AN ABSTRACT OF THE THESIS OF

Thomas A. Doerge for the degree of Doctor of Philosophy in
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Title: Evaluation of Long Term Reacidification and Growth of Alfalfa on Selected Limed Soils in Western Oregon

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E. Hugh Gardner

Soil acidity is widespread in the Willamette Valley of western Oregon and is responsible for many of the region's soil fertility problems. Lime applications ranging from 0 to 14.6 Mg ha^{-1} were made on a Nekia sicl (pH 5.0) and from 0 to 11.2 Mg ha^{-1} on a Woodburn sil (pH 5.3) in 1971-72. Monitoring of soil pH and levels of extractable basic cations for 11 to 12 years permitted estimation of the rate of acidification of soils receiving different amounts of lime. Soil acidification rates were found to increase with increasing quantities of lime initially applied.

The acidification rate of unlimed Nekia soil was 0.025 pH units y^{-1} while the unlimed Woodburn soil showed no net acidification. Maximum rates of acidification of 0.090 pH units y^{-1} on the Nekia soil and 0.077 pH units y^{-1} on the Woodburn soil were measured on the plots receiving the highest amounts of lime. Faster reacidification of soils amended with higher lime rates is explained by the pH

dependence of acidifying processes such as nitrification, CO_2 release via plant and microbial respiration, mineralization of organic matter and dissociation of organic acids in soil solution. Calcium release via mineral weathering appeared to have an important effect on soil pH and extractable Ca, particularly in the absence of large inputs of acidifying materials such as NH_4 fertilizers.

The Woodburn sil is an important agricultural soil in the Willamette Valley which is well suited for alfalfa (Medicago sativa L.) production. The growth response of alfalfa to lime was examined on a soil at pH 5.5. Growth was very poor in unlimed soil although soil and plant tissue analysis did not identify elements other than N in critical nutrient deficiency or toxicity ranges. Nitrogen was deficient but only in plants grown in soil below pH 6.0.

Field and greenhouse experiments with pH, Ca, N and Mo variables and evaluation of nodulation were used to characterize the 300-400% increase in dry matter yield when lime applications increased the soil pH to the recommended level of 6.4. Plants grown at pH levels between 5.5 to 6.4 in the field and 5.3 to 6.5 in the greenhouse were all well nodulated. No increase in yield or nodulation was measured in response to the application of $CaSO_4$.

Marked response to N and Mo, especially at the lower pH levels, suggested that the growth response of alfalfa to lime is due primarily to increased nodule efficiency, resulting from greater Mo availability as soil pH is raised. Application of Mo to alfalfa grown in the Woodburn or similar soils may be a feasible alternative to large lime applications in cases where Mo deficiency, and not poor nodulation, is the major growth limiting factor.

Evaluation of Long Term Reacidification and Growth of Alfalfa on Selected Limed Soils in Western Oregon

by

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INTRODUCTION

The Willamette Valley in northwestern Oregon is an important agricultural area characterized by wide diversity in both crops and soils. The climate is Mediterranean, with about 70% of the 100 to 150 cm of annual precipitation falling as rain between November and March (Knezevich, 1976). This has resulted in leaching of basic cations and widespread occurrence of acid soils. Increasing use of NH_4 fertilizers and irrigation have contributed to the severity of the soil acidity problem in this area. The use of agricultural lime is commonly practiced. Between 1976 and 1982 an average of 142,000 Mg of lime were sold per year in Oregon, the vast majority being used west of the Cascade Mountains (Oregon Department of Agriculture, 1983).

A wide variety of crops have shown significant growth responses to the application of lime. These include grains (Kauffman, 1978), vegetable crops (Hemphill et al., 1982; Hemphill and Jackson, 1982), tree crops (Baron and Gardner, 1975), and forage legumes (James et al., 1968; Jackson et al., 1964). Considerable work has been devoted to predicting when a given crop will respond to lime. The critical pH levels of most important crops grown in the Willamette Valley have been determined.

Much soil acidity research has focused on developing a reasonably accurate method for predicting the quantity of lime required to adjust a soil's pH to a predetermined level. The SMP buffer procedure (Shoemaker et al., 1961) and modifications of this procedure have received the most attention (Baker and Chae, 1977; Petersen, 1972).

It is well known that the effect of lime in raising soil pH extends beyond the first year after application. However, prediction of the rate at which limed soils reacidify is often not known. The difficulty in maintaining the integrity of long term lime experiments for the required 10 or more years is a major problem for this type of research, and probably accounts for the lack of work done in this area. The reacidification of limed soils and identification of soil-plant processes which contribute to soil acidification were the subject of this study. The objectives of this portion of the study were:

1. Quantify the long term acidification rates of two lime amended soils in western Oregon.
2. Identify soil-plant processes which control acidification rates.

Few agricultural practices can compare with liming in ability to alter the chemical and biological environment of a soil (Jackson, 1967). This combined with a broad diversity among acid soils and different crops' response to soil acidity-related conditions, complicates the task of understanding a specific plant's growth response to the application of lime. Liming has corrected both Al and Mn toxicities as well as alleviated deficiencies of Ca, P, and Mo (Jackson, 1967). Identification of soil acidity-related limitations is normally accomplished by using techniques including plant tissue analysis, diagnosis of foliar symptoms, morphological examination of roots, and demonstrating plant response to a potentially deficient nutrient.

Characterization of response to lime is considerably simplified for those plants not dependent on N_2 fixation. Toxicities of Al in wheat (*Triticum aestivum* L.) (Kauffman, 1978) and Mn in snap beans (*Phaeseolus vulgaris*) (Jackson et al., 1966) have been well documented for Willamette Valley soils, as has the increased availability of P in limed soil (Hemphill and Jackson, 1982). Deficiencies of Mo in nonlegumes are not widespread in this area, although application of Mo is routinely suggested for some members of the Cruciferae family (Mansour et al., 1983). Calcium deficiencies in nonlegumes have not been observed in western Oregon. Adams and Moore (1983) did identify Ca deficiencies in cotton (*Gossypium hirsuteum* L.) in four highly-weathered Alabama subsoils, but only at exchangeable Ca levels below 0.4 cmol (+) kg^{-1}.

Characterizing the effect of soil acidity and the application of lime on the growth of legumes is considerably more complex than for nonlegumes due to their symbiosis with *Rhizobium* sp. bacteria. In addition to effects on the host plant, the survival of native and applied *Rhizobia* sp. can also be affected by acid soil conditions

(Mahler, 1983). Important N_2 fixation factors such as nodulation (Andrew, 1976; Munns, 1970), nodule efficiency (Munns et al., 1977), and nodule occupancy (Dughri and Bottomley, 1983) can be affected by soil acidity related conditions.

The growth response of alfalfa (Medicago sativa L.) to the application of lime has been extensively studied on a wide variety of acid soils (Munns, 1976). The beneficial effect of lime on plant growth has normally been attributed to the correction of one or more soil acidity related limitations such as Al toxicity (Janghorbani et al., 1975), P deficiency and Al toxicity (Mahler, 1983; Munns, 1964a), Ca deficiency (Munns et al., 1977), and Mo deficiency (James et al., 1968; Mortvedt, 1981). Often, however, the soils investigated were Ultisols, Oxisols or andic Inceptisols and represented harsh or atypical conditions for alfalfa production.

The Willamette Valley contains extensive acreages of soils which are well adapted for alfalfa growth. One example is the Woodburn sil (Aquultic Argixeroll) which is neither highly weathered nor dominated by volcanic ash. Alfalfa grown in this soil responds markedly to lime if the soil pH is significantly below the recommended level of 6.4, even when toxicities of Al and Mn or deficiencies of Ca, P, and Mo are not detected. Thus, the objective of this portion of the research was:

3. Characterize the growth response of alfalfa to lime on a moderately acid, but otherwise fertile Woodburn soil.

Details of the long term reacidification study are presented in

Chapter 1, which is a manuscript submitted to the Soil Science Society of America Journal. Characterization of alfalfa's growth response to lime and Mo on a moderately acid, high P Woodburn soil is presented in Chapter 2, which will be submitted to the Agronomy Journal.

CHAPTER ONE

Reacidification of Two Lime Amended Soils in Western Oregon[1]

Thomas A. Doerge and E. Hugh Gardner[2]

ABSTRACT

Leaching of basic cations by winter rainfall and irrigation water and the increasing use of NH_4^+-fertilizers have resulted in widespread soil acidity in western Oregon. While applications of liming materials are often made in this region, the rates at which limed soils reacidify are generally not known. The objectives of this study were to: (1) quantify long-term acidification rates of two lime-amended soils in western Oregon, and (2) identify soil-plant processes which may control acidification rates. Lime applications ranging from 0 to 14,650 kg ha^{-1} were made on a Nekia sicl (Xeric Haplohumult, initial pH 5.0) and from 0 to 11,200 kg ha^{-1} on a Woodburn sil (Aquultic Argixeroll, pH 5.3) in the Willamette Valley of western Oregon in 1971-72. Monitoring of soil pH and levels of extractable basic cations applied in the liming materials for 11 to

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[1] Contribution from the Dep. of Soil Science, Oregon State Univ., Corvallis, OR 97331. Oregon Agric. Exp. Stn. Technical paper no. 7236.

[2] Research Assistant and Professor of Soil Science.

12 y permitted estimation of the rate of acidification of soils receiving different amounts of lime. Whether estimated by declines in pH or extractable basic cations, soil acidification rates increased with increasing quantities of lime initially applied. Acidification rates of unlimed Nekia soil were 0.025 pH units y^{-1} and 0.17 cmol(+) Ca^{2+} + Mg^{2+} $kg^{-1}y^{-1}$ while the unlimed Woodburn soil showed no net acidification. Maximum rates of acidification of 0.09 pH units y^{-1} and 0.62 cmol(+) extractable Ca^{2+} + Mg^{2+} $kg^{-1}y^{-1}$ on the Nekia soil and 0.08 pH units y^{-1} and 0.36 cmol(+) extractable Ca^{2+} $kg^{-1}y^{-1}$ on the Woodburn soil were measured on plots receiving the highest amounts of lime. Faster reacidification of soils amended with higher lime rates is explained by the pH dependence of acidifying processes such as nitrification, CO_2 release via plant and microbial respiration, mineralization of organic matter and dissociation of organic acids in soil solution. Ca^{2+} release from mineral weathering appeared to have an important effect on soil pH and extractable Ca^{2+}, particularly in the absence of large inputs of acidifying materials such as NH_4^+-fertilizers. Accurate prediction of soil acidification rates will require additional information concerning the pH dependence of soil acidifying processes, the quantity and composition of seasonal through drainage, and the rates of mineral weathering in soils.

Additional index words: Soil acidity, pH decline, Basic cations, Leaching.

INTRODUCTION

The soils of the Willamette Valley in western Oregon are acidic and soil acidity is responsible for many of the region's soil fertility problems. Selection of acid-tolerant crops is often practiced to avoid expensive lime applications. Even so, yield responses to liming would be expected in over 30% of the fields in this area (Doerge and Gardner, 1984 unpublished report). The effect of lime in raising soil pH extends beyond the first year after application, but predicted rates at which limed soils reacidify are often not known. Prediction of soil acidification rates could provide important information for projecting lime needs.

Past studies have reported an empirical relationship between the rate at which limed soils acidify and the amount of lime applied (Bolton, 1977; Heintze, 1949; and Walker, 1953). In every case, the apparent rate of acidification, measured as the decrease in extractable calcium (Ca), increased as the amount of lime applied increased. However, when these studies are compared, no consistent relationship between acidification rate and soil pH emerges. Trends on individual soils are consistent, but trends across different locations and management systems are not consistent. Thus, while soil pH itself provides a measurement of soil acidification, it also regulates biogeochemical processes which contribute to soil acidification.

The objectives of this study were to: (1) quantify long-term acidification rates of two lime-amended soils in western Oregon and, (2) identify soil-plant processes which control acidification rates.

MATERIALS AND METHODS

Soils and Experimental Design

In the early 1970's liming experiments were initiated on two acid soils in the Willamette Valley of western Oregon (Kauffman, 1976) (Table 1). Lime plots were established in October 1972 on the Nekia and October 1971 on the Woodburn soil (Table 2). The highest lime rates (L_3) were calculated to give approximately 100% base saturation. The L_1 and L_2 treatments were selected as intermediate rates. Dolomitic lime was included in the treatments on the Nekia soil due to a low initial soil test level for magnesium (Mg). The experimental design at both sites was a split-split plot factorial with two crop types as the main plots and two methods of lime incorporation (disced or rototilled) as the subplots. The four lime rates (Table 2) were the sub-subplot variables. All treatments were replicated three times. Lime was mixed into the soil to depths varying from 7.5 to 10 cm for the disced treatments to 12.5 to 15 cm for the rototilled treatments. Individual plots were 6.1 x 12.2 m at the Nekia site and 4.6 x 10.7 m at the Woodburn location.

