

SOIL CHEMICAL CHANGES AFTER NINE YEARS OF DIFFERENTIAL N FERTILIZATION IN A NO-TILL DRYLAND WHEAT-CORN-FALLOW ROTATION

R. A. Bowman and A. D. Halvorson

Intensively cropped dryland systems in the central Great Plains require adequate N fertilization for optimum residue and grain production. However, this N fertilization could be slowly changing the chemistry of the surface soil because of a decrease in soil pH and an increase in soil organic matter (SOM) and basic cations, even in previously well buffered calcareous soil systems. We investigated the effects of five increasing ammonium-N fertilizer rates in a Platner loam, on physical and chemical changes at the 0 to 5, and 0 to 15-cm depths after three cycles of no-till wheat (*Triticum aestivum* L.)-corn (*Zea mays* L.)-fallow rotation. We measured soil pH, texture, bulk density, cation exchange capacity (CEC), total P, soluble and total soil organic carbon (SOC), nitrate-N to a depth of 60 cm, and grain yields. No significant changes were found with soil texture, bulk densities, CEC, and total P. The data showed a significant reduction in surface (0-5 cm) soil pH (6.5 to 5.1) with the highest N rate (112 kg/ha), but this was accompanied by a 40% increase in SOC. Although there were significant increases in Al and Mn and decreases in Ca concentrations in the surface 0 to 5 cm at the highest N rate, no reduction in grain yields occurred relative to lower N levels with near neutral pHs. Because only a shallow depth of the soil was affected, residue, SOM, and rapid root growth could be compensating for surface acidity. Over the longer term, we need to monitor the effects of ammoniacal-N on downward soil acidity and yield trends under these new intensive cropping systems. (Soil Science 1998; 163:241-247)

Key words: Acidity, pH, organic matter.

CULTIVATED soils of the central Great Plains generally exhibit pH values in the neutral to slightly alkaline range because of calcareous parent material at relatively shallow depths and the result of the lower amounts of precipitation these areas receive compared with the more leached acidic soils of the Pacific Northwest, Midwest, and Eastern States. Even though many of these Plains soils are classified as Mollisols, their fertility as measured by soil organic matter (SOM) levels and cation exchange capacity (CEC) is generally low because of soil degradation caused by the traditional clean-till winter wheat-summer fallow (W-F) system

(Campbell 1978). Generally, clean-till enhances SOM decomposition and increases nutrient and SOM losses from erosion (Bowman et al. 1990; Havlin et al. 1991). As the depth of the surface soil decreases as a result of erosion, conventional tillage mixes the surface soil with deeper soils of higher pH and lower SOM values, and this mixing tends to buffer surface soil pH against decreases.

Because of this built-in buffering with CaCO_3 , few farmers and researchers in the central Great Plains have worried about increasing acidity problems such as phosphorus (P) fixation, herbicide effectiveness, and aluminum (Al) toxicity and its attendant reduction in root biomass. However, certain current management practices may be reversing this trend. The shift to spring and summer crops with reduced- and no-till practices and increased use of ammoniacal (NH_4^+) fertilizers may

be changing the chemistry of the surface soil layer more quickly than previously thought relative to pH, cation exchange, and SOM. Under no-tillage conditions, lower soil horizons with higher pH are not mixed with the surface lower pH soils; thus, neutralization of acidity caused by ammonium- or urea-based fertilizer is minimal. Volatilization is also less than under conventional tillage (Mahler and Harder 1984). Given sufficient time, reduced- or no-till practice and the continuous use of ammoniacal (NH_4^+) fertilizers could lead to a significant drop in soil pH because of the production of acidity (hydrogen ions) as a result of the conversion of NH_4^+ to nitrate (NO_3^-) (Van Breemen et al. 1983). However, these management practices also engender a slow buildup of surface soil basic cations and SOM by reducing decompositional losses of SOM associated with summer fallow and by increasing plant biomass and the recycling of residues and nutrients to the soil.

