Effects of Nitrogen Fertilizer Use on Soil Characteristics and Productivity

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Introduction

Nitrogen fertilizers have been used extensively to increase crop yields for more than 50 years. One of the consequences of adding ammonium forms of nitrogen to soils is the acidity generated through the nitrification reaction when ammonium ions are converted to nitrate by soil microorganisms. Traditionally, acidity generated by nitrification of ammonium and other soil reactions is neutralized by addition of aglime. The beneficial effects of liming include increasing soil pH, improving yields, reducing toxicity of aluminum, manganese and other metals, and adding calcium and magnesium to the soil.

Recent work by Barak et al. (1997) shows that another consequence of the acidity generated by long-term N use is a decrease in the soil cation exchange capacity (CEC). Barak et al. (1997) found that a decrease in soil CEC was directly related to the increase in soil acidity due to long term nitrogen use. Soil CEC is a key characteristic related to soil productivity since it is a measure of the soil's ability to hold cationic nutrients in a plant-available form. Therefore, a permanent decline in CEC could lead to an eventual decrease in soil productivity.

To study the effects of long-term nitrogen use on soil characteristics and soil productivity, we obtained soil samples from four long-term experiments with a history of N fertilizer use. The age of the experimental sites ranged from 30 to 123 years. The sites are the Morrow Plots in Illinois, Sanborn Field in Missouri, and experiments at the Lancaster and Arlington research stations in Wisconsin.

The objectives of this study were to determine the effects of long-term N use on soil acidity and CEC, to evaluate the effect of liming on CEC changes, and to evaluate N use effects on soil productivity.

Materials and Methods

The treatments sampled in each of the long-term experiments are described in Table 1, and a summary of each of the long-term experiments is provided below.

Long-term Experiment Histories-

Morrow Plots - The Morrow Plots located at Urbana, Illinois on the University of Illinois campus (40° 06' north latitude, 88° 13' west longitude) are the oldest (established in 1876) agronomic research plots in the United States (Aref and Wander, 1998; Mitchell et al., 1991). The soil at the Morrow Plots is a Flanagan silt loam, a fine mesic Aquic Argiudoll (Fehrenbacher et al., 1984). The soils from Morrow Plots (Table 1) used in

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this experiment included three crop rotations were (1) continuous corn, (2) corn-oats-alfalfa, (3) and corn-soybean. Each cropping history had an N rate of either 0 (not limed) lb N/acre or 200 lb N/acre (limed) applied as urea to corn (Odell et al., 1984).

Sanborn Field - Sanborn Field (established in 1876) located at the University of Missouri-Columbia (38°57' north latitude, 93°20' west longitude) is the second oldest permanent research plot in the United States (Mitchell et al., 1991). Sanborn Field is composed of two soils: Mexico silt loam, a fine montmorillonitic, mesic Typic Ochraqualfs; and Lindley loam, a fine-loamy, mixed, mesic Typic Hapludalfs (Buyanovsky, 1997). Three soil samples (Table 1) were obtained from this experiment (1) corn-soybean-wheat/red clover, N rate 208 lb N/acre, limed, (2) continuous corn, N rate 0 lb N/acre, not limed and (3) continuous corn, N rate 208 lb N/acre, limed.

Lancaster- In 1967, a crop rotation experiment was established at the University of Wisconsin Lancaster Agricultural Research Station (45°51' north longitude, 90° 42' west latitude). The soil at Lancaster is Rosetta silt loam, a fine-silty, mixed mesic, Typic Hapludalfs and is typical of the soils of the unglaciated region of Southwestern Wisconsin. The experiment was initiated to study crop rotation effects on yields, N contributions from legume crops, and N responses of corn in rotation compared with N fertilized continuous corn (Baldock et al., 1981; Higgs et al., 1990; Vanotti et al., 1997). The entire experiment has been limed periodically to maintain optimum soil pH values for the crop rotations. The soils used from the Lancaster experiment (Table 1) were obtained from the continuous corn rotation treatment at the 0 and 200 lb N/acre rates and from the corn-corn-oat-alfalfa-alfalfa rotation at the 0 and 200 lb N/acre rates.