All soil and plant materials sampled throughout the experiments were taken from the central portion of each plot to avoid the effects of soil mixing from adjacent plots. The cropping sequences for both sites are listed in Table 3. Conventional tillage methods were employed at both sites prior to the seeding of annual crops and establishment of perennial crops. On the Nekia soil this included discing or chisel-plowing to a depth of 15 cm followed by one or two secondary tillage operations. Tillage of the Woodburn soil included

Table 1. Description of soils.

			Initial Soil Test Values (0-15 cm)				
			pH	Ca	Mg		
Soil series	Taxonomy	Clay mineralogy†	1:2 soil to H_2O	Ammonium acetate extractable		CEC	Organic matter
				----cmol(+/-) kg^{-1}----			g kg^{-1}
Nekia sicl	Clayey, mixed, mesic Xeric Haplohumult	Kl, Ch, Vm	5.0	4.2	0.56	22.2	68
Woodburn sil	Fine-silty, mixed, mesic Aquultic Argixeroll	Mi, Ch, Kl	5.3	6.3	1.1	15.6	34

† Clay minerals listed in order of decreasing abundance.
Kl= kaolinite, Ch = chlorite, Vm = vermiculite, Mi = mica

Table 2. Quantity, chemical composition and fineness of liming materials initally applied to experimental plots located on Nekia and Woodburn soils.

Treatment	Dolomitic[†] lime	Calcitic[‡] lime	Total quantity of lime
	---------------	kg ha^{-1}	---------------
		Nekia[§]	
L_0	0	0	0
L_1	2,250	0	2,250
L_2	2,250	6,170	8,420
L_3	2,250	12,400	14,650
		Woodburn[§]	
L_0	--	0	0
L_1	--	2,250	2,250
L_2	--	6,740	6,740
L_3	--	11,200	11,200

[†] 34% $CaCO_3$ and 56% $MgCO_3$, 85% passing a 0.25 mm sieve.

[‡] 93% $CaCO_3$, 90% passing a 0.25 mm sieve.

[§] Lime applied in 10/1972 and 10/1971 to the Nekia and Woodburn soils, respectively.

Table 3. Cropping sequences for long term lime experiments on Nekia and Woodburn soils.

Year(s)	Crop(s) grown[†]
	Nekia
1973-75	alfalfa (50%), winter wheat (50%)
1976	alfalfa (50%), winter wheat (25%), oats (12%), crimson clover (12%)
1977-81	winter wheat
1982	red clover
1983	winter wheat
	Woodburn
1972	alfalfa (50%), snap beans (50%)
1973-74	alfalfa (50%), winter wheat (50%)
1975-76	alfalfa (50%), fallow (50%)
1977-79	fallow
1980	winter wheat
1981-83	alfalfa

[†] When more than one crop was grown in different plots during the same year, the figure following the crop name is the percentage of the experimental area on which that crop was grown.

plowing to a depth varying from 15 to 20 cm and two to three surface tillages as needed for adequate seedbed preparation. Recommended practices for chemical weed control, seeding, fertilization, and harvesting were performed uniformly over similarly cropped areas. The total and mean annual application rates of chemical fertilizer nutrients, averaged across all crops grown each year, are listed in Table 4.

Soil Analysis

Composite soil samples from the surface 15 cm were taken periodically to monitor changes in chemical properties related to liming. Soil pH was measured in a 1:2 soil to distilled water suspension (Jackson, 1974). Calcium (Ca^{2+}) and Mg^{2+} were extracted using 1 M ammonium acetate at pH 7 and measured by atomic absorption spectrophotometry (Berg and Gardner, 1978). The presence of unreacted CO_3^{2-} was detected using the titrimetric method of Bundy and Bremner (1972).

In October 1979 four additional rates of calcitic lime ($CaCO_3$), 0; 2,250; 8,420; and 14,650 kg ha^{-1} on the Nekia and 0; 1,680; 5,050; and 8,430 kg ha^{-1} on the Woodburn soil were applied factorially to the four plots in each replication which had received the same initial rate of lime. This was done to permit evaluation of soil properties over pH ranges of 4.8 to 7.1 and 5.5 to 6.7 on the Nekia and Woodburn soils, respectively. The pH and extractable cation data reported in Figures 2, 3, and 4 for years 0 to 7 on the Nekia and 0 to 8 on the Woodburn are the mean of 12 determinations; those following these times are the mean of 3 determinations. During

Table 4. Total and mean annual fertilizer application rates made during two long term lime experiments.

	Fertilizer application rate						
	NH_4^+-N	NO_3^--N	P_4^{3-}-P	K^+	SO_4^{2-}-S	Cl^-	Ca^{2+}
	--------------------kmol(+) ha^{-1}--------------------						
				Nekia†			
Total	77.6	18.4	18.9	17.7	27.0	21.1	2.2
Mean Annual	7.05	1.67	1.72	1.61	2.45	1.92	0.20
				Woodburn‡			
Total	24.3	7.1	1.7	5.0	16.6	3.3	5.7
Mean Annual	2.02	0.59	0.14	0.42	1.38	0.28	0.48

†1973-83 crop years.

‡1972-83 crop years.

December 1983 to January 1984, 0 to 15 cm soil samples were obtained from twelve selected plots at each site for analysis of extractable Ca^{2+} and Mg^{2+} and all major ionic species in soil solution. Samples were taken at least 24 h after the most recent rainfall event to permit re-equilibration of the soil solution. Saturation extracts were obtained by placing 500 g of field moist soil in a paper cup, saturating the soil with distilled water, mixing the paste, and then equilibrating for 24 h at 4°C (Richards, 1954). After equilibration the paste was transferred to a filter funnel and suction applied to remove the soil solution (saturation extract). Samples and soil solution extracts were stored at 4°C prior to extraction or analysis, respectively. Calcium, Mg^{2+}, K^+ and Na^+ were determined by atomic absorption. Ammonium-N, NO_3^--N and PO_4^{3-}-P were determined on a Continuous Flow Analyzer, Model 200 using Technicon Method Nos. 334-74A/A, 329-74 W/A, and 334-74A/A, respectively. Sulfate-S was determined turbidimetrically using $BaCl_2$ (Tabatabai and Bremner, 1970) and by distillation (Johnson and Nishita, 1952), both giving comparable results. Chloride was measured by potentiometric titration with $AgNO_3$ (Cantliffe et al., 1970).

RESULTS

Carbonate Disappearance

The amounts of liming materials originally applied are listed in Table 2. The amounts of CO_3^{2-} contained in the applications were calculated and are plotted at time=0 in Figure 1. The disappearance of CO_3^{2-} from each soil is related to the rate of application and degree of mixing (Figure 1). At the 2250 kg ha^{-1} liming rate (L_1), essentially all CO_3^{2-} had been released within the first 6 to 7 months after application to both soils. At the higher lime rates, significant amounts of CO_3^{2-} were present for up to 3.5 y. The effect of mixing on the reaction rate of lime was highly influenced by the rate of application. When 90% or more of the applied CO_3^{2-} was released within the first 2 y, the disappearance of CO_3^{2-} followed first order kinetics. This included all treatments except the L_3-disc treatment on the Nekia and the L_3-rototill and L_3-disc treatments on the Woodburn soil. Kinetics were of the form:

$$-\frac{d[CO_3^{2-}]}{dt} = k_1[CO_3^{2-}] \qquad [1]$$

or in its integrated form:

$$-\ln([CO_3^{2-}]_t/[CO_3^{2-}]_0) = k_1t. \qquad [2]$$

Rate constants (k_1 values) for the Nekia and Woodburn soils averaged 3.8 and 2.6 y^{-1} respectively and reflect the lower initial pH and

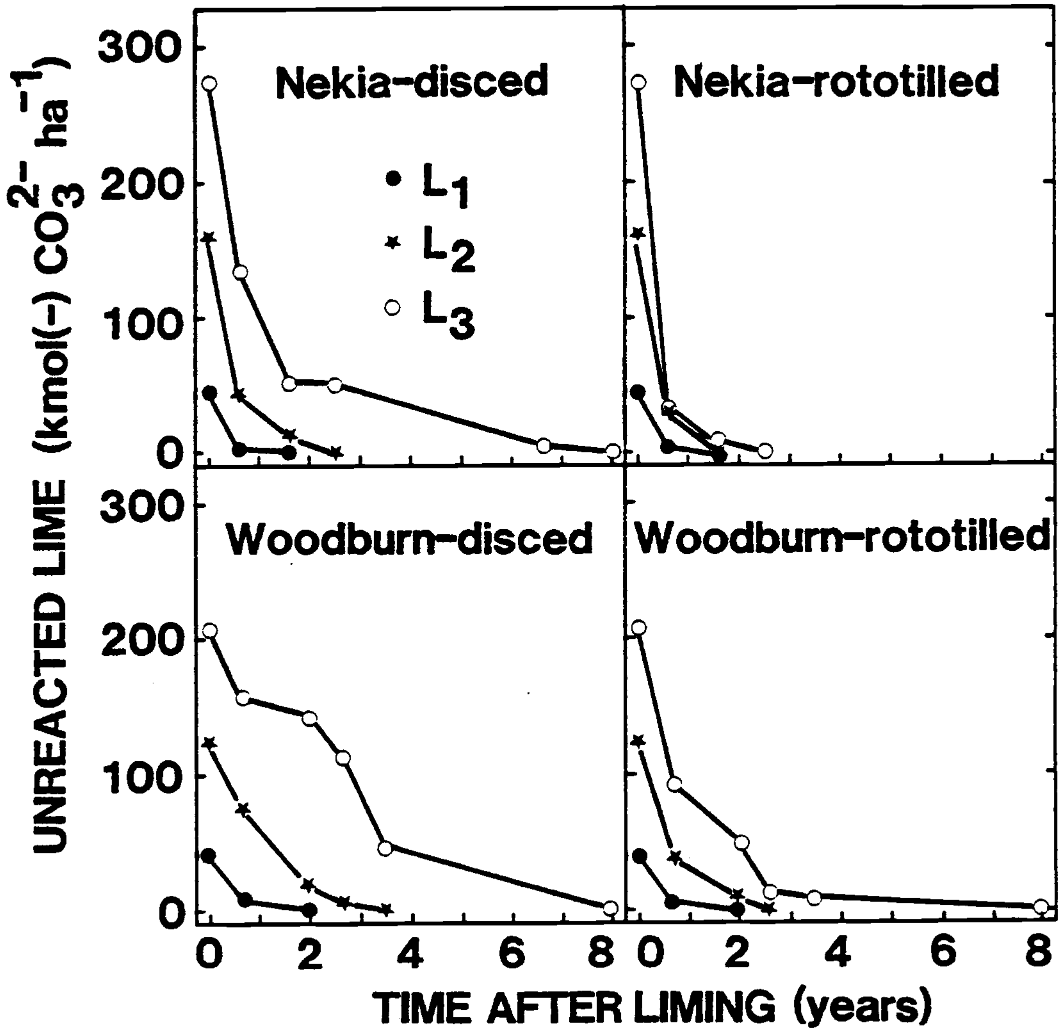

Figure 1. Kinetics of carbonate dissolution in Nekia and Woodburn soils as related to rate of application and method of lime incorporation.

greater exchange acidity of the Nekia soil and the greater application of ammonium fertilizers at that site. Correcting for the acidifying effect of NH_4^+ applied during the time when lime was still reacting indicated that very little of the difference in k_1 values was due to the difference in ammonium fertilizer applied at each site. First order kinetics were not observed if less than 90% of the applied CO_3^{2-} reacted within the first 2 y.

Long Term Changes in pH and Basic Cations

Soil pH trends for the surface 15 cm of soil at both sites are given in Figure 2. The values given are the means of all crop and soil mixing treatments receiving the same rate of lime. There were no consistent differences among the pH values observed for plots receiving different treatments other than lime rate.