Studies on tillage and different rotations are being conducted in the central Great Plains (Kitchen et al. 1990; Wood et al. 1991; Westfall et al. 1992; Halvorson and Reule 1994), but there is little information about pH decline in semiarid environments and about how this decline is affected by SOM and basic cations released from crop residues. Whereas known soil chemistry principles predict acidification, the level of cumulative fertilizers N of ammoniacal source and the maintenance N level at which improved fertility with basic cations buffers the negative effects of increasing hydrogen production require investigation with respect to both time and pH decrease with soil depth.

The objectives of this study, therefore, were (i) to quantify the changes in soil pH, soil CEC, and soil organic carbon (SOC) caused by the application of increasing $\text{NH}_4\text{-N}$ levels (0 to 672 kg/ha) after three cycles of no-till dryland wheat-corn-fallow and (ii) to quantify the effects of these chemical changes on biomass production and grain yields.

MATERIALS AND METHODS

The experiment was conducted in Washington County, Colorado. This area receives an average of 420 mm of precipitation per year, with about 80% occurring from April to September (200 mm in May, June, and July). Snowfall averages 750 mm per year, and the frost-free season is an average of 139 days, with average frost-free dates of May 11 to September 28. Site elevation is about 1400 m. Open pan evaporation, an index of potential evapotranspiration (PET) for the cropping season, is about 1000 mm.

The study was initiated in 1985 and consisted of a randomized complete block design comprising three rotation phases or blocks (wheat(W)-corn(C)-fallow(F), phase A; C-F-W, phase B; and F-W-C, phase C) and five nitrogen treatments (0, 28, 56, 84, and 112 kg N/ha) replicated four times within each rotation phase (Fig. 1). Thus, each phase of the rotation was present every year. However, because of confounding from erosion in the second rotation phase (high pH from lime at the 0 to 5-cm depth in some plots), only phases A and C were evaluated. These comprised 40 treatment plots (2 rotation phases, 5 N rates, 4 replicates). Plot size of N treatments was 9 m \times 12 m, and the

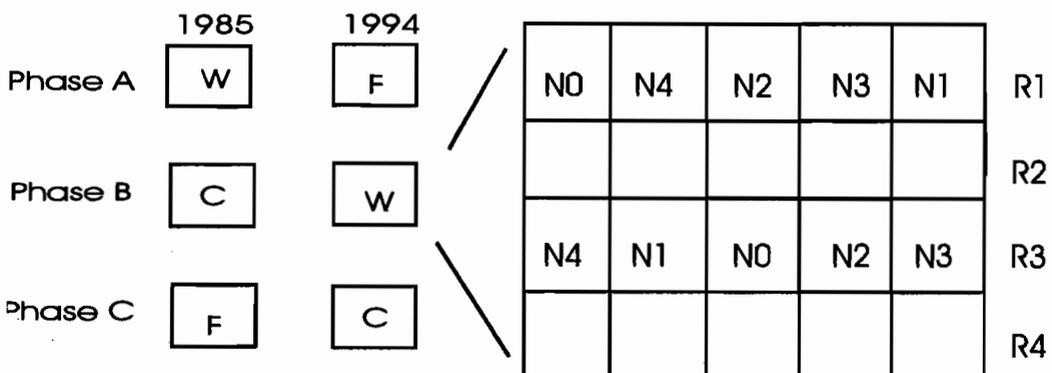


Fig. 1. Layout of field plots with three phases, 5 N rates, and 4 replications.

N was applied before planting. During the 9-year period, nitrogen was applied as either NH_4NO_3 (surface applied) or as anhydrous NH_3 (narrow shank blades 30 cm apart). Because the main intent of the research was to quantify grain yields with increasing N rates, the confounding of total ammonium source (anhydrous NH_3) and partial ammonium source (NH_4NO_3) with time was not considered. The soil was a Platner loam, which classified as fine, montmorillonitic, mesic Aridic Paleustolls (Table 1).

For rotation phase W-C-F winter wheat (initially TAM 105 and in later years TAM 107) was seeded in September 1985 and harvested in July 1986; corn (Pioneer 3732) was seeded in May 1987 and harvested in November 1987; the fallow period was from November 1987 to September 1988. The other two sites (phases), initiated in 1986, began with corn, and fallow (Fig. 1). Wheat was planted at a rate of about 2.2 million seeds/ha with a no-till disk drill (about 0.17-m row spacing). Corn was planted at about 37,000 seeds/ha, (0.76-m row spacing). Blanket P application (about 30 kg P/ha) was made on all sites initially and then at 20 kg P/ha every 3 years with wheat seeding.