Arlington - A continuous corn experiment with three long-term N fertilizer rates was initiated at the University of Wisconsin Agriculture Research Station at Arlington in 1958. Nitrogen was applied as anhydrous ammonia from 1963-1984 and from 1993-1998. During 1984-1992, each long-term N treatment received N rates of 0, 75, 150 and 225 lb N/ acre as urea to study the residual effects of the original treatments (Motavalli et al., 1992). In 1993, long-term N treatments of 0, 125, and 250 lb N/acre as anhydrous ammonia were resumed on the original plots. In 1985, one half of each long-term N plot was limed to raise the pH to 6.5 to 7.0. An additional lime application consisting of 4.5 tons/acre of 80-89 lime was made in 1988 (Vanotti et al., 1997). Treatments sampled for cation exchange capacity determinations included the three long-term N rates in limed and unlimed plots resulting in total of six treatments (Table 1). Samples were taken from each of the four field replications of each treatment.

Method for Cation Exchange Capacity

Soil samples from four long-term N rate experiments (Table 1) were analyzed in triplicate for CEC. In June 1999, eight cores of soil from each of the designated plots were taken from Lancaster and Arlington. The soils were sampled to a depth of 8 inches. The samples from Morrow and Sanborn were taken to a depth of 8 inches in 1997 (Van Schaik, 1998). All the samples were dried (32° C), ground to pass a 2-mm screen, and a subsample was finely ground with a mortar and pestle before CEC analysis. Cation exchange capacity (CEC) was determined using the method described by Avila-Segura (1999). In this procedure, 100 mg of soil was weighed into 1.5-mL microcentrifuge tubes, 0.5 mL of deionized H_2O was added, and the samples were shaken for 1h. After shaking, 0.5 mL of 200mM $BaCl_2$ was added and the solution was shaken for 10 additional minutes. Next the test tubes were centrifuged for 10 minutes at 5600 x g. The supernatant was diluted with deionized water to 10 ml. The diluted supernatant samples were analyzed by inductively coupled plasma-atomic emission spectroscopy (ICP-AES) for Ca, Mg, Na, K, Mn and Al. The cation exchange capacity of each soil sample was calculated from the sum of the cations (Ca, Mg, Na, K, Mn, Al) expressed in cmol (+)/ kg of soil.

Method for pH

Soil pH values in each sample were measured in H_2O and $CaCl_2$ using methods described by Thomas (1996). Measurements were made with an Orion Research MicroProcessor pH/millivolt meter model 811 equipped with a glass AgCl electrode.

Method for Organic C and N

Total C and N concentrations in soil samples (Table 2) were determined by using dry combustion technique with a Carlo Erba Mode NA 1500 C and N analyzer.

Results and Discussion

Nitrogen and lime treatment effects in long-term experiments

The effects of long-term nitrogen rates, and other crop and soil management practices on soil pH and cation exchange capacity are shown in Table 3 for the four long-term N use experiments included in this study. In general, soil pH values follow the expected trend toward greater acidity where fertilizer N was applied for many years without lime addition. Where lime was added periodically during the study, pH values in long-term N fertilizer treatments were usually similar to those where no fertilizer N was applied. This confirms the effectiveness of liming as an agricultural practice for maintaining soil pH values in the optimum range.

Arlington Experiment - The long-term continuous corn experiment at Arlington provides an opportunity to study the effects of both long-term N and lime treatments on pH and CEC (Table 3). Where no lime was added, CEC values decreased substantially with increasing long-term N rate, consistent with the findings of Barak et al. (1997). However, with lime, CEC increased at all N rates including the control or no N treatment. In the limed treatments, CEC was higher at the highest N rate than in the control treatment that received no fertilizer N. Part of the increase in CEC at the high long-term N rate could be the higher organic matter content of this treatment relative to the control (Table 2). However, this does not explain the low CEC in the unlimed, high N rate treatment.

An analysis of variance using the field plot design for the experiment (SAS Institute, Inc., 1992) was performed to test for significant treatment effects (Table 4). Water pH was significantly affected by N rate and lime, while pH in $CaCl_2$ was affected only by lime treatment. Cation exchange capacity was not significantly influenced by N treatment, but was affected by lime additions. Exchangeable Ca, Mg, and Mn were affected by the lime treatment. Increases in Ca and Mg are due to addition of these elements in dolomitic lime, while the increase in pH associated with liming reduces exchangeable Mn in the soil. Significant N x lime treatment interactions were detected for pH in H_2O, CEC and exchangeable Ca. In the absence of lime, pH in H_2O decreased with increasing long-term N rate while the corresponding pH values remained relatively stable as N rate increased in the with lime treatment (Fig. 1). Where lime was added, CEC was not affected by long-term N rate although actual CEC values increased from 19.2 to 21.4 cmol(+)/kg of soil as N rate increased from 0 to 250 lb N/acre (Fig. 2). Without lime, CEC decreased significantly with N rate. Changes in exchangeable calcium levels in limed and unlimed treatments are consistent with the addition of calcium in the lime applications.