Gross changes in soil pH over time may not give the best estimate of long-term liming effects due to seasonal pH variations of 0.3 to 0.4 units for these soils. Figure 3 shows the changes in "residual liming effect" (RLE) at each site, where:

$$\text{RLE} = (\text{pH limed soil}) - (\text{pH unlimed soil}). \qquad [3]$$

The decreases in RLE with time were much more linear than were decreases of soil pH (Fig. 3). The slopes of the regression lines in Figure 3 illustrate that, relative to unlimed soil, the rate at which the pH of limed soil declines increases as the amount of lime applied increases. This phenomenon has been observed by other authors (Bolton, 1977; Heintze, 1949; Walker, 1953).

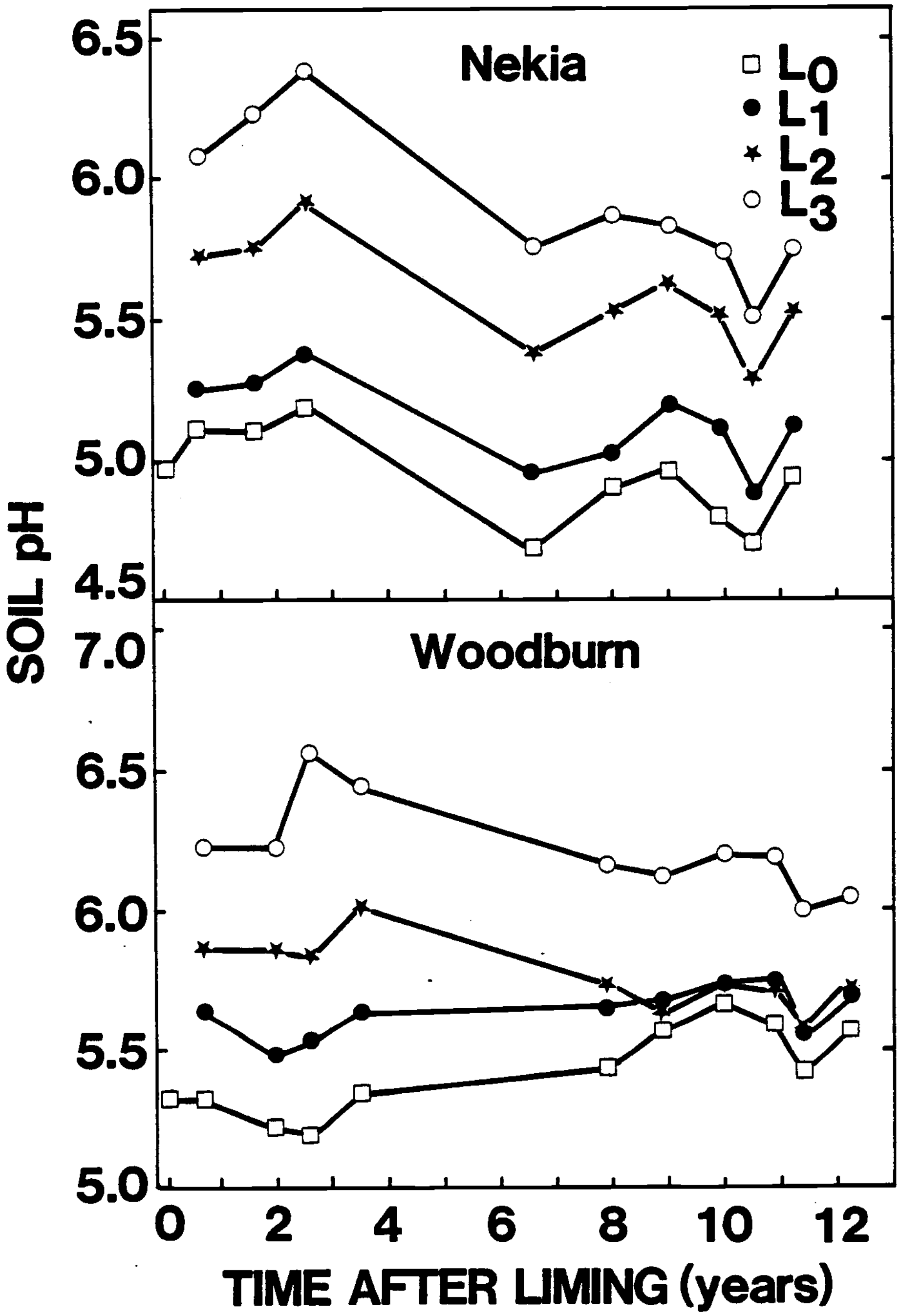

Figure 2. Changes in soil pH of Nekia and Woodburn soils (0-15 cm) receiving different rates of lime.

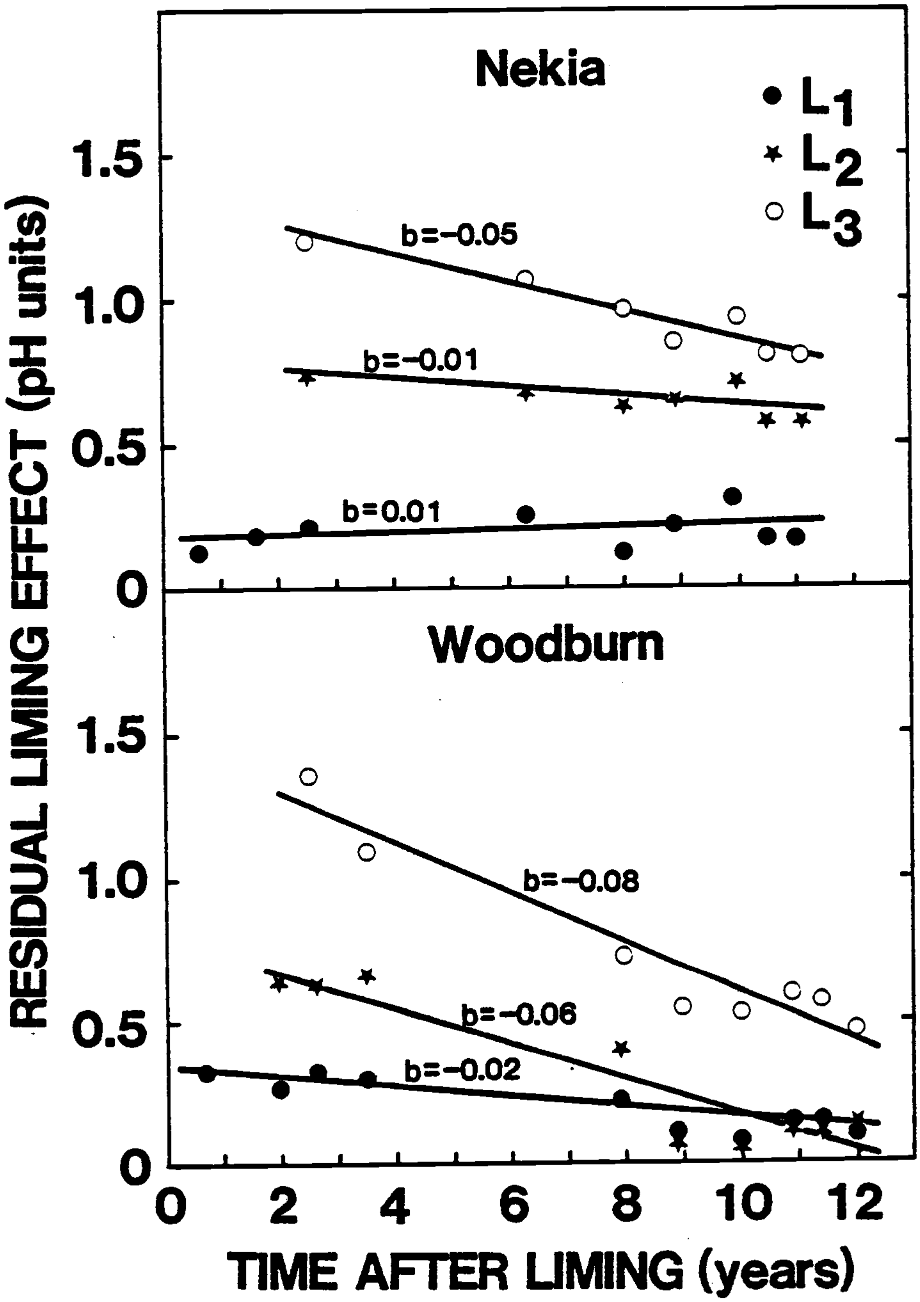

Figure 3. Changes in residual liming effect (RLE) of Nekia and Woodburn soils (0-15 cm) receiving different rates of lime.

Changes in the levels of extractable cations applied in liming materials have also been used to estimate the rates at which limed soils acidify (Bolton, 1977; Hoyt and Hennig, 1982). In both experiments the amount of Ca^{2+} or $Ca^{2+}+Mg^{2+}$ extractable in 1 M ammonium acetate, pH 7 varied linearly with time (Fig. 4). Annual rates of change in extractable cations were calculated from linear regressions fitted to the data (Table 5). As with soil pH, the slopes of the regression lines became increasingly negative as the rate of lime applied increased. The Woodburn soil receiving no lime recorded a slight increase in extractable Ca^{2+}, although the slope of this regression was not significantly different from 0 ($p \leq 0.05$). Hoyt and Hennig (1982) also observed a net increase in the amount of extractable Ca over an eight year period following liming of a soil in the Peace River region of Canada.

In 1982 soil samples were taken at both sites from plots to which additional lime had been applied in 1979. Regression analysis indicates that over 97% of the variation in pH levels was explained by variation in the level(s) of the basic cation(s) applied in the liming materials. Therefore, knowing the relationship between pH and levels of extractable basic cations for each soil (Fig. 5) and the measured annual change in these cations (Fig. 4), acidification rates in terms of pH units y^{-1} can be computed (Table 4), using the following equation:

$$(\Delta pH/\Delta \text{basic cations}) \times (\Delta \text{basic cations}/y) = \Delta pH/y \qquad [4]$$

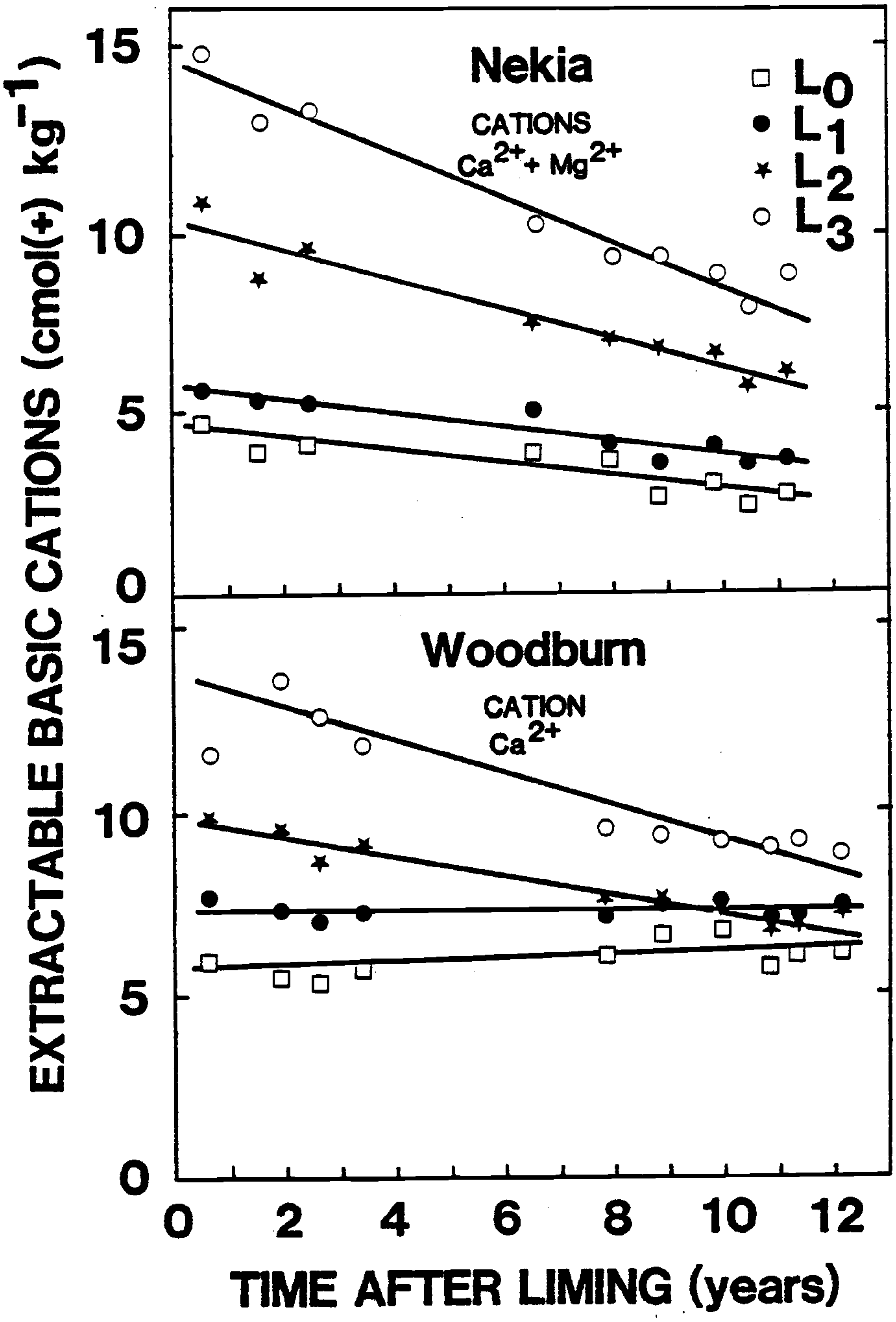

Figure 4. Changes in ammonium acetate extractable basic cations for Nekia and Woodburn soils (0-15 cm) receiving different rates of lime.

