot^{-1}				
		N	P	K	Ca	Mg	N	P	K	Ca	Mg
						Without lime addition					
1. $N_0P_0K_0$	181	27	0.8	9.0	19	4.7	3.9	0.14	1.8	3.3	0.82
2. $N_0P_{40}K_{80}$	83	33	0.7	10.4	20	4.9	2.8	0.06	0.9	1.7	0.41
3. $N_{80}P_{40}K_{80}$	232	39	0.8	12.1	21	4.9	10.0	0.17	2.5	4.8	1.13
4. $N_{160}P_{40}K_{80}$	138	28	0.6	8.4	17	4.1	3.9	0.09	1.2	2.3	0.60
5. $N_{80}P_0K_{80}$	126	33	0.7	9.2	16	4.7	3.9	0.10	1.3	1.9	0.58
6. $N_{80}P_{80}K_{80}$	279	22	1.0	12.1	17	4.2	4.3	0.31	2.8	4.8	1.04
7. $N_{80}P_{40}K_0$	94	36	0.7	8.3	19	5.0	3.4	0.07	0.9	1.8	0.53
8. $N_{160}P_{80}K_{160}$	218	28	1.0	14.1	16	4.3	6.4	0.20	3.2	3.5	0.91
Contrast:											
– N linear (2 vs. 3 vs. 4)	NS^x	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
N quadratic	0.10	NS	NS	NS	NS	NS	<0.01	NS	0.08	0.04	0.03
– P linear (5 vs. 3 vs. 6)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
P quadratic	NS	NS	NS	0.09	0.02	NS	0.01	NS	NS	0.05	0.06
– No K vs. K (7 vs. 3)	0.03	NS	NS	0.09	NS	NS	0.02	NS	0.10	0.05	0.07
– NPK linear (1 vs. 3 vs.8)	NS	NS	NS	0.03	NS	NS	NS	NS	NS	NS	NS
NPK quadratic	NS	0.08	NS	NS	0.05	NS	0.04	NS	NS	NS	NS
						With addition of 2.5 g $CaCO_3$ kg^{-1}					
1. $N_0P_0K_0$	195	35	0.7	8.7	35	2.7	6.6	0.14	1.6	6.8	0.52
2. $N_0P_{40}K_{80}$	650	17	1.0	10.6	24	1.9	10.8	0.64	6.9	15.4	1.26
3. $N_{80}P_{40}K_{80}$	592	23	1.0	9.9	27	2.1	13.3	0.62	5.8	16.3	1.25
4. $N_{160}P_{40}K_{80}$	528	24	0.8	7.1	31	2.0	11.6	0.35	3.8	16.3	1.00
5. $N_{80}P_0K_{80}$	344	35	0.8	10.8	32	2.7	10.4	0.27	3.7	10.5	0.90
6. $N_{80}P_{80}K_{80}$	613	20	1.3	7.5	29	1.9	11.3	0.81	4.7	17.0	1.17
7. $N_{80}P_{40}K_0$	451	20	0.9	6.2	30	2.2	8.8	0.40	2.8	13.3	0.98
8. $N_{160}P_{80}K_{160}$	619	18	1.1	11.6	24	1.7	11.2	0.65	7.3	14.5	1.07
Contrast											
– N linear (2 vs. 3 vs. 4)	NS	NS	NS	0.05	0.01	NS	NS	0.10	0.02	NS	NS
N quadratic	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
– P linear (5 vs. 3 vs. 6)	0.05	0.03	NS	0.04	NS	0.01	NS	NS	NS	0.01	NS
P quadratic	0.05	NS	<0.01	NS	0.05	NS	NS	0.02	0.06	NS	0.06
– No K vs. K (7 vs. 3)	NS	NS	NS	0.04	NS	NS	0.04	0.09	0.02	NS	NS
– NPK linear (1 vs. 3 vs.8)	<0.01	<0.01	<0.01	0.09	<0.01	<0.01	0.03	<0.01	<0.01	<0.01	0.01
NPK quadratic	0.02	NS	0.08	NS	NS	NS	0.02	0.04	NS	<0.01	0.01
No lime vs. lime	<0.01	<0.01	<0.01	0.07	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01

^{x}NS: not significant.

corn was corroborated by very low tissue K concentration that reflects an inability of corn to access soil K. On the other hand, canola with a finer root system showed a better ability to access K from the soil and was a better crop for testing soil nutrient capacity.