No-till treatment consisted of post-harvest residual herbicides and contact herbicides only (no mechanical tillage). Generally, 2,4-D was applied to the wheat crop during the spring. After the wheat harvest in July, residual herbicides such as clomazone and atrazine were applied in August. The following summer, either glyphosate or paraquat was applied to control weed escapes. For corn weed control, atrazine was applied preemergence and dicamba postemergence.

All soil samples were taken at the 0 to 5- (stratification zone) and 0 to 15-cm depths. Although all crop harvests were completed by November 1994, the soil samples were taken in the spring of 1995. Soil data collected included pH (McLean 1982), 1.0 M KCl extractable Al, Mn, and Ca (Barnhisel and Bertsch 1982), CEC and ex-

changeable cations (Rhoades 1982), bulk density (Blake and Hartge 1982) and total C and N by dry combustion with a C and N analyzer, and nitrate-N to a depth of 60 cm. Manganese and Ca were determined from the KCl extracts by atomic absorption spectroscopy, and Al was determined colorimetrically (Wilson 1984). A soluble carbon fraction was determined by extracting 5 g of soil with 50 mL of 0.5M NaHCO_3 (pH 8.0). A 10-mL aliquot sample was concentrated to dryness at 60 C, and the resultant carbon in the sample was determined colorimetrically by chromic acid reduction (Heanes 1984).

Statistical analyses included analysis of variance ($P < 0.10$) and mean comparisons by least significance difference (LSD), where treatment significance was obtained, as well as regression analysis of pH by N rates. Soil reaction changes from rotational effects were not evaluated because preliminary data showed no significant differences. All N treatments by replications and rotations were, therefore, composited.

RESULTS AND DISCUSSION

Selected physical and chemical soil properties for the control in 1986 and 1995 are presented in Table 1. Results show that bulk densities, soil textures, CEC, and total soil P did not vary significantly with time for the two rotation phases. Specific bulk densities varied from 1.2 to 1.5, but they were not different by year. Texture varied from silty clay loam to loam, and lime was present at depths of about 50 to 60 cm. Cation exchange capacity remained unchanged. Total surface (0–5 cm) soil P, an indicator of possible erosion, varied widely across the field, but, again, differences after 9 years were not significant for the two rotation phases.

In 1995, research plots with 0, 56, and 112 kg N/ha were sampled in 2.5-cm increments (Fig. 2) to a depth of 15 cm to assess pH changes. A significant drop in pH was observed with the 112 kg N/ha at the 0 to 2.5- and 2.5 to 5.0-cm depths

TABLE 1
Selected physical and chemical soil properties of Platner loam. (Zero N rate in 1986 and 1995)

Soil† depth	pH (H_2O)	BD Mg/m ³	Fines‡ %	CEC cmol/kg	TP mg/kg				
						BD Mg/m ³	Fines‡ %	CEC cmol/kg	TP mg/kg
						1986			
0–15	6.2	1.40	54	10	404	1.50	50	10	420
15–30	6.6	1.45	29	12	371	1.45	31	13	382
30–60	7.5	1.45	28		370	1.45	30		380

†Free CaCO_3 at 55 cm.

‡Fines = clay + silt.

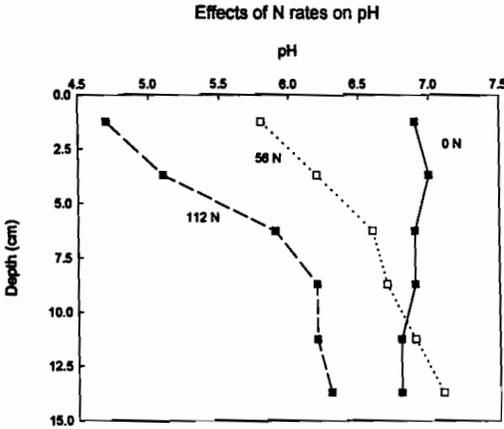


Fig. 2. Effects of 0, 56, and 112 kg N/ha on pH changes to 15 cm in 0 to 2.5-cm increments in 1995.