Table 5. Annual changes of extractable basic cations and computed pH levels in the Nekia and Woodburn surface (0-15 cm) soils receiving different rates of lime.

Lime treatment	Mean annual change in extractable cations		Computed annual[†] pH change
	Ca^{2+}	$Ca^{2+} + Mg^{2+}$	
	-----cmol(+) $kg^{-1} y^{-1}$-----		pH units y^{-1}
		Nekia	
L_0	-0.15	-0.17	-0.02
L_1	-0.13	-0.19	-0.03
L_2	-0.38	-0.40	-0.06
L_3	-0.61	-0.62	-0.09
		Woodburn	
L_0	+0.05	--	+0.01
L_1	+0.01	--	0
L_2	-0.24	--	-0.05
L_3	-0.36	--	-0.08

[†] Calculated from the relationship between soil pH and extractable cation levels, and measured rates of change of extractable cations as described in Eqn. [4].

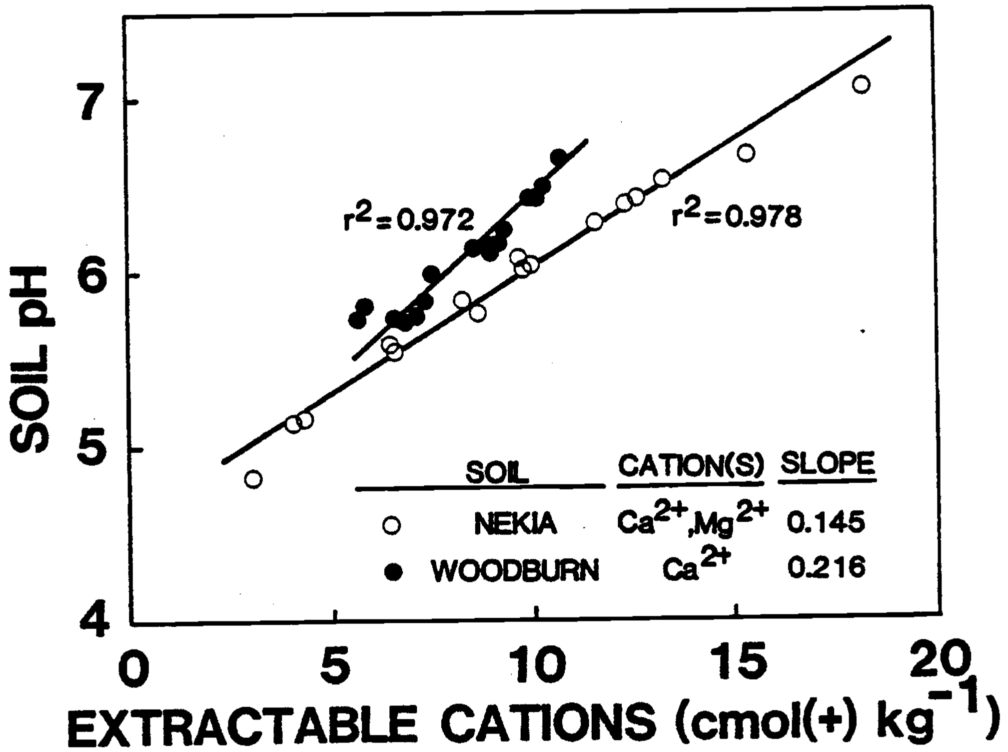

Figure 5. Relationship between soil pH and ammonium acetate extractable cations applied in liming materials to a Nekia and a Woodburn soil (0-15 cm)

Composition of Soil Solutions

At both sites, total cations (i.e. $Ca^{2+} + Mg^{2+} + K^{+} + Na^{+} + NH_4^{+}$) and NO_3^{-} concentrations in soil solution were significantly and positively correlated with soil pH (Fig. 6). For each soil, the slopes of the total cation and the NO_3^{-} versus pH curves were not statistically different from each other ($p<0.05$). The concentrations of both Cl^{-} and SO_4^{2-} were not significantly correlated with soil pH ($p<0.05$) at either site. The Cl^{-} and SO_4^{2-} concentrations averaged 0.68 and 0.10 $mmol(-)L^{-1}$ in the Nekia and 0.62 and 0.35 $mmol(-)L^{-1}$ in the Woodburn soil solutions. Levels of soil solution orthophosphate species never exceeded 0.01 $mmol(-)L^{-1}$. Expected levels of HCO_3^{-} can be calculated using Henry's Law and the dissociation constants for $H_2CO_3^{*}$ (Johnson et al., 1977). Theoretical concentrations of HCO_3^{-} are included in Figure 6 assuming a P_{CO_2} of 0.30 kPa (Buyanovsky and Wagner, 1983 and Russell and Appleyard, 1915).

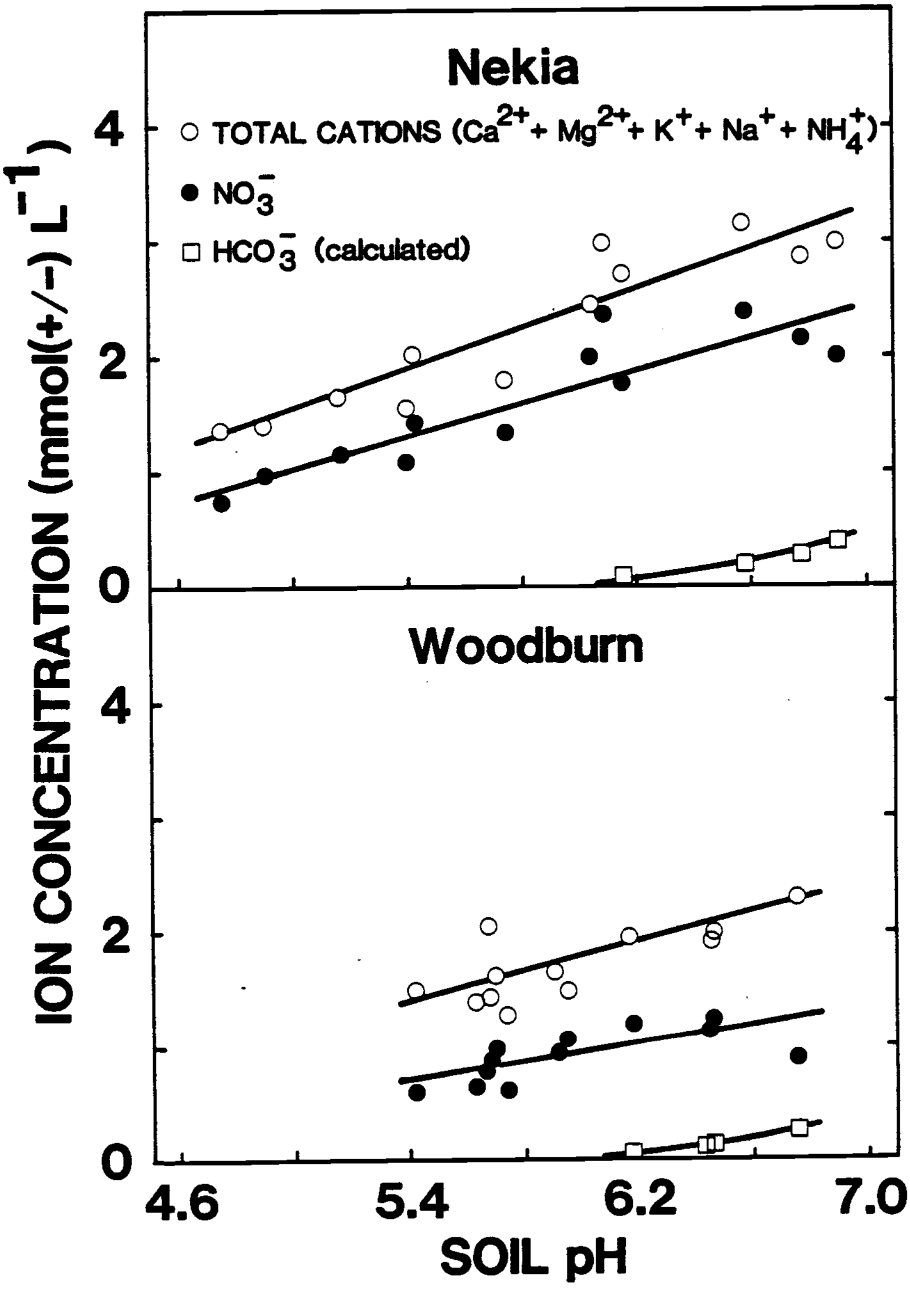

Figure 6. Relationship between soil pH and concentration of NO_3 and total cations $Ca^{2+} + Mg^{2+} + K^+ + Na^+ + NH_4^+$) in soil solution of the Nekia and Woodburn soils (0-15 cm). Curves for HCO_3^- are calculated from CO_2-H_2O equilibrium relationships at $P_{CO_2} = 0.30$ kPa.

DISCUSSION

Conceptually, rates of soil acidification should be measured in terms of changes in H^+ activity per unit of time. However, the sources and sinks of H^+ in soil are more numerous and complicated than those of exchangeable basic cations such as Ca^{2+}. This, combined with the high degree of correlation between soil pH and basic cation saturation may explain why soil acidification has been expressed as the apparent loss of extractable Ca^{2+} (Bolton, 1977; Hoyt and Hennig, 1982; Walker, 1953).

Under environmental conditions where drainage occurs, any soil process which produces both H^+ and leachable anions will result in soil acidification. This occurs due to the replacement of exchangeable basic cations (i.e. Ca^{2+}) by H^+ and leaching of Ca salts during periods of excess precipitation or over-irrigation. Soil acidity can also be affected by mineral sources of buffering such as iron (Fe) and aluminum (Al) hydrolysis and the dissociation of H^+ from Fe oxide/hydroxides.

Some soil processes which result in acidification are nitrification, respiration of CO_2 and subsequent formation of carbonic acid, mineralization of organic matter and dissociation of organic acids. Liming of an acid soil would favor these processes and result in accelerated formation of products including H^+ and leachable anions.

The inhibition of nitrification in acid soils is well documented (Alexander, 1965). While nitrification does occur in soils well below pH 7, a reduced rate of nitrification will reduce the amount of NH_4^+ in a soil which is converted to NO_3^-. As residence time of NH_4^+ in the soil increases, the likelihood of direct uptake of NH_4^+ by plants and soil microbes as well as fixation in clay lattices increases. Thus, stimulation of nitrification by liming would contribute to more rapid reacidification, especially where large, frequent applications of NH_4^+-fertilizers are made. The significant positive correlation between pH and NO_3^- concentration in soil solution for both soils (Figure 6) suggests that nitrification does proceed to a greater extent in limed soil.

The effect of pH on $H_2CO_3^*$ equilibria can be easily calculated for pure systems if the P_{CO_2} of the system is known (Johnson et al., 1977). Liming of an acid soil would increase HCO_3^- activity in soil solution for two reasons. First, solubility of HCO_3^- and CO_3^{2-} increases as pH increases (Stumm and Morgan, 1981). Second, production of CO_2 is higher in limed than unlimed soil due to increased respiration of CO_2 by expanded microbial populations and more vigorous crop plants (Ivarson, 1977; Waksman and Starky, 1924). Increases in the evolution of CO_2 from incubated Nekia and Woodburn soils of 90 and 21% were measured across pH ranges of 4.8 to 7.0 and 5.5 to 6.8, respectively (data not shown).