Without lime, canola (Table 5) showed significant increases in growth and N, K, Ca and Mg uptake at the 80 kg N ha^{-1} rate compared to the control. It is suggested that 80 kg N ha^{-1} in combination with 40 kg P_2O_5 ha^{-1} and 80 kg K_2O ha^{-1} added yearly for nine years for cassava production improved soil fertility and soil nutrient balance for growth of subsequent crops. Similar to corn, canola growth and nutrient uptake was lower in the highest N rate (160 kg N ha^{-1}) than in the 80 kg N ha^{-1} rate. With lime addition the decreases in canola P and K uptake and tissue K concentration with increasing N rates suggest that long-term applications of N also depleted soil P and K availability.

Effects of long-term phosphorus fertilization

Long-term P applications significantly increased N concentration and uptake by corn (Table 4) up to 40 kg P_2O_5 ha^{-}

^{1} and reduced tissue K concentration and soil K supply rates (Table 3) under unlimed conditions. However, with the addition of lime, corn yield and most nutrient concentrations and uptake linearly or quadratically responded to increasing P rates (Table 4). It suggests that long-term P applications in a form of superphosphate improved soil nutrient status in terms of supplying soil P, Ca, S and Mg.

Without the addition of lime, canola N, Ca, Mg uptake significantly increased up to the rate of 40 kg P_2O_5 ha^{-1} but canola P uptake did not (Table 5). An increase in canola and Mg uptake with an increasing P rates may result from the additions of Ca and some Mg in the single superphosphate fertilizer while increase in N uptake may be related to higher soil N mineralization at higher soil pH due to long-term P application. The lack of a significant increase in canola P uptake may indicate that canola had a very limited ability to access residual P after long-term P applications under soil conditions of high soil acidity and low availability of other nutrients.

With the addition of lime, long-term P addition significantly increased canola growth and total P, K, Ca and Mg uptake (Table 5). The decreases in canola tissue N, P, and Mg concentration with increasing canola growth due to P application suggest that these soils were very limited in their ability to supply N, K and Mg for plant growth.

The lack of significant effects of P application on corn and canola P uptake when lime was not added suggests that residual P from long-term P fertilization is quite insoluble and of low accessibility by plants in these acidic soils. The significant increases in corn and canola P uptake with the addition of lime compared to a insignificant differences when lime was not added are consistent with increasing soil P availability when amended with lime. Soil K and Mg supply rates decreased and Ca supply rates increased with lime addition due to competitive effects among cations.

Effects of long-term potassium fertilization

Both corn and canola dry matter yield significantly increased with added K under unlimed conditions (Tables 4 and 5), Moreover, canola N, K, Ca, and Mg uptake was significantly higher at the 80 kg K_2O ha^{-1} treatment than the control treatment (Table 5). K addition increased soil K supply rates to 12.7 μg cm^{-2} week^{-1} compared to 8.5 μg cm^{-2} week^{-1} in the control treatment (Table 3). It is suggested that long-term K applications at 80 kg K_2O ha^{-1} have a residual influence on increasing soil K fertility over the control treatment.

Corn and canola dry matter yield did not significantly increase with K rates under limed conditions (Table 4 and 5). Additionally, canola N, P and K uptake significantly increased over the control at the high K rate (80 kg K_2O ha^{-1}) while corn nutrient uptake did not. Soil K supply rates were significantly higher in treatments with K than the control treatment (Table 5). Increase of soil exchangeable K with long-term K application has been reported by Lutz and Jones (1974), Robinson *et al.* (1990) and Cassman *et al.* (1992). Accumulation of soil K due to K application depends on soil properties such as soil pH, texture and cation exchange capacity (CEC) and climate conditions (Adams, 1984). Adams (1984) indicated that raising soil CEC by liming increased efficiency of K fertilizer and K accumulation in soil following K application.