(pH 4.7, 5.1) compared with the control plots (pH 6.9, 7.0). The pH for the 56 kg/ha N rate was intermediate for these two surface depths, but the lower depths coincided more with the 0-N rate, which essentially showed neutral pHs. Although not listed in Table 1, pH values at all N rates for the 15 to 30-cm depths were between 6.6 and 7.1. For this reason only the 0 to 5- and 0 to 15-cm depths were analyzed and reported. The 0 to 5- and 0 to 15-cm depths were chosen and sampled instead of the 0 to 5- and 5 to 15-cm depths because this latter approach eliminated the need to average a nonlinear parameter (pH).

Although soil acidification is a natural process, given sufficient time (the C, N, S cycles result in acidification), the imposition of agriculture accelerates this process. Generally, the pH range most affected by change is 4.5 to 7.5 because higher pH values are affected minimally as a result of the

strong buffering of carbonates (Jenny 1980) and the lower pH values by the buffering of aluminum hydrous oxides (Helyar and Porter 1989). Acidification under the no-till system in the Plains is caused primarily by two factors: lack of mixing to 15 cm and oxidation of ammonium ions. Hydrogen ions are produced when organic matter-N and ammonium fertilizers are converted to nitrate. In addition, residue and organic matter accumulate under no-till conditions, where decomposition and mineralization of these materials result in the production of organic acids in the surface layers. As the pH drops, both of these elements become more soluble and toxic (Stumpe and Vlek 1991). The aluminum ion hydrolyzes further and produces more acidity (Coleman and Thomas 1967). Although significant pH differences can exist statistically (a drop in pH from 7.3 to 6.3), the pH levels at which Mn and Al solubilities can cause toxicities (about 5.5 and 5.0, respectively), are more important biological benchmarks.

Once it was determined that significant changes occurred only in the 0 to 5- and 0 to 15-cm depths, a more thorough evaluation of the changes in soil chemical properties caused by increasing N rates was made (Table 2). Soil pH in the top 5 cm decreased linearly ($r = -0.90, P = 0.10$) during the 9 years of the study. This reduction was equivalent to a decrease of 0.20 pH units/100 kg N applied ($pH = 6.4 - 0.002 * \text{kg N Applied}$), which is much greater than the 0.04 pH units found by Rasmussen and Rohde (1989) in Oregon. Although many confounding differences existed between the two studies, our no-tillage versus their sweep tillage and our 5-cm depth versus their 7-cm depth can account for some of these differences. At the 0 to 15-cm depth, only the 112-N rate showed a pH value less than 5.5. In Idaho, Mahler and McDole (1987) found a reduction in wheat yields, and an even greater reduction

TABLE 2
Effects of N rates on selected soil chemical changes at 0 to 5- and 0 to 15-cm depths

N rates kg/ha	Total N	0-5 cm		0-15	
		pH (H ₂ O)	Al cmol/kg	pH (H ₂ O)	Al cmol/kg
0	0	6.3	<0.01	6.8	<0.01
28	168	6.2	<0.01	6.7	<0.01
56	336	5.8	<0.01	6.2	<0.01
84	504	5.4	0.06	6.0	<0.01
112	672	5.0	0.15	5.5	<0.01
x†		0.6	0.04	0.5	0.01

†Critical level for mean comparison using LSD ($P < 0.10$).

in legumes, with similar low pH levels. By far the greatest changes occurred at the 0 to 5-cm pH values lower than 5.5. These two N rates also showed significant changes in KCl-extractable Al compared with the other lower N rates. Manganese concentration was increased only at the high N rate in the 0 to 5-cm depth. Aluminum concentration increased about eightfold with the 84-N level, and about 20-fold with the 112-N rate. In a long-term fertilizer study in Kansas, Hetrick and Schwab (1992) inferred a closer solubility relationship of Al with montmorillonite than with gibbsite. Our Platner loam is classified in the former category. On the positive side, phosphate (relatively high in our study), sulfate, and fluoride have been found to detoxify Al (Cameron et al. 1986). Because of its chelating properties, soil organic matter is also an efficient buffer against Al toxicity (Thomas 1975).