Increasing soil pH can lead to accelerated decomposition of organic matter and increased release of reduced forms of N and S. Oxidation of these compounds would result in greater production of H^+ ions in limed versus unlimed soils. Net mineralization of organic matter following liming was estimated in both soils during a 22 day incubation under glasshouse conditions. Marked increases in mineralized N were measured when liming raised the pH above 5.0 and

5.9 for the Nekia and Woodburn soils, respectively. Increases in mineralization of organic S would also be expected.

Significant dissociation of organic acids in soil solution would be favored by an increase in pH to a level approaching or exceeding their pKa values (i.e. the negative log of the acid dissociation constants). Increased quantities of root exudates and plant residues returned to the soil following crop response to liming would contribute to higher levels of organic acids in soil solution.

Removal of Ca^{2+} in harvested plant materials undoubtedly accounts for a portion of the decrease in extractable Ca^{2+} within the surface 15 cm of these soils (Table 5). As plant roots also take up appreciable Ca from subsoil layers, total crop removal of Ca cannot be assumed to come solely from the surface 15 cm. Even so, the measured declines in extractable Ca^{2+} in the L_3 treated surface soils were from 3 to 7 times the estimated crop removal of Ca from the Woodburn and Nekia, respectively. This indicates that mechanisms other than crop removal (i.e. leaching) account for the majority of Ca loss from these limed soils.

Weathering of minerals containing Ca can contribute exchangeable Ca^{2+} and consume H^+ in soil solution (Stumm and Morgan, 1981). This probably occurs at a slow rate compared to the rates of H^+ addition mentioned above, but must be considered in a complete discussion of soil acidification. Estimates of Ca^{2+} input via mineral weathering range from 8 to 118 kg $ha^{-1}y^{-1}$ (Clayton, 1983; Johnson et al., 1968; Sollins et al., 1980). Of these three studies, the estimate of Sollins et al. (1980) of 118 kg $ha^{-1}y^{-1}$ may most closely approximate the Ca^{2+} input for these soils, as it came from a western Oregon site of somewhat comparable climate and lithology. The slight increase of extractable Ca^{2+} in the unlimed Woodburn soil (Table 5) of 21.4 kg $ha^{-1}y^{-1}$ (including 9.6 kg $ha^{-1}y^{-1}$ from Ca fertilizers) might well be explained by release of Ca^{2+} through weathering.

For the Nekia soil, levels of extractable Ca^{2+} measured in every lime rate decreased throughout the experiment. In this soil the rate at which Ca^{2+} is being removed exceeds the rate at which it is released by weathering. This is reasonable because Nekia is an old, highly weathered soil which contains only about 4% of the Ca originally in the basalt parent material (Corcoran and Libbey, 1956).

It follows from the preceding discussion that acidification of limed soil is a self limiting process. When a soil is limed, acidifying processes are stimulated and net soil acidification occurs at an accelerated rate. As the pH of the soil drops, so does the rate of acidification. Eventually, the pH of the previously limed soil will approach that of the soil which received no lime. This is well illustrated by the L_0 and L_2 treated Woodburn soils (Fig. 2). Applications of acidifying materials which produce H^+ in larger quantities than consumed via mineral weathering will result in long-term acidification of even unlimed soil. This appears to be occurring in the Nekia soil where annual application of NH_4^+-based fertilizers averaged 99 kg N $ha^{-1}y^{-1}$.

Because of the many factors which affect soil acidification, any meaningful model used to predict the rate at which it occurs would, of necessity, be very comprehensive (Chen et al., 1983). Further research necessary to more accurately characterize soil acidification would include quantification of the pH dependence of important soil acidifying processes, accurate prediction of the quantity and composition of seasonal through drainage, and assessment of the rates of mineral weathering in soils.

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CHAPTER TWO

Effect of pH and Mo on the Growth and N Content of Alfalfa Grown on a Moderately Acid, High P Soil[1]

T. A. Doerge, P. J. Bottomley, and E. H. Gardner[2]

ABSTRACT

The Woodburn sil (Aquultic Argixeroll) is an important agricultural soil occupying 86,000 ha in the Willamette Valley of western Oregon and is well suited for alfalfa (Medicago sativa L.) forage production. Alfalfa grown in this soil at pH 5.5 produced very low yields unless sufficient lime ($CaCO_3$) was applied to raise the pH to a level approaching 6.4. Soil analysis for Al, Mn, Ca, and P, however, did not predict the occurrence of nutrient deficiency or

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[3] Mention of a trademark, vendor, or proprietory product does not constitute a guarantee or warranty of the vendor or product by Oregon State University. It does not imply its approval to the exclusion of other vendors or products that may also be suitable.

toxicity conditions. Similarly, analysis of field grown plant tissue indicated that Ca, P, Mn, Mo, and Mg concentrations were above accepted critical levels and that toxic concentrations of these nutrients were not present. Only N was deficient in plants grown in unlimed soil. Field and greenhouse experiments with pH, Ca, N and Mo variables and evaluation of nodulation were undertaken to characterize the increase in dry matter production from 2.4 to 11.0 Mg ha^{-1} when lime applications increased the soil pH to the recommended level of 6.4. Plants at all pH levels (5.5 to 6.4 in the field and 5.3 to 6.5 in the greenhouse) were well nodulated. Under greenhouse conditions the application of 1 mg Mo kg^{-1} unamended soil resulted in a total dry matter yield, total N uptake and shoot N concentration of 9.87 g pot^{-1}, 0.216 g pot^{-1}, and 26.5 g kg^{-1}, respectively, compared to corresponding values of 2.96, 0.040, and 20.6 for plants grown without Mo. The application of ammonium nitrate to alfalfa grown in unamended soil increased shoot dry matter production from 1.46 to 7.01 g pot^{-1} in the greenhouse and 3.7 to 12.0 Mg ha^{-1} under field conditions. Responses to N and Mo, especially at the lower pH levels, suggested that the growth response to lime is due primarily to increased nodule efficiency, resulting from greater Mo availability as soil pH is raised. No response in yield or nodulation to the application of $CaSO_4$ was measured. Application of Mo to well nodulated but N-limited alfalfa stands grown in the Woodburn or similar soils may provide an economical, effective means for increasing production in cases where Mo deficiency is the major growth limiting factor.

Additional Index Words: soil acidity, nodulation, nodule efficiency.

INTRODUCTION

Characterizing the effect(s) of soil acidity and the application of lime on the growth of a legume such as alfalfa (Medicago sativa L.) can be complex due to the large number of soil chemical properties which are simultaneously altered when lime ($CaCO_3$) is applied. The most commonly cited effects include reductions in the activities of potentially toxic Al, Mn and H ions and the increased availability of Ca, P and Mo (Jackson, 1967). The symbiotic growth habit of legumes further complicates this characterization. In addition to effects on the host plant, the survival of native and applied Rhizobium sp. can also be affected (Mahler, 1983; Mulder and Van Veen, 1960). Important N_2 fixation factors such as nodulation (Andrew, 1976; Munns, 1970), nodule effectiveness (Munns et al., 1977), and nodule occupancy (Dughri and Bottomley, 1983; Jones and Morley, 1981) can all be affected by soil acidity related conditions.

The growth response of alfalfa to lime has been studied on a wide variety of acid soils, with the beneficial effect of lime being attributed to the correction of one or more soil acidity related limitations such as Al toxicity (Janghorbani et al., 1975), P deficiency and Al toxicity (Mahler, 1983; Munns, 1964a), Ca deficiency (Munns et al., 1977), and Mo deficiency (James et al., 1968; Mortvedt, 1981). Often, however, the soils investigated represent harsh or atypical conditions for alfalfa production.

The Woodburn sil (Aquultic Argixeroll) is an important agricultural soil in the Willamette Valley of western Oregon and is well suited for growing alfalfa. At pH values in excess of 5.4, levels of extractable Al and Mn are typically quite low (Chao et al., 1961), while Ca and especially P are often well above the established critical levels (Gardner et al., 1983). Sorption of Mo by Fe oxides would probably be low (Jarrell and Dawson, 1978; Reisenhauer et al., 1961). Yet, plants grown in this soil below pH 6.0 (1:2 soil:water suspension) are obviously stunted and chlorotic. The objective of this research was to characterize the growth response of alfalfa to lime on this moderately acid, but otherwise fertile Woodburn sil soil.

MATERIALS AND METHODS

Soil and Site Description

The soil used was a deep, moderately-well drained sil of the Woodburn series, a member of the fine-silty, mixed, mesic Aquultic Argixerolls. The soil was located on the Oregon State University Hyslop Crop Science Field Laboratory and had been used predominately for small grain and grass seed crops. Alfalfa had been grown as recently as 5 years prior to initiation of this research. Specific soil characteristics were as follows: pH 5.5 (1:2 soil:water suspension); Ca 6.2 cmol(+) kg^{-1}, Mg 1.1 cmol(+) kg^{-1}, and K 0.48 cmol(+) kg^{-1} (1 $\underline{M}$ ammonium acetate, pH 7); Al 0.06 mg kg^{-1} (0.2 $\underline{M}$ $CaCl_2$); Mn 10.0 mg kg^{-1} (DTPA); Fe 17 g kg^{-1} (dithionite-citrate-bicarbonate); CEC 15.4 cmol(NH_4^+) kg^{-1}; organic matter 24 g kg^{-1} (Walkley-Black method); and P 120 mg kg^{-1} (dilute acid, ammonium fluoride).

Field Experiment

Lime ($CaCO_3$) was initially applied in October 1971 at the rates 0, 2.2, 6.7, and 11.2 Mg lime ha^{-1} as part of a long term reacidification study (Doerge and Gardner, in press). The experimental design was a split-split plot factorial with two crop types as the main plots, two methods of lime incorporation as the subplots, and the lime rates as the sub-subplot variable. In October 1979 four additional rates of lime, 0, 1.7, 5.0 and 8.4 Mg ha^{-1}, were applied factorially to the four plots in each of the three replications which had received the same initial rate of lime. This provided 16 liming treatments covering a range in soil pH of 5.5 to 6.7. Individual plots were 4.6 x 10.7 m.

'Du Puits' alfalfa was seeded into a fine, preirrigated seedbed in September 1980. Seed was coated immediately prior to seeding with a mixture of two commercial peat inoculum preparations (Nitragin® and Noculator®) at a rate of 2.2 g kg^{-1} seed which was several times the manufacturer's recommended rate. Fertilizer application was based on analysis of the surface 15 cm of soil (Gardner et al., 1983). Sulfur as $CaSO_4 \cdot 2H_2O$ or K_2SO_4 was uniformly applied annually in the early spring at rates of 34 to 45 kg S ha^{-1}. Annual uniform applications of 2.2 to 4.4 kg B ha^{-1} as $Na_2B_{10}O_{16} \cdot 10H_2O$ were made beginning one year after seeding. Weed control was accomplished using pronamide [N-(1,1-dimethylpropyl)-3,5-dichlorobenzamide], diuron [3-(3,4-dichlorophenyl)-1,1-dimethylurea], and paraquat [1,1'-dimethyl-4,4'-bipyridium ion] according to manufacturer's recommendations.

Dry matter yields were measured on 10 May, 24 June, 9 August, and 21 September in 1982 and on 23 May, 11 July, and 24 August in 1983. Herbage was harvested at the early bloom stage by mowing a 0.9 x 10.1 m strip in the central portion of each plot at a height of 0.1 m. Plant tissue samples for chemical analysis were taken within 1 day of the second 1982 harvest and all three of the 1983 harvests. Plant part sampled was the upper 2/3 of the top in the second 1982 harvest and the entire harvested portion in the three 1983 harvests to permit calculation of total N uptake in harvested material. Plant samples were digested using the Kjeldahl method and analyzed for N and P on a Continuous Flow Analyzer, Model 200, using Technicon Method No. 334-74A/A. Calcium, K, Mg, Mn and Mo were determined using nitric-perchloric acid digestion (Jackson, 1974) and analysis by atomic absorption.