Lancaster Rotation Experiment - Cation exchange capacity values in the Lancaster experiment follow the pattern identified by Barak et al. (1997) in that CEC values were lower where long-term fertilizer N treatments were applied compared to plots that received no fertilizer N. This was particularly evident in the continuous corn rotation, possibly due to the more frequent N applications relative to the CCOMM rotation which received fertilizer N only when corn was grown (two years in five). The apparent CEC differences at Lancaster occurred even though lime was applied at a uniform rate to all treatments in the experiment.

An analysis of variance based on the design of the field experiment (SAS Institute, Inc., 1992) was applied to data obtained with soils from the Lancaster rotation experiment (data not shown). These results showed no statistically significant effect of either N rate or rotation on pH, CEC, or exchangeable cations. The absence of significant treatment effects may be due to the uniform application of lime across all treatments and the presence of only two field replications in the experimental design which reduces the discriminating power of the statistical test.

Sanborn Field Experiment - Results with soil samples from this experiment are not in complete agreement with those from Arlington and Lancaster (Table 3). While CEC decreases in plots with a long-term history of N use relative to the control plots, the influence of lime on pH and CEC is difficult to interpret. Specifically, soil pH in the high N continuous corn treatment is very low and similar to the unlimed treatment without N. Rotation compared to continuous corn had little influence on CEC.

Morrow Plots Experiment - Soils from the Morrow Plots include three rotations, two N rates and a lime treatment (Table 3). Unfortunately, the limed plots also received the high rate of fertilizer N when corn was grown, while the no N plots did not receive lime. Thus, the relative influences of N additions and lime on CEC cannot be conclusively determined. Generally, limed treatments had higher soil pH values. It is apparent that the N fertilized treatments that also received lime have higher CEC values than the unlimed no N treatments. This is similar to the findings in the Arlington experiment. As shown in Table 2, the N fertilized, limed continuous corn treatment had a higher organic matter content than the control treatment, likely due to the return of higher amounts of relatively N rich crop residues for many years. The higher organic matter content could contribute to the higher CEC values found in the limed, N fertilized treatments. A trend toward higher CEC values in rotations compared to continuous corn is apparent in the N fertilized, limed treatments. This is in contrast to the absence of a crop rotation influence on CEC in the Lancaster experiment, but the Morrow plot crop rotations have been in place for much longer than at Lancaster.

Long-term N use effects on soil productivity

The initial work by Barak et al. (1997) suggested that the loss of CEC from long-term N use could be, at least partially, irreversible. This could lead to permanent loss of CEC over time, and eventually would reduce soil productivity. In this study, we examined crop yields and yield trends in several long-term experiments with a history of N fertilization for indications of productivity loss due to long-term N fertilization. Recent corn yields in the Morrow, Sanborn, and Lancaster experiments are shown in Table 5. In all cases, N fertilization increased yields relative to the unfertilized treatments, reflecting the expected corn response to N. Any decrease in productivity due to long-term N use is masked by a substantial crop response to N fertilization in these studies. Except for the Lancaster experiment, lime additions are also a variable in these experiments that would tend to enhance the beneficial response to N fertilization. The effect of crop rotation in maintaining soil productivity is apparent in the data from the Morrow and Lancaster experiments. In both studies, yields in the absence of N fertilization are much higher in the rotations than in continuous corn. This observation also applies to the N fertilized treatments, with the exception of the C-O-M rotation in the Morrow Plots.

The effects of long-term N fertilization on continuous corn yields in the Arlington experiment during several time periods from the start of the experiment to the present are shown in Table 6. These results indicate that yields have remained relatively constant in the absence of N fertilization, but they have increased substantially over time in those treatments where N fertilizers have been applied annually since 1958. Much of this yield increase can probably be attributed to improvements in corn hybrid yield potential and corn production practices since the beginning of the experiment. These yields do not indicate any reduction in soil productivity due to long-term N fertilization. Considered with data in Table 3 showing significant CEC reductions in long-term N treatments without lime, the absence of yield limitations in these treatments suggests that the reduced CEC levels are not yield limiting.

An analysis of variance showing the influence of long-term N rates and lime on corn yields in individual years since 1984 in the Arlington experiment are shown in Table 7. Yields were significantly increased by N fertilization each year, and lime increased yields in most years. Interestingly, the N x lime treatment interaction was not significant in most years indicating that the N and lime effects are usually independent influences on yield. The effects of N and lime treatments on yields for individual years since 1958 are shown in Table 8. It is interesting to note that the highest yields in the 41-year history of the experiment were obtained in the most recent year (1998).