Results for Ca showed decreasing concentrations (Table 2) at the 0 to 5-cm depth with increasing N rates. This element and molybdenum are the two most negatively affected nutrients under extreme acid conditions. Calcium activity has also been built into some Al toxicity equations to predict relative root length (Fey et al. 1991). In a greenhouse study with the low pH soil (0 to 5-cm depth) from the 112-N rate, Bowman found bleaching on the main tiller of young wheat plants, which may indicate Ca deficiency (Wiese 1993); however, the secondary tillers were not affected (unpublished data). Under field conditions, where the roots of the wheat seedling grow quickly to below the 0 to 5-cm zone of low pH, Ca deficiency in semiarid Plains soils may be difficult to detect.

Although $\text{NH}_4\text{-N}$ rates affected pH changes, these rates also affected crop yield and biomass production, which ultimately affected residue and SOC (Table 3). An increase in organic matter as a result of N treatments has also been documented by Rasmussen et al. (1980), Glendining and Powlson (1991), and Paustian et al. (1992). Our data showed significant increases in both total and soluble organic carbon with N treatments compared with the control. Given the three cycles of no-till W-C-F, the increases in yield and recycled straw (56% for wheat and 89% for corn) contributed to this soil organic carbon increase. There also seemed to be an accumulation of nitrates in the soil profile with the highest N rate. This downward nitrate movement with the extra available water under no-till is probably responsible for the loss of Ca as $\text{Ca}(\text{NO}_3)_2$ in the surface 5-cm depth (Raney 1960).

Although there were significant differences in pH and Al and Mn with varying N levels, these chemical differences did not result in grain yield reductions at the high levels of N (Table 3). There appeared to be no detrimental effects, but this was not verified with an experiment containing lime treatments. Alessi and Power (1972) also did not find yield reduction with spring grain in the Northern Plains. Our data did show, however, that the highest rates of 112-N on a continued basis may not be necessary under dryland conditions because some nitrates remained in the soil profile during the years of lower rainfall when production yields were not realized.

Do these results mean that the continued practice of high ammoniacal-N fertilization in no-till and reduced-till systems in the semiarid Plains will not result in a reduction of yield? As

TABLE 3
Grain and straw production, surface soil organic carbon (SOC) at the 0 to 5-cm depth,
and soil nitrate-N to a depth of 60 cm as a function of N rates

N rates	SOC		Wheat		Corn		$\text{NO}_3\text{-N}^\ddagger$ (0-60 cm)
	Total	Soluble	Grain	Straw [†]	Grain	Straw [†]	
kg/ha	%	mg/kg	-----kg/ha-----				
0	0.78	378	2265	3851	1837	3675	20
28	0.91	440	3135	5329	2997	5595	
56	1.08	495	3498	5947	3268	6535	39
84	1.07	531	3589	6102	3312	6623	
112	1.12	657	3542	6012	3481	6962	65
$\times\text{§}$	0.20	55	320		480		

[†]Straw conversion: wheat grain \times 1.7; corn grain \times 2.0.

[‡]Cumulative $\text{NO}_3\text{-N}$ to a depth of 60 cm in 1995.

[§]Critical level for mean comparison using LSD ($P < 0.10$).

greater depths become acidified more quickly with higher N rates, it is possible that there may be a reduction in yield. However, the effect of this high level of N on yield is easily confounded when available water initially causes greater vegetation growth, but later, grain fill is preceded by drought (Nielsen and Halvorson 1991). Any reduction from acidification, however, will probably be less than the yield loss that would be measured if no fertilizer N were applied. At this time, the N and P provide quick root growth sufficient to avoid Ca deficiency and other possible problems associated with Mn and Al concentrations in the surface 5 cm. A second significant concern, however, is the probable inactivation of herbicides, especially the triazines, when these surface soils become acidified (Lowder and Weber, 1982) and the probable buildup of nitrates beyond the root zone during the fallow period.

Nine years of 672 kg N applied/ha did not seem to cause the significant downward movement of acidity and Ca to affect yields. The increase in basic cations from crop residue cycling also did not significantly increase the surface soil CEC. Whereas some researchers have used an excess base-to-N ratio of the crop residue to predict the direction of pH change (Pierre and Banwart 1973; Pierre et al. 1970), Pocknee and Sumner (1997) showed Ca-containing organics had a positive liming effect on soil pH. Our degradation of basic cations from residue, especially Ca mineralization, was probably much slower than that of the synthetic substrates used by Pocknee and Sumner.