In August 1982, intact root + soil cores were taken from 3 treatments whose pH's averaged 5.5, 5.8 and 6.4 to examine nodulation, root morphology, and root mass. Cores were cylindrical, 30 cm in height, and 10 cm in diameter. Fifteen cores, consisting of 5 from each replication, were taken from each treatment. Cores were soaked overnight in a 4% (w/v) Calgon solution to disperse soil aggregates and facilitate recovery of root and nodule tissue. Cores were then placed on a 1 mm mesh screen and rinsed repeatedly with a fine spray of water until all soil was removed. Nodule lobes (hereafter referred to as nodules) were counted, root morphology was visually evaluated, and root and nodule tissue was oven-dried at 60°C for 48 h and weighed.

Composite surface (0 to 15 cm) soil samples were taken each fall to evaluate soil pH. Samples were obtained from a 3 x 6 m area in the center of each plot to avoid possible soil mixing from adjacent plots.

Prior to the 1983 growing season, plots were split and treated with two rates of N, 0 and 672 kg N ha^{-1} as NH_4NO_3. Three hundred thirty-six kg N ha^{-1} was applied in mid-March, prior to initiation of regrowth, with 168 kg N ha^{-1} applied immediately after the first and the second cuttings, respectively. This N rate was calculated to supply 140% of the N required for maximum yield of alfalfa on this site, estimated to be 16 Mg root plus shoot dry matter ha^{-1} with an average N content of 30 mg kg^{-1}.

Greenhouse Experiments

Experiment 1. pH-Ca-N. A bulk sample of unlimed surface (0 to 15 cm) soil (pH 5.3) from a border strip between replications in the field experiment was obtained in the fall of 1982. The soil was crushed to pass a 0.7 mm sieve, air-dried and thoroughly mixed. Plastic lined pots 0.083 m in diameter were filled with 0.90 kg of soil and equipped with a 0.013 m diameter perforated PVC watering tube extending the full height of the pot to facilitate watering and addition of fertilizer solutions.

Three rates of $K_2CO_3 \cdot 1\frac{1}{2}H_2O$ and Ca as $CaSO_4$ and two rates of N as NH_4NO_3 were applied to pots in a randomized block factorial design with 4 replications. The rates of potassium carbonate were those required to adjust the soil pH to 5.3, 5.8 and 6.5 as determined in a previous equilibration study under comparable conditions. Potassium carbonate and Ca were applied as dry reagents and mixed into individual pots at rates of 0, 1.3 and 3.5 cmol (+) kg^{-1} soil. Cumulative N rates were 0 and 714 mg N kg^{-1} soil. Nitrogen solution applications were made every 10 days beginning 3 weeks after planting in amounts sufficient to supply all required N assuming at least 60% recovery in plant tissue. Other fertilizer applications included 2 cmol(+) Mg kg^{-1} soil as dry reagent $MgSO_4$ and 2 mg B kg^{-1} soil as boric acid solution. Identical levels of K were maintained in all pots by addition of K_2SO_4 as necessary. Pots were then brought to field capacity (-0.033 MPa), by adding 0.24 kg distilled water kg^{-1} soil and allowed to equilibrate for 22 days.

Each pot was planted with 8 inoculated 'Du Puits' alfalfa seeds in February 1983 and thinned to 3 when plants were 2 to 5 cm in height. Greenhouse conditions included a 16 h photoperiod and an ambient temperature of 20 to 25°C. Pots were weighed every 1 to 2 days and watered with distilled water as required to maintain soil water content near -0.033 MPa.

All herbage more than 0.02 m above the soil surface was harvested 42, 77, 102 and 127 d after planting. Plant material was dried at 60°C for 48 h, weighed, and ground to pass a 1.3 mm sieve for analysis of total Kjeldahl N. Following the final harvest, intact roots were recovered from each pot and placed on a 1-mm mesh screen. Soil adhering to the root systems was removed by repeated rinsing with a fine spray of water. Nodules were counted and root and nodule tissue was oven dried at 60°C for 48 h and weighed.

Shoot and root growth, N uptake, and nodulation data were analyzed using standard analysis of variance techniques to identify the level of significance of treatment differences.

Experiment 2. Mo. Unlimed surface soil (pH 5.6) was obtained and prepared exactly as in Experiment 1. The fertilizer application was the same as the -N, -Ca treatment at pH 5.3. Molybdenum as ammonium molybdate was applied at 0 and 1.0 mg Mo kg^{-1} soil using a randomized block design with four replications. Growth conditions, seeding and harvest dates, and methods of data analysis were identical to those used in Experiment 1.

RESULTS

Field Experiment - 1982

A marked increase in alfalfa dry matter yield was measured in the first full year of production as soil pH increased from 5.5 to above 6.1 (Fig. 7). Plant concentrations of Ca, P, and Mg varied little with soil pH (Fig. 8) and in all treatments exceeded reported critical nutrient levels (Rogers et al., 1981). Plant Mn content decreased as soil pH increased from pH 5.5 to 6.1 but changed little as pH increased above 6.1. Plant N content increased appreciably as soil pH increased, being less than 30 g N kg^{-1} below pH 6.0. Nitrogen concentrations below 30 g kg^{-1} are considered deficient and are consistent with field observations of stunted shoots and chlorotic foliage on plants grown in soil below pH 6.0. Plant content of Mo did increase very slightly with increasing pH although in every treatment it was above the 0.5 mg Mo kg^{-1} level considered adequate for alfalfa growth (Reisenhauer, 1956).

Root dry weights from intact core samples nearly doubled as soil pH increased from 5.5 to 6.4 (2.1 to 4.1 g plant^{-1}). As expected, roots at all three pH levels showed none of the morphological abnormalities associated with Al toxicity such as thickened roots and reduced lateral root development. There were no significant differences in nodulation of plants at all pH levels with 65, 68 and 70 nodules plant^{-1} at pH values of 5.5, 5.8, and 6.4, respectively.

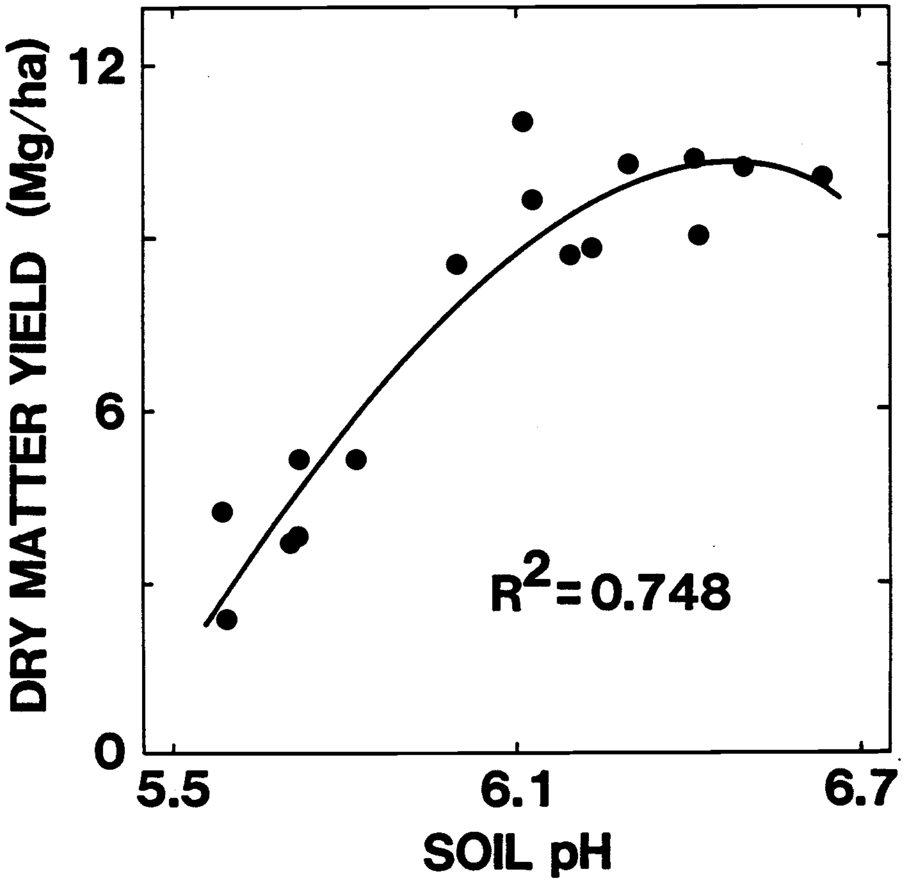

Figure 7. The relationship between shoot dry matter yield of field grown alfalfa and pH of a Woodburn sil measured in four 1982 harvests.

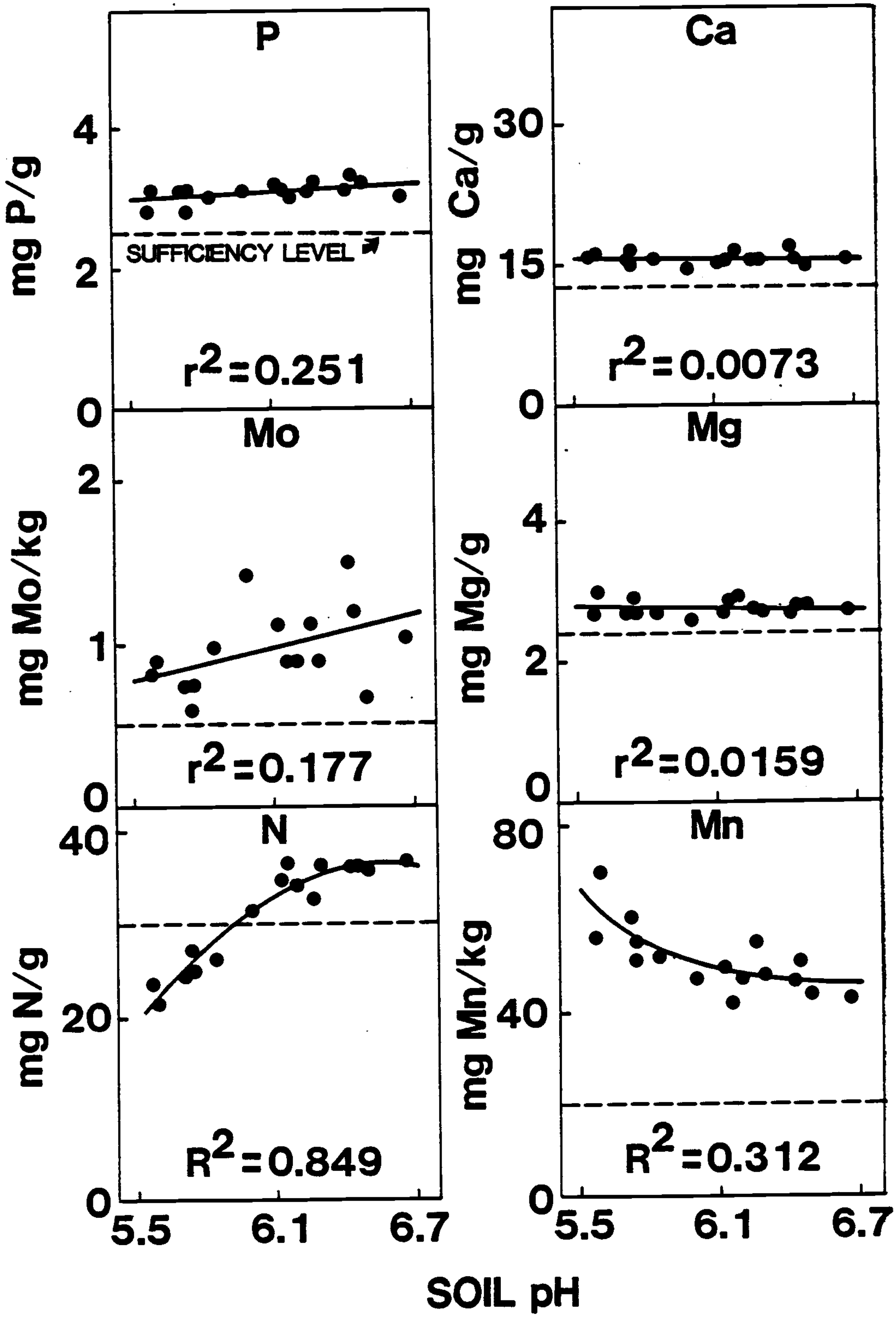

Figure 8. The relationship between plant tissue contents of Ca, P, Mn, Mg, N and Mo and the pH of a Woodburn sil as compared to tabulated sufficiency levels. Values are for the upper 2/3 of the plant tops sampled at 1/10 bloom on 24 June 1982.