Conclusions

- Long-term N fertilizer use increases soil acidity and reduces CEC.
- In soils with a long-term history of N fertilization, lime additions maintain or increase CEC relative to no N control treatments.
- Crop yield results from several long-term N use experiments show no evidence soil productivity loss due to long-term N use.
- Yield trends in a long-term continuous corn experiment show constant yields in the absence of N fertilization and a dramatic increase in yields over time with long-term N fertilization. Yield increases are likely due to improvements in hybrid genetics and management practices.

References

Aref, S., and M.M.Wander. 1998. Long-Term Trends of Corn Yield and Soil Organic Matter in Different Crop Sequences and Soil Fertility Treatments on the Morrow Plots. Advances in Agronomy 62: 153-197.

Avila-Segura, M. 1999. Techniques for Evaluating Changes in Chemical and Mineralogical Properties of Acidified Soils. M.S. Thesis, Dept. of Soil Science, University of Wisconsin-Madison.

Baldock, J.O., R.L. Higgs, W.H. Paulson, J.A. Jackobs, and W.D. Shrader. 1981. Legume and Mineral Effects on Crop Yields in Several Crop Sequences in the Upper Mississippi Valley. Journal of Production Agriculture 73: 885-890.

Barak, P., B.O. Jobe, A.R.Krueger, L.A. Peterson, and D.A. Laird. 1997. Effects of long-term soil acidification due to nitrogen fertilizer inputs in Wisconsin. Plant Soil 197:61-69.

Bundy, L.G., and Andraski, T.W. 1998. Maintenance of Long-Term Nitrogen Fertilizer Plots In Continuous Corn at Arlington, Wisconsin. Progress Rep. to Farmland Industries from Dept. Soil Science Univ. of Wisconsin-Madison.

Buyanovasky, G.A., J.R. Brown, and G.H.Wagner. 1997. Sanborn Field: Effect of 100 years of cropping on soil parameters influencing productivity. p. 205-226. *In* Paul, E.A., Paustian, K., Elliott, E.T., and Cole, C.V. (ed.) Soil Organic Matter in Temperate Agrosystems, Long-Term Experiments in North America. CRC, NewYork.

Fehrenbacher, J.B., Alexander, J.D., Jansen, I.J., Darmody, R.G., Pope, R.A., Flock, M.A., Scott, J.W., Andres, W.F., and Bushue, L.J. 1984. Soils of Illinois, Agric. Exp. Stn. Bull. 778, College of Agriculture, University of Illinois, Urbana.

Higgs, R. L., A. E. Peterson, and W.H. Paulson. 1990. Crop rotations sustainable and profitable. J. Soil and Water Cons. 45: 68-70.

Lorenz, T., and J.R. Brown. 1997. Sanborn Field 1996 Annual Report Dept. of Soil and Atmospheric Sciences Univ. of Missouri-Columbia

Mitchell, C.C., R.L. Westerman, J.R. Brown, and T.R. Peck. 1991. Overview of Long-Term Research. Agronomy Journal. 83:11-23.

Motavalli, P.P., L.G. Bundy, T.W. Andraski, and A.E. Peterson. 1992. Residual Effects of Long-Term Nitrogen Fertilization on Nitrogen Availability to Corn. Journal of Production Agriculture 5: 363-368.

Odell, R.T., W.M. Walker, L.V. Boone, and M.G. Oldham. 1984. The Morrow Plots- A Century of Learning, Agric. Exp. Stn. Bull. 775, College of Agriculture, University of Illinois, Urbana.
SAS Institute, Inc. 1992. SAS/STAT user's guide. Release 6.03/4th ed. SAS Inst., Cary, NC.
Thomas, G.W. 1996. Soil pH and Soil Acidity. p. 475-491. *In* Bigham, J.M. (ed. in chief) Methods of Soil Analysis Part 3 Chemical Methods. SSSA, Madison, WI.
Vanotti, M.B., L.G. Bundy, and A.E. Peterson. 1997. Nitrogen Fertilizer and Legume-Cereal Potation Effects on Soil Productivity and Organic Matter Dynamics in Wisconsin. p. 105-120. *In* Paul, E.A., Paustian, K., Elliott, E.T., and Cole, C.V. (ed.) Soil Organic Matter in Temperate Agrosystems, Long-Term experiments in North America. CRC, NewYork.
Van Schaik, C.C. 1998. Nitrogen Availability in Wisconsin Cropping Systems. M.S. Thesis, Dept. of Soil Science, University of Wisconsin-Madison.

Table 1. Location and management history of several long-term experiments.