Effects of long-term application of NPK combinations

Compared to the control without NPK application, K and Mg supply rates under unlimed condition, respectively, increased and decreased significantly in the soils subjected to long-term application of NPK (Table 3), while dry matter yield and nutrient uptake of corn and canola did not show any significant differences among different combinations of NPK except increases in Mg uptake of corn and N uptake of canola (Tables 4 and 5). It suggests that when lime was not added, corn and canola were not effective in showing nutrient availability differences. Under limed condition corn growth and K uptake significantly increased (Table 4). Similarly, canola yield and N, P, K, Ca, and Mg uptake increased with NPK rates up to the 80 kg N ha^{-1}, 40 kg P_2O_5 ha^{-1} and 80 kg K_2O ha^{-1} combination (Table 4). Significant differences were not shown in soil K and Mg supply rates among the combinations NPK. This might have resulted from the competition of the Ca added as lime with K and Mg.

Effects of lime on plant growth, nutrient uptake and soil nutrient supply rates

Liming acid soil did not have a significant effect on corn dry matter yield and plant nutrient composition except fora significant increase of plant N concentration. However, liming significantly increased N, P and Ca uptake by corn but did not significantly increase K and Mg uptake (Table 4). The lack of significant differences in K and Mg uptake by corn indicates that there was competition of the Ca added as lime with K and Mg. The competition between Ca and other cations such as NH_4-N, K, and Mg was indicated by nutrient supply rates (Table 3). Lime addition significantly increased canola growth and plant nutrient concentrations and uptake. Finally, liming significantly increased soil SO_4-S and Ca supply rates but reduced soil NH_4-N, NO_3-N, K and Mg supply rates, likely due to competitive ion effects in the case of cations. That is, the much lower value for cation supply rates in limed conditions compared to unlimed conditions may be caused by Ca out-competing other cations for the sites on the membrane in limed conditions.

These results indicate that corn growth is less sensitive to soil acidity than canola. Liming acid soil has been reported to increase corn growth and yield by Howeler (1991) and Fageria *et al.* (1995). The lack of significant effects of liming on corn dry matter yield might have resulted from the high limitation of other nutrients such as K and Mg in the soil. Canola, however, has a finer root system so it may be more effective in accessing soil K and Mg from the soil.

N concentration and uptake in both corn and canola increased significantly by liming. Liming soil to neutral pH increases mineralization to release inorganic N (Adams, 1984; Arnold *et al.*, 1994). Nitrification rate is optimum at pH 6.6 to 8.0 and becomes negligible below pH 5.0 (Adams, 1984). However, lime accelerates N losses through volatilization. The increases in plant N uptake by corn and canola might have resulted from higher N supplying capacity of the soil under neutral pH than acidic conditions. However, soil NH_4-N and NO_3-N supply rates as measured by ion exchange membranes decreased with liming. The reduction in soil NH_4-N supply rates may be due to cation competition between Ca^{++} and NH_4^+ and ammonia volatilization The decrease in soil NO_3-N supply rates may be explained by greater ammonia volatilization rates at pH values near or above neutrality.

A significant increase in plant P concentration and uptake was observed for both corn and canola in response to liming. It suggests that liming may increase soil P supplying capacity. Singh and Seatz (1961) and Soltanpour *et al.* (1974) agreed that if soil pH was low, liming soil to pH 6.0 to 6.5 increased the availability of subsequently added P fertilizer but liming under the same condition after the P fertilizer was added decreased P availability. In the current study, lime was added after nine years of P addition in the field without lime. However, Adams (1984) indicated that liming soil might increase soil P availability that did not come from soil mineral P but from decomposition of mineralizable organic matter. The increase in soil SO_4-S supply rates may be the same as for N and P, resulting from higher soil organic matter decomposition in neutral pH soil.

Liming did not increase corn K and Mg plant concentrations and uptake but did increase K and Mg concentrations and uptake by canola. Liming has been reported to decrease plant K and Mg concentration and uptake (Rogers, 1948; Pearson, 1958; Martin & Liebhardt, 1994; Fageria *et al.*, 1995). The increase in canola K and Mg uptake may be attributed to favorable soil conditions for canola growth and nutrient uptake following liming rather than its direct effects on soil K and Mg supplying capacity. Decreases in soil K and Mg supply rates measured by membranes were attributed to two reasons: (1) Ca-K or Ca-Mg competition; (2) reduction in solution K and Mg following liming. The reduced K and Mg in soil solution following liming acid soils was reported by Pearson (1958) and Sumner *et al.* (1978).

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