Greenhouse Experiments

The application of Ca to alfalfa did not affect root or total shoot yield, nodulation, or N uptake. The interaction between pH and N was significant as illustrated by total shoot and root dry matter yields (Table 6). No toxicity or nutrient deficiency symptoms were observed in any treatments other than a yellowish green color of foliage from the -N treatment at pH 5.3.

The effect of pH on nodulation, average N content of shoot tissue, and total N uptake for plants receiving no N fertilizer is shown in Table 7. Plant roots grown at all pH levels were well nodulated and, as expected, showed no apparent effects commonly associated with Al toxicity. The number of nodules per plant doubled as the pH increased from 5.3 to 6.5. This is due primarily to the large increase in root growth, and when compared on the basis of number of nodules per g of root, the plants grown at pH 5.3 had the highest nodule density. Plants supplied with N were nearly devoid of nodules and data for nodulation and N uptake are not reported.

Highly significant increases in dry matter yield of tops and roots, shoot N content, and total N uptake resulted from the application of Mo (Table 8). Total dry matter yields of tops and roots in Mo treated pots approached those obtained in the -N treatments at pH 6.5 from Experiment 1 (89 and 80% of the -N, pH 6.5 values, respectively). Total N uptake and average shoot N content also approached the values measured in the -N treatments at pH 6.5 (76 and 92% respectively).

In both experiments the total NH_4 + organic N content of the soil from each pot receiving no N fertilizer was determined to

Table 6. The effect of soil pH and N on the dry matter yield of alfalfa tops and roots grown in a Woodburn sil under greenhouse conditions.

	Soil pH					
	5.3		5.8		6.5	
N treatment	Tops†	Roots	Tops†	Roots	Tops†	Roots
	g/pot					
-N	1.46	0.91	3.54	2.33	7.34	4.18
+N	7.01	3.45	9.07	4.78	10.00	4.91

† Total of 4 harvests.

$LSD_{0.05}$ = 0.69 and 0.59 g pot^{-1} for dry matter yield of tops and roots, respectively.

Table 7. The effect of pH on nodulation, N content and total N uptake for alfalfa grown in a Woodburn sil under greenhouse conditions without N fertilizer.

	Nodulation†			
pH	Nodules $plant^{-1}$	Nodules g^{-1} root	N content of tops†	Total N uptake‡
			g kg^{-1}	g pot^{-1}
5.3	33.2	111	24.7	0.052
5.8	62.3	84.4	26.3	0.127
6.5	67.3	52.8	29.0	0.286
$LSD_{0.01}$	16.3	38.9	3.0	0.027
F value	18.6**	8.1**	7.7**	273**

†N_0 treatments.

‡Total of 4 harvests plus roots.

Table 8. The effect of application of 1.0 mg Mo kg^{-1} soil on dry matter yields and N uptake for alfalfa grown in a Woodburn sil at pH 5.6 under greenhouse conditions.

Treatment	Dry matter yield Tops†	 Roots	N content of tops†	Total N uptake‡
	--- g pot^{-1} ---		g kg^{-1}	g pot^{-1}
-Mo	1.78	1.18	20.6	0.049
+Mo	6.52	3.35	26.5	0.216
$LSD_{0.01}$	3.06	1.39	3.0	0.070
F value	49.5**	50.1**	77.3**	118.**

†Total of 4 harvests.

‡Total of 4 harvests plus roots.

evaluate whether increased N uptake from potassium carbonate or Mo treated soil could be the result of an increased contribution from soil N. There were no significant differences in the levels of NH_4 + organic N between any of the -N treatments in either experiment. There was also no measurable difference between the levels of total N in the soil before and after plant growth had occurred.

Field Experiment - 1983

Yield and N uptake responses of alfalfa to the application of N were measured at all pH levels with the largest differences occurring at the lowest pH's (Fig. 9). The yield of -N and +N subplots were not significantly different above pH 6.1. A significant ($p<0.01$) pH x N interaction was observed, similar to that seen in the first greenhouse experiment. The N concentration in the herbage harvested from the -N plots followed a relationship similar to 1982 (Fig. 8). In the +N plots the N concentration in the alfalfa was essentially independent of soil pH and averaged 34.0 g N kg^{-1} across all pH levels. Increases in yield, plant N content, and N uptake from the application of N fertilizer were the most pronounced in the first cutting (22 May) when the soil was moist and soil temperatures were low. The average daily high temperature at 20 cm depth for the 3 weeks prior to harvest was 14.3°C. By the second and third cuttings, the responses to N were small above pH 6.1. In the 3 weeks prior to these cuttings the average daily high temperatures at 20 cm depth were 18.4 and 23.4°C, respectively.

Prior to the initiation of regrowth in March 1983, 2.2 kg Mo ha^{-1} as sodium molybdate in solution was broadcast-applied to alfalfa

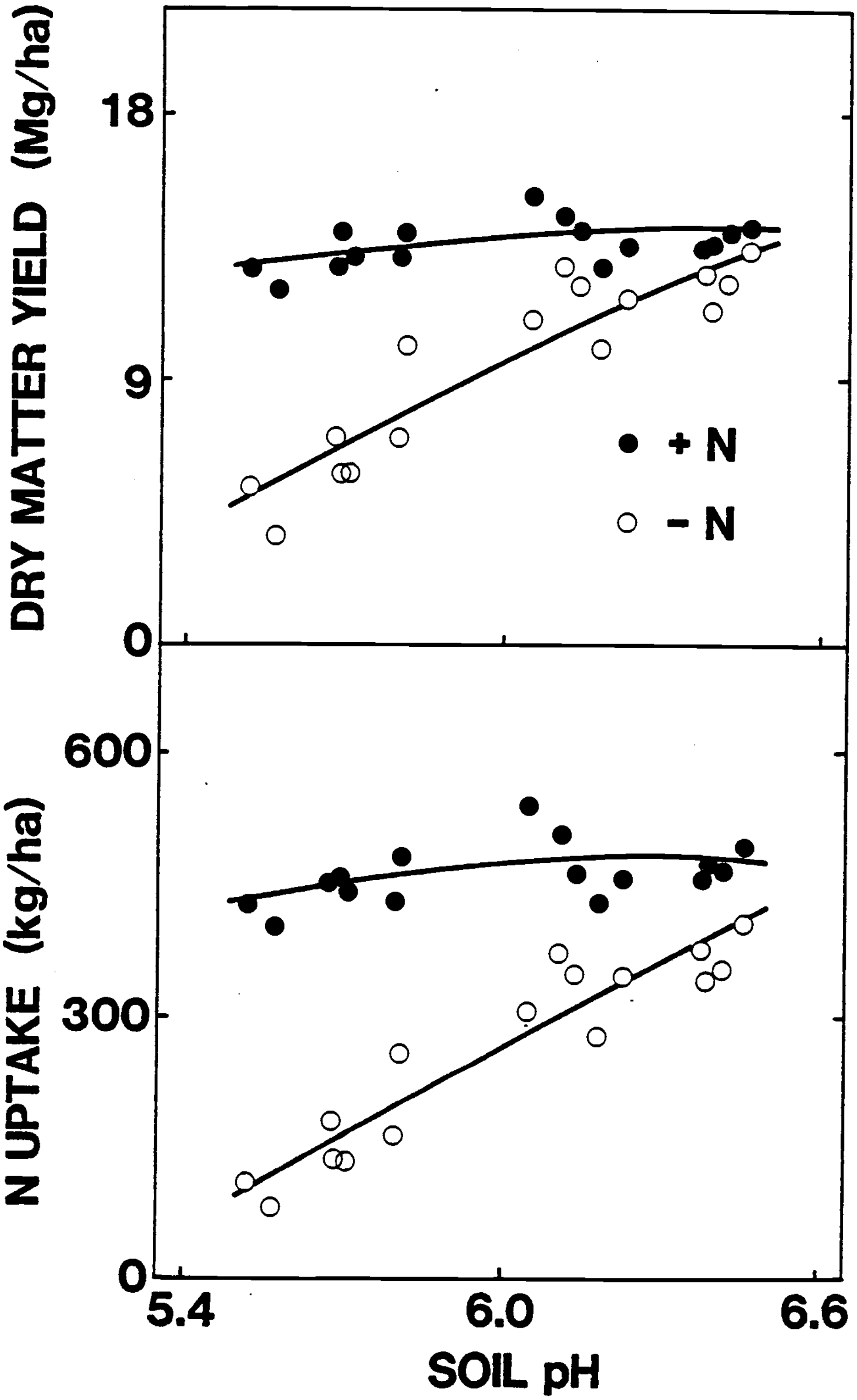

Figure 9. The relationships between shoot dry matter yields (a) and N uptake (b) for symbiotic and N fertilized alfalfa with the pH of a Woodburn sil. Yields are the total of the three 1983 harvests.

growing in adjacent unlimed border plots. Gradually, growth and color responses were observed, with maximum response occurring in the final harvest. By visual estimate dry matter yield in the final cutting was more than double that obtained from unlimed soil not receiving Mo. This is in spite of a somewhat reduced stand and greater weed competition in the unlimed soil as compared to that observed in plots at pH's sufficient to produce maximum yields.

DISCUSSION

The relationship between the 1982 yield of field grown alfalfa and soil pH (Fig. 7) is similar to results previously obtained on this soil (M.D. Kauffman, 1976, unpublished data). Plant tissue analysis suggests that of the nutrients most likely to be affected by soil acidity, only N was deficient at the lower pH levels (Fig. 8). Minimal variation of plant P content (Fig. 8) and the presence of adequate levels of P in plants from all lime treatments strongly suggest that improved P availability is not the basis for alfalfa's response to lime on this soil. This is in contrast to the findings of Mahler (1983) on an andic soil. Manganese was well below tabulated toxicity levels of 380 mg kg^{-1} (Andrew and Hegarty, 1969) and 175 mg kg^{-1} (Ouellette and Dessureaux, 1958).

Neither soil nor plant analysis data suggest Ca deficiency or Al toxicity in this soil. The absence of a response to Ca in the greenhouse provides additional evidence that neither Ca deficiency nor Al toxicity are occurring. Munns (1964b) reports that the presence of Ca mitigates the toxic effects of moderate concentrations of Al with the protective action of Ca failing only at relatively high levels of soluble Al. Thus if Al toxicity were a factor in this soil, the application of Ca would be expected to provide some positive effect. Such an effect, either on nodulation, root morphology, N uptake or dry matter yield, was not observed.

The examination of nodulation of field grown plants at pH's of 5.5, 5.8 and 6.4 strongly indicates that the N deficiency in plants grown in soil below pH 6.0 is not due to poor nodulation *per se*.

This is confirmed by the nodulation observed in the greenhouse experiments.

The marked response to NH_4NO_3 in both greenhouse experiment 1 and the 1983 field experiment is consistent with earlier findings that alfalfa is more sensitive to soil acidity when dependent on N_2 fixation rather than N fertilizer (Andrew, 1976; Munns, 1964a). Munns (1964a) reports that alfalfa's ability to respond to N fertilizer begins to decrease below a pH of about 5.5; presumably as Al and/or Mn toxicities begin to seriously impair the plant's capability to utilize N. The results of this study are consistent with this finding as optimum yields of N fertilized plants could be achieved at pH 5.5 in the field (Fig. 9) and pH 5.8 in the greenhouse (Table 6). The response of field grown plants to N fertilizer at the lower pH may be the result of their ability to explore more favorable subsoil layers where the pH increases to 5.8 at depths below 0.45 m.

The yield depression of N fertilized alfalfa below pH 5.8 in the greenhouse (Table 6) and the increase in plant Mn content in this same pH range (Fig. 8) may suggest that the threshold level of Mn toxicity for alfalfa grown in this soil is about 70 mg kg^{-1}. This value is well below published critical levels for alfalfa of 175 (Ouellette and Dessureaux, 1958) and 380 mg kg^{-1} (Andrew and Hegarty, 1969). Further research would be required to establish whether Mn may indeed be limiting growth below pH 5.8 in this soil or if there is some other inhibitory factor which is removed by increasing soil pH (Franco and Munns, 1981).