Location	Crop Rotation	Corn N Rate	Lime
		lb/a	
Lancaster	Continuous corn	0	Yes
	Continuous corn	200	Yes
	C-C-O-M-M	0	Yes
	C-C-O-M-M	200	Yes
Arlington	Continuous Corn	0	No
	Continuous Corn	0	Yes
	Continuous Corn	125	No
	Continuous Corn	125	Yes
	Continuous Corn	250	No
	Continuous Corn	250	Yes
Sanborn	Continuous Corn	208	Yes
	Continuous Corn	0	No
	C-SB-WHT/RC	208	Yes
Morrow	Continuous Corn	200	Yes
	Continuous Corn	0	No
	C-SB	200	Yes
	C-SB	0	No
	C-O-M	200	Yes
	C-O-M	0	No

C = corn; SB =soybean; O =Oats; M = alfalfa; RC= red clover; WHT =wheat

Table 2. Total N, C, and C/N ratio in soils from several long-term continuous corn experiments.[1]

Site	N rate	Total Soil N	Total Soil C	C/N	Aglime
	lb/a	%	%		
Morrow Plots (1997)[2]	200	0.134	1.964	14.7	Yes
Morrow Plots (1997)	0	0.100	1.636	16.4	No
Sanborn Field (1997)	208	0.076	1.074	14.1	No
Sanborn Field (1997)	0	0.104	1.392	13.4	Yes
Lancaster (1996)	200	0.113	1.052	9.3	Yes
Lancaster (1996)	0	0.110	1.101	10.3	Yes
Arlington (1997)[3]	250	0.193	2.175	11.3	Yes
Arlington (1997)	250	0.198	2.129	10.8	No
Arlington (1997)	125	0.202	2.297	11.4	Yes
Arlington (1997)	125	0.187	2.058	11.0	No
Arlington (1997)	0	0.158	1.792	11.4	Yes
Arlington (1997)	0	0.160	1.818	11.4	No

[1] (Van Schaik, 1998; Bundy and Andraski, 1998).
[2] Year in parentheses indicates year of soil sample collection.
[3] Each sample had 12 replications were a homogenous subsample was ground to pass a 100-mesh sieve and total N and C analysis was performed.

Table 3. Location, management history, pH, and CEC in several long-term N use experiments.

Location	Crop Rotation[1]	Corn N Rate	Lime	CEC Mean	pH Mean	pH Mean
		lb/a		cmol(+)/kg	$CaCl_2$	H_2O
Lancaster	Continuous corn	0	Yes	14.15	6.50	6.44
	Continuous corn	200	Yes	12.54	6.08	6.14
	C-C-O-M-M	0	Yes	13.61	6.16	6.75
	C-C-O-M-M	200	Yes	13.43	5.52	5.95
Arlington	Continuous Corn	0	No	17.78	5.59	5.64
	Continuous Corn	0	Yes	19.18	6.14	6.50
	Continuous Corn	125	No	15.10	4.75	5.40
	Continuous Corn	125	Yes	19.37	5.83	6.17
	Continuous Corn	250	No	14.19	4.92	4.91
	Continuous Corn	250	Yes	21.45	5.99	6.28
Sanborn	Continuous Corn	208	Yes	15.27	4.59	5.10
	Continuous Corn	0	No	20.39	4.82	5.45
	C-SB-WHT/RC	208	Yes	15.29	6.72	7.37
Morrow	Continuous Corn	200	Yes	21.81	6.35	6.30
	Continuous Corn	0	No	17.39	6.36	5.73
	C-SB	200	Yes	22.15	5.86	6.31
	C-SB	0	No	18.19	5.68	5.90
	C-O-M	200	Yes	23.60	5.97	6.37
	C-O-M	0	No	17.46	5.34	5.87

[1] C = corn; SB =soybean; O =Oats; M = alfalfa; RC= red clover; WHT =wheat

Table 4. Analysis of variance summary for the effects of long-term nitrogen rates and lime on soil pH, cation exchange capacity and exchangeable cations in a long-term nitrogen rate experiment at Arlington, WI.

	pH			Exchangeable Cation					
Source	H_2O	$CaCl_2$	CEC	Ca	K	Mg	Na	Mn	Al
N rate (N)	**	NS	NS	NS	NS	NS	NS	*	NS
Lime (L)	***	***	***	***	NS	***	NS	***	*
N x L	***	NS	**	**	NS	*	NS	*	NS

***, **, * = Significant at 0.01, 0.05, 0.10 probability levels; NS = not significant

Table 5. Recent corn yield averages in several long-term experiments[1]