CONCLUSIONS

Once we convert to no-tillage with no or very little summer fallow, we will be using 50 to 100 kg N every year. We will thus reduce the time for significant acidification to occur compared with the traditional wheat-fallow rotation or with systems in which volatilization is more pronounced. Even though this acidification occurs primarily in the top 5 cm, we need to monitor the downward movement of this acidity and its effects on calcium deficiency, especially on the legume crops that are more sensitive to acidity than is wheat. Present studies with continuous cropping at the Research Station at Akron are already showing pH values below 5.5 (water) or 5.0 (CaCl₂) after just 5 years. Inasmuch as these rotation studies will continue, we will be able to assess downward acidity movement, surface root proliferation, SOM, and calcium exchange chemistry. If or when yields become reduced, a probable N choice under conditions where lime is not easily applied might

be Ca(NO₃)₂ if the economics and soil allow it. No further soil acidification would occur, and a source of Ca would be provided to the surface 0 to 5 cm.

REFERENCES

- Alessi, J., and J. F. Power. 1972. Influence of nitrogen source and rate on growth of spring grain and soil pH. *Agron. J.* 64:506-508.
- Barnhisel, R., and P. M. Bertsch. 1982. Aluminum. *In* Methods of soil analysis, part 2. A. L. Page et al. (eds). Agron. Monogr. No. 9, ASA, Madison, WI, pp. 275-300.
- Blake, G. R., and K. H. Hartge. 1982. Bulk density, p. 363-375. *In* Methods of soil analysis, part 1. 2nd. Ed. A. Klute (ed.). Agron. Monogr. No. 9, ASA, Madison, WI, pp. 363-375.
- Bowman, R. A., J. D. Reeder, and R. Lober. 1990. Changes in soil properties in a Central Plains rangeland soil after 3, 20, and 60 years of cultivation. *Soil Sci.* 150:851-857.
- Campbell, C. A. 1978. Soil organic carbon, nitrogen, and fertility. *Dev. Soil Sci.* 8:173-271.
- Cameron, R. C., R. C. Richie, and A. D. Robson. 1986. The relative toxicities of inorganic aluminum complexes to barley. *Soil Sci. Soc. Am. J.* 50:1231-1236.
- Coleman, N. T., and G. W. Thomas. 1967. The basic chemistry of soil acidity. *In* Soil acidity and liming. R. W. Pearson and F. Adams (eds.). ASA, Madison, WI, pp. 1-41.
- Fey, M. V., A. D. Noble, and M. E. Sumner. 1991. Reply to comments on the Ca-Al balance. *Soil Sci. Soc. Am. J.* 55:898.
- Glendining, M. J., and D. S. Powlson. 1991. The effect of long-term applications of inorganic nitrogen fertilizer on soil organic nitrogen. *In* Advances in soil organic matter research: Impact on agriculture and the environment. W. S. Wilson et al. (eds.). R. Soc. Chem., Cambridge, England, pp. 329-338.
- Halvorson, A. D., and C. A. Reule. 1994. Nitrogen fertilizer requirements in an annual dryland cropping system. *Agron. J.* 86:315-318.
- Havlin, J. L., D. E. Kissel, L. D. Maddux, M. M. Claassen, and J. H. Long. 1991. Crop rotation and tillage effects on soil organic carbon and nitrogen. *Soil Sci. Soc. Am. J.* 54:448-452.
- Heanes, D. L. 1984. Determination of total organic C in soils by an improved chromic acid digestion and spectrophotometric procedure. *Commun. Soil Sci. Plant Anal.* 15:1191-1213.
- Helyar, K. R., and W. M. Porter. 1989. Soil acidification, its measurements and the processes involved. *In* Soil acidity and plant growth. A. D. Robson (ed.). Academic Press, New York, pp. 61-101.
- Hetrick, J. A., and A. P. Schwab. 1992. Changes in aluminum and phosphorus solubilities in response to long-term fertilization. *Soil Sci. Soc. Am. J.* 56:755-761.
- Jenny, H. 1980. The soil resource: Origin and behavior. Springer-Verlag, New York.