Experiment	Years	Year Started	Crop Rotations	Lime	N rate lbs/a	Yield bu/a
Morrow	1990-1996	1876	Continuous corn	Yes	0	47
Morrow	1990-1996	1876	Continuous corn	No	200	155
Morrow	1990-1996	1876	C-SB	Yes	0	87
Morrow	1990-1996	1876	C-SB	No	200	170
Morrow	1990-1996	1876	C-O-M	Yes	0	102
Morrow	1990-1996	1876	C-O-M	No	200	158
Sanborn	1987-1997	1888	Continuous corn	Yes	208	117
Sanborn	1987-1997	1888	Continuous corn	No	0	14
Sanborn	1987-1997	1888	C-SB-WHT/RC	Yes	208	116
Lancaster	1984-1995	1967	Continuous corn	Yes	0	44
Lancaster	1984-1995	1967	Continuous corn	Yes	200	138
Lancaster	1984-1995	1967	C-C[2]-O-M-M	Yes	0	116
Lancaster	1984-1995	1967	C-C-O-M-M	Yes	200	150

[1] (Lorenz and Brown, 1996; Swan et al., 1987-1997 Progress Report).
[2] Underline indicates the rotation phase where corn yield was measured

Table 6. Continuous corn yield averages for several time periods in the long-term N use experiment at Arlington (1958-1998)[1]

	Long Term N Rate		
Year	None	Medium	High
	Yield, bu/ac		
1958-1962	60	90	97
1968-1977	52	107	115
1978-1987	78	148	153
1988-1998	65	156	162

[1] (Peterson, 1980 personal communication; Motiavalli at al. 1992; Bundy and Andraski progress report 1992-1998). Values are means of limed and unlimed plots.

Table 7. Analysis of variance summary for the effects of long-term N rates and lime on corn grain yield, Arlington, WI, 1984-1998.[1]

	Variable		
Year	LTN[2]	Lime	LTN x Lime
1984	***	-	-
1985	***	NS	NS
1986	***	**	*
1987	***	NS	**
1988	***	*	NS
1989	***	NS	NS
1990	***	***	**
1991	***	***	NS
1992	***	***	NS
1993	***	**	NS
1994	***	***	NS
1995	***	NS	NS
1996	***	***	***
1997	***	***	NS
1998	***	*	NS

***,**,*= Significant at the 0.01, 0.05, and 0.10 probability levels, respectively. NS= Not significant

[1] (Bundy and Andraski, Progress report 1992-1998).

[2] LTN = Long term nitrogen rate.

Table 8. Continuous corn yields in the Arlington long-term N use experiment 1958-1998[1]

Year	Aglime	Long Term N Rate None	Medium	High
		---Yield, bu/ac---		
1958	No	41	65	68
1959	No	65	94	95
1960	No	69	104	110
1961	No	65	95	109
1962	No	58	94	103
No yield data collected from 1963-1967, but N rates continued through these years.				
1968	No	78	117	131
1969	No	49	126	128
1970	No	49	88	110
1971	No	43	129	141
1972	No	48	94	95
1973	No	95	141	140
1974	No	38	80	84
1975	No	64	118	128
1976	No	25	58	72
1977	No	30	114	120
1978	No	59	127	141
1979	No	73	120	130
1980	No	57	124	135
1981	No	121	143	134
1982	No	104	132	139
1983	No	33	135	126
1984	No	62	141	147
1985	Yes	89	161	155
1985	No	75	152	153
1986	Yes	99	203	194
1986	No	82	188	206
1987	Yes	86	141	165
1987	No	76	159	159
1988	Yes	73	90	92
1988	No	72	103	91
1989	Yes	86	141	148
1989	No	67	144	146
1990	Yes	55	169	171
1990	No	59	156	172
1991	Yes	70	169	183
1991	No	63	160	170
1992	Yes	51	167	176
1992	No	47	153	167
1993	Yes	49	125	155
1993	No	43	122	130
1994	Yes	81	191	187
1994	No	69	179	178
1995	Yes	73	154	166
1995	No	72	152	156
1996	Yes	63	163	159
1996	No	47	144	139
1997	Yes	70	167	178
1997	No	67	152	157
1998	Yes	91	230	223
1998	No	66	214	225

[1] (Peterson, 1980 personal communication; Motiavalli et al. 1992; Bundy and Andraski progress reports 1992-1998).

Figure 1. Interactive effects of fertilizer N rate and lime on soil water pH, in a long-term N rate experiment at Arlington, WI.

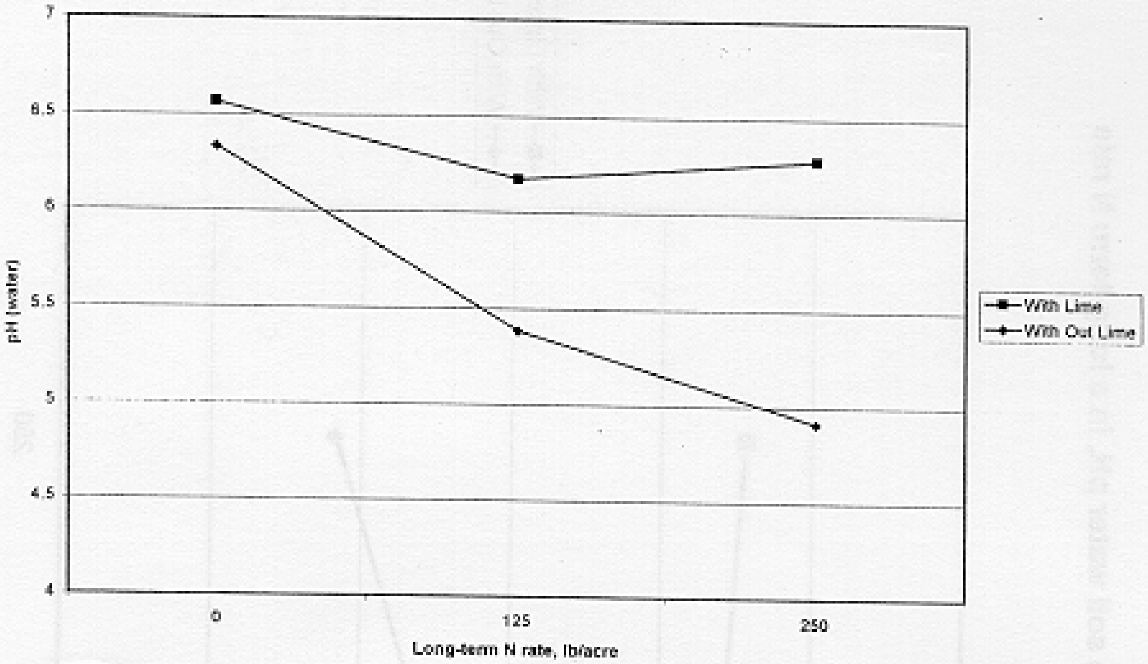

Figure 2. Interactive effects of fertilizer N rate and lime on cation exchange capacity, in a long-term N rate experiment at Arlington, WI.

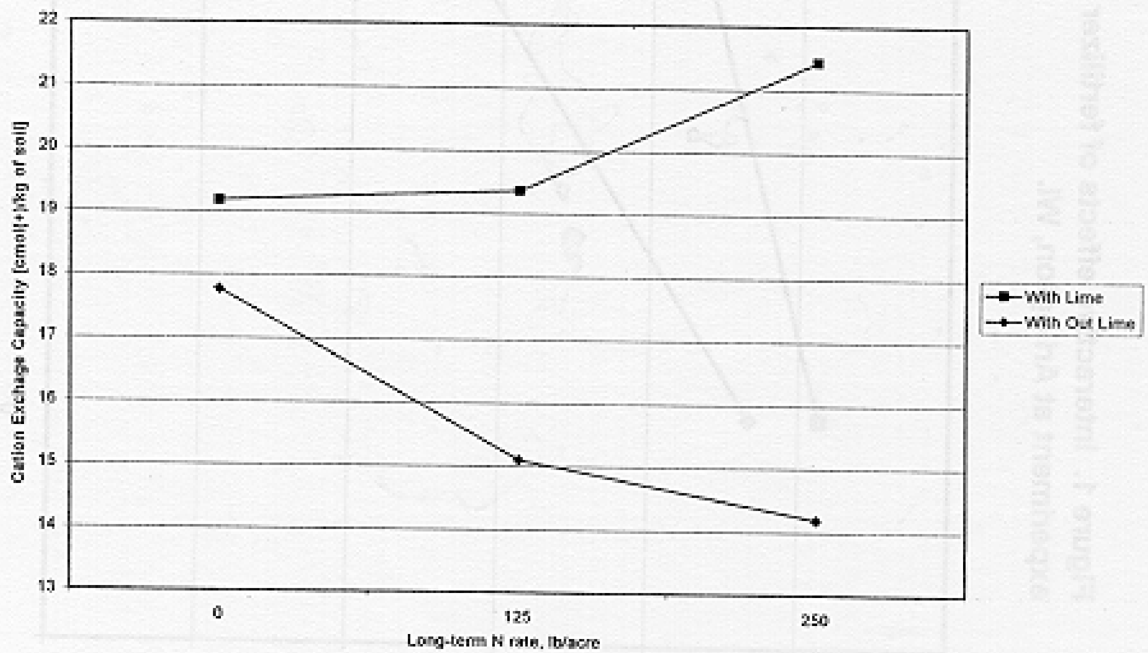

Figure 1. Interactive effects of fertilizer N rate and lime on soil water pH, in a long-term N rate experiment at Arlington, WI.