- Kitchen, N. R., D. G. Westfall, and G. A. Peterson. 1990. Nitrogen fertilization management in no-till dryland cropping systems. *Am. Soc. Agron., Madison, WI, Agron. Abstr.* p. 272.
- Lowder, S. W., and J. B. Weber. 1982. Atrazine efficacy and longevity as affected by tillage, liming, and fertilizer type. *Weed Sci.* 30:273-280.
- Mahler, R. L., and R. E. McDole. 1987. Effect of soil pH on crop yield in northern Idaho. *Agron. J.* 79:751-755.
- Mahler, R. L., and R. W. Harder. 1984. The influence of tillage methods, cropping sequence, and N rates on the acidification of a northern Idaho soil. *Soil Sci.* 137:52-60.
- McLean, E. O. 1982. Soil pH and lime requirement. *In* Methods of soil analysis, part 2, 2nd Ed. A. L. Page et al. (eds.). Agron. Monogr. No. 9, ASA, Madison, WI, pp 199-224.
- Nielsen, D. C., and A. D. Halvorson. 1991. Nitrogen fertility influence on water stress and yield of winter wheat. *Agron. J.* 83:1065-1070.
- Paustian, K., W. J. Parton, and J. Persson. 1992. Modeling soil organic matter in organic-amended and nitrogen-fertilized long-term plots. *Soil Sci. Soc. Am. J.* 56:476-488.
- Pierre, W. H., and W. L. Banwart. 1973. Excess-base and excess-base/Nitrogen ratios of various crop species and parts of plants. *Agron. J.* 65:91-96.
- Pierre, W. H., J. Meisinger, and J. R. Birchett. 1970. Cation-anion balance in crops as a factor in determining the effect of nitrogen fertilizer on soil acidity. *Agron. J.* 62:106-112.
- Pocknee, S., and M. Sumner. 1997. Cation and nitrogen contents of organic matter determines its soil liming potential. *Soil Sci. Soc. Am. J.* 61:86-92.
- Raney, W. A. 1960. The dominant role of nitrogen in leaching losses from soils of the humid regions. *Agron. J.* 52:563-566.
- Rasmussen, P. E., R. R. Allmaras, C. R. Rohde, and N. C. Roach, Jr. 1980. Crop residue influence on soil carbon and nitrogen in a wheat-fallow system. *Soil Sci. Soc. Am. J.* 44:596-600.
- Rhoades, J. D. 1982. Cation exchange capacity p. 149-165. *In* A. L. Page et al. (ed.) *In* Methods of soil analysis, part 2, 2nd Ed. Agron. Monogr. 9. ASA, Madison, WI.
- Stumpe, J. M., and P. L. G. Vlek. 1991. Acidification induced by different nitrogen sources in columns of selected tropical soils. *Soil Sci. Soc. Am. J.* 55:145-151.
- Thomas, G. W. 1975. The relationship between organic matter content and exchangeable Al in acid soil. *Soil Sci. Soc. Am. Proc.* 39:591.
- Van Breemen, L., N. J. Mulder, and C. T. Driscoll. 1983. Acidification and alkalization of soils. *Plant Soil* 75:282-308.
- Westfall, D. G., R. L. Kolberg, and G. A. Peterson. 1992. Nitrogen fertilizer use efficiency in dryland no-till crop rotations. *In* Proc. Fluid Fert. Symp., March 1992, Scottsdale, AZ, pp. 244-257.
- Wiese, M. V. 1993. Wheat and other small grains. *In* Nutrient deficiencies and toxicities in crop plants. William F. Bennett (ed.). The American Phytopathological Society, St. Paul, MN, pp. 27-33.
- Wilson, D. O. 1984. Determination of aluminum in plant tissue digests using a catechol violet colorimetric method. *Commun. Soil Sci. Plant Anal.* 15:1269-1279.
- Wood, C. W., G. A. Peterson, D. G. Westfall, C. V. Cole, and W. F. Willis. 1991. Nitrogen balance and biomass production of newly established no-till dryland agroecosystems. *Agron. J.* 83:519-526.