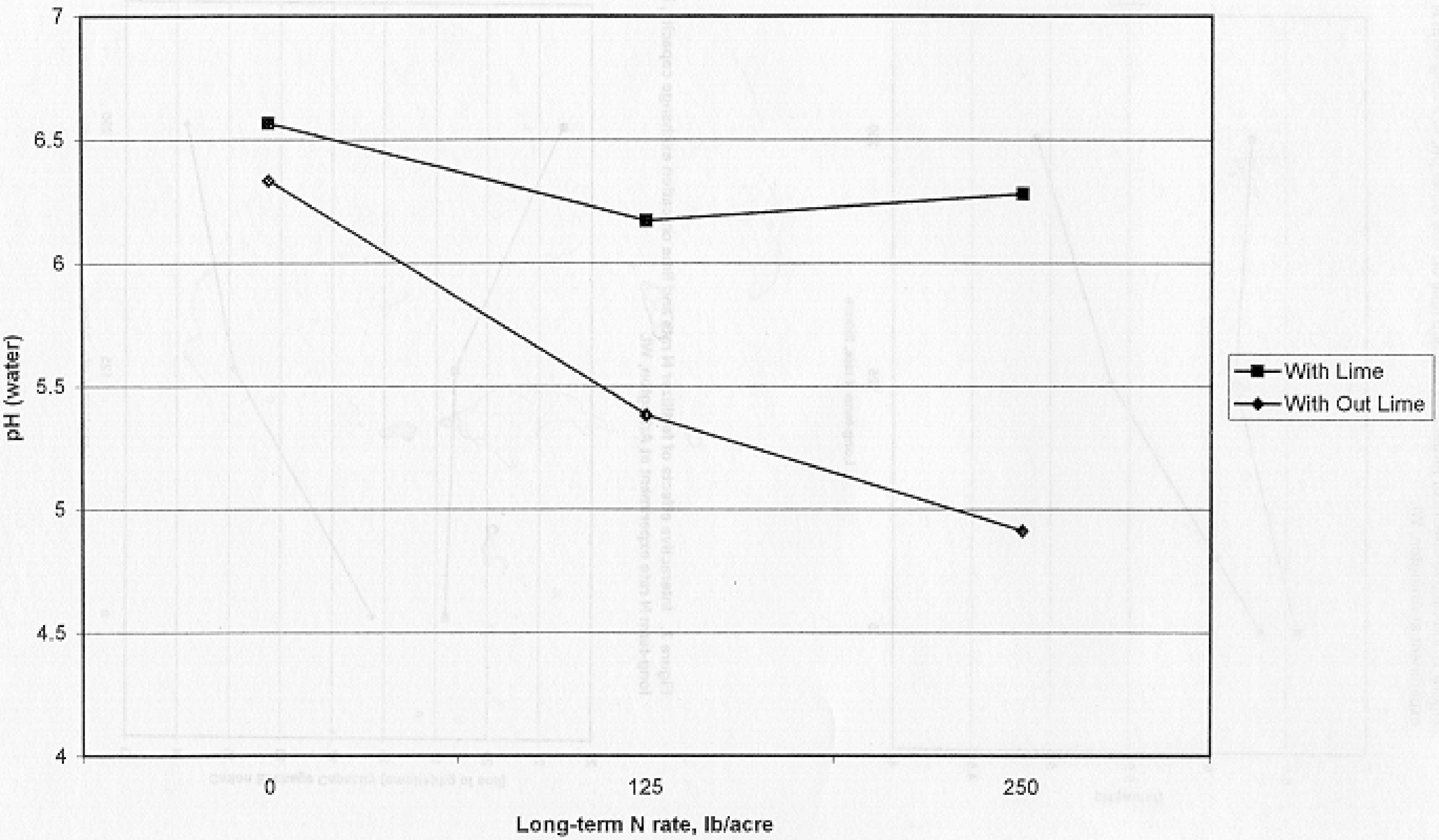

Figure 2. Interactive effects of fertilizer N rate and lime on cation exchange capacity, in a long-term N rate experiment at Arlington, WI.