Balancing all K levels in the pH-Ca-N experiment using K_2SO_4 introduced a sulfate variable which could have an effect on Rhizobia availability of Mo due to adsorption would be much less pronounced than in acid soils high in Fe oxides. Also, it does not appear to impose any of the more obvious acid soil restrictions characteristic of many soils below pH 5.4. In previous work, the contribution of improved Mo availability to plant growth when acid soils are limed may have gone unrecognized for three main reasons. First, if no Mo treatments are included, the entire growth response to lime may be attributed solely to other more readily apparent limitations associated with soil acidity (Janghorbani et al., 1975; Mahler, 1983). Second, if Mo treatments are included, a response may not be observed if some other soil acidity related factor is more limiting than Mo deficiency. Also, a Mo response may not be detected if applied Mo is unavailable, as in the case of Mo sorption following a broadcast application to the soil surface (Reisenhauer, 1963; Sims et al., 1983). And third, Mo is often included in uniform supplemental fertilizer applications to greenhouse and field studies in which the response of alfalfa to lime is being evaluated (Munns, 1964a; Munns et al., 1977). This may confound results by either reducing or eliminating improved plant growth due to greater Mo availability following liming.

The results of this study also raise the question of how acidity should be managed on these soils when used rotationally for legume and wheat production. Liming of moderately acid Willamette Valley soils to a pH above 6.0 has been shown to increase winter wheat yield losses due to take-all root rot (Taylor et al., 1983). Applying just enough lime to inactivate toxic substances and supplying additional Mo as recommended for highly weathered, leached soils (Kamprath,

1970) may be a feasible alternative to liming this soil to the recommended pH level of 6.4. Caution in using this approach is required as combined applications of lime and Mo to legumes may result in excessive levels of Mo in plant tissue for use as forage (James et al., 1968; Petrie and Jackson, 1982). Applications of Mo to well nodulated but N-limited alfalfa stands may provide a means for increasing production in cases where Mo deficiency is the major growth limiting factor.

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SUMMARY AND CONCLUSIONS

In one portion of this study the long term reacidification of two important Willamette Valley soils was investigated. The rate of disappearance of carbonates applied in the liming materials was related to the degree to which lime was mixed with the soil, rate of lime application, and initial soil pH. At lime rates up to 8.4 Mg ha^{-1} at least 90% of the applied CO_3^{2-} was released within the first two years. At the higher lime rates, significant amounts of CO_3^{2-} were present for up to 3.5 years.

Measurement of the long term changes of pH and extractable basic cations contained in the liming materials in the surface (0 to 15 cm) soil were found to follow similar trends and provided convenient measures with which to express soil acidification. Direct measurement of acidification rates in terms of pH units decline per year was complicated by seasonal pH variations of 0.3 to 0.4 units for the soils used. The declines in extractable cations were much more linear and permitted the calculation of acidification rates in terms of pH units y^{-1}. This was possible by knowing the relationship between pH and levels of extractable basic cations for each soil and the measured annual changes in these cations. In both soils the rates of acidification increased with increasing quantities of lime initially applied.

The composition of soil solution during the leaching season was determined at both sites from plots covering a wide range in soil pH.

Ca^{2+}, Mg^{2+}, and NO_3^- concentrations were significantly and positively correlated with soil pH. Estimated levels of HCO_3^-, based on Henry's Law and the dissociation constants for $H_2CO_3^*$, were low. Nitrate was the dominant anion in soil solutions at both locations. The significant positive correlation between pH and NO_3^- concentration in soil solution indicates that nitrification does proceed to a greater extent in limed soils. This would be consistent with more rapid acidification of limed compared to non-limed soil.

The application of lime was also found to stimulate the acidifying processes of CO_2 evolution and organic matter mineralization.

Calcium release from mineral weathering appeared to have an important effect on soil pH and extractable Ca, particularly in the absence of large inputs of acidifying fertilizer materials.

The reacidification of limed soil was found to be a self-limiting process. When a soil is limed, acidifying processes are stimulated and net soil acidification occurs at an accelerated rate. As the pH of the soil drops, so does the rate of acidification. Because of the many biogeochemical factors involved, any attempt to predict soil acidification would require a very comprehensive model. Additional information required to construct such a model would include quantification of the pH dependence of important soil acidifying processes, accurate prediction of the quantity and composition of seasonal through drainage, and assessment of the rates of mineral weathering in soils.

The second portion of this study characterized the marked growth response of alfalfa to lime on a moderately acid (pH 5.5), high P Woodburn sil soil. Growth was very poor in unlimed soil although soil and plant tissue analysis did not identify elements other than N in critical nutrient deficiency or toxicity ranges. Nitrogen was found to be deficient but only in plants grown in soil below pH 6.0.

Response of inoculated alfalfa to pH, Ca, Mo and N treatments was examined in two greenhouse experiments while alfalfa's response to N was evaluated in a field experiment. Plants at all pH levels in all experiments were well nodulated; even down to pH 5.3. The application of $CaSO_4$ resulted in no significant increase in plant yield or nodulation.

Marked response to N and to Mo in the absence of applied N, especially at the lower pH levels, suggested that alfalfa's growth response to lime is largely due to increased nodule efficiency resulting from greater Mo availability as soil pH is raised. A response of alfalfa to Mo was not anticipated as Woodburn soil is not highly weathered and does not contain high levels of Fe oxides which absorb Mo thus reducing its availability. The results of this study raise a question concerning the extent of Mo deficiencies in the Woodburn and other similar soils in the Willamette Valley when used for legume production. Also can a small quantity of Mo be substituted for a large quantity of lime. This could be important as Woodburn soil is often used rotationally for legume and wheat production and liming to a pH above 6.0 could seriously increase winter wheat yield losses due to take-all root rot. Applying just enough lime to inactivate toxic substances and supplying additional Mo may be a feasible alternative to heavy lime applications in cases where Mo deficiency, and not poor nodulation, is the major factor limiting alfalfa growth.

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APPENDICES

Appendix Table 1.

Unreacted Carbonate in Field Experiment on the Woodburn Soil

Lime Rate	Crop[1] Type	Mixing[2] Treatment	1972			1973			1974			1975		
			Rep 1	Rep 2	Rep 3	Rep 1	Rep 2	Rep 3	Rep 1	Rep 2	Rep 3	Rep 1	Rep 2	Rep 3
Mg ha^{-1}			kmol(-) ha^{-1}											
2.2	A	Min	18.5	5.3	9.9	-	-	-	-	-	-	-	-	-
		Max	9.0	-	8.4	3.0	-	1.7	-	-	-	-	-	-
	P	Min	4.0	1.3	4.7	-	11.1	9.8	-	-	-	-	-	-
		Max	11.7	1.1	8.4	-	1.0	5.0	-	-	-	-	-	-
6.7	A	Min	*	119.0	67.4	13.1	7.1	13.7	-	-	1.1	-	-	-
		Max	24.9	28.8	40.7	1.7	1.7	1.0	-	-	-	-	-	-
	P	Min	61.5	50.3	32.4	26.3	13.7	18.4	18.9	3.1	11.7	-	-	-
		Max	50.0	24.9	35.4	27.5	5.7	15.6	-	-	1.0	-	-	-
11.2	A	Min	137.0	107.0	153.0	122.0	52.1	55.5	*	35.8	47.8	20.3	12.4	16.3
		Max	64.9	65.6	121.0	55.3	15.8	52.5	*	*	5.1	4.3	5.6	9.5
	P	Min	212.0	95.0	126.0	101.0	246.0	180.0	106.0	69.7	245.0	31.9	30.9	142.0
		Max	68.4	52.9	119.2	35.6	42.6	61.3	5.1	36.1	3.6	0.3	10.2	18.8

[1] A = annual crop, P = perennial crop

[2] Min = disced, Max = rototilled

[3] * = no sample

[4] - = no detectable carbonate

[5] no carbonate was detected after 1979.

Appendix Table 2.

Unreacted carbonate in field experiment on the Nekia Soil

Lime Rate	Crop Type	Mixing Treatment	1973			1974			1975			1979[1]		
			Rep 1	Rep 2	Rep 3	Rep 1	Rep 2	Rep 3	Rep 1	Rep 2	Rep 3	Rep 1	Rep 2	Rep 3
Mg ha^{-1}			kmol(-) ha^{-1}											
2.2	A	Min	10.6	5.3	*	7.2	-	-	-	-	-	-	-	-
		Max	4.1	2.8	*	-	-	-	-	-	-	-	-	-
	P	Min	4.6	-	*	-	-	-	-	-	-	-	-	-
		Max	-	3.5	9.4	-	-	-	-	-	-	-	-	-
8.4	A	Min	41.6	40.3	*	6.5	10.5	13.8	-	-	-	-	-	-
		Max	*	9.4	20.0	-	-	-	-	-	-	-	-	-
	P	Min	53.5	64.1	15.2	*	*	18.4	-	-	-	-	-	-
		Max	*	8.7	64.2	-	-	-	-	-	-	-	-	-
14.6	A	Min	115.0	79.2	*	25.7	54.7	38.9	26.0	31.9	26.6	-	9.2	0.7
		Max	*	*	*	3.5	6.1	14.7	-	-	-	-	-	-
	P	Min	239.0	122.0	126.0	*	*	95.7	59.0	111.0	51.7	12.6	5.3	4.6
		Max	22.6	18.7	35.8	*	*	8.1	-	-	-	-	-	-

[1] no carbonate was detected after 1979.

Appendix Table 3.

Plot Identification for Field Experiment on the Nekia Soil. 1973 -1979.

14.6 1/ Max 2/ P 3/	0 Max P	8.4 Min P	14.6 Min P	2.2 Min A	14.6 Min A	14.6 Max A	0 Max A	Rep 1
2.2 Max P	8.4 Max P	2.2 Min P	0 Min P	8.4 Min A	0 Min A	8.4 Max A	2.2 Max A	
8.4 Max A	2.2 Max A	2.2 Min A	0 Min A	14.6 Max P	0 Max P	8.4 Min P	2.2 Min P	Rep 2
0 Max A	14.6 Max A	14.6 Min A	8.4 Min A	8.4 Max P	2.2 Max P	14.6 Min P	0 Min P	
0 Min P	2.2 Min P	0 Max P	14.6 Max P	0 Min A	8.4 Min A	8.4 Max A	0 Max A	Rep 3
14.6 Min P	8.4 Min P	2.2 Max P	8.4 Max P	2.2 Min A	14.6 Min A	1.2 Max A	14.6 Max A	

1/Lime application rate in Mg ha-1; applied 10/1972.

2/Mixing treatment: Max = rototilled, Min = disced.

3/Crop Type: P = perennial, A = annual.

Appendix Table 4

Plot Identification for Field Experiment on the Nekia Soil 1980-1983

14.6[1] 8.4[2] 15 [3]	0 2.2 2	8.4 14.6 12	14.6 0 13	2.2 14.6 8	14.6 14.6 16	14.6 2.2 14	0 0 1	Rep 1
2.2 0 5	8.4 8.4 11	2.2 2.2 6	0 8.4 3	8.4 2.2 10	0 14.6 4	8.4 0 9	2.2 8.4 7	
8.4 8.4 11	2.2 8.4 7	2.2 14.6 8	0 14.6 4	14.6 8.4 15	0 8.4 3	8.4 0 9	2.2 0 5	Rep 2
0 2.2 2	14.6 2.2 14	14.6 0 13	8.4 14.6 12	8.4 2.2 10	2.2 2.2 6	14.6 14.6 16	0 0 1	
0 8.4 3	2.2 0 5	0 2.2 2	14.6 2.2 14	0 14.6 4	8.4 0 9	8.4 8.4 11	0 0 1	Rep 3
14.6 0 13	8.4 14.6 12	2.2 8.4 7	8.4 2.2 10	2.2 14.6 8	14.6 14.6 16	2.2 2.2 6	14.6 8.4 15	

[1] Lime application rate in Mg ha^{-1}; applied 10/1972.

[2] Lime application rate in Mg ha^{-1}; applied 10/1979.

[3] Treatment No.

Appendix Table 5

Soil Test (0-15 cm) Data for the 1979 Field Experiment on the Nekia Soil

Lime Rate	Crop Type	Mixing Treatment	Soil Test Data								
			Rep 1			Rep 2			Rep 3		
			pH	Ca	Mg	pH	Ca	Mg	pH	Ca	Mg
Mg ha^{-1}				cmol(+) kg^{-1}			cmol(+) kg^{-1}			cmol(+) kg^{-1}	
0	A	Min	4.6	2.3	0.35	4.7	3.5	0.54	4.8	4.2	0.48
		Max	4.4	2.1	0.34	4.5	2.4	0.37	4.8	3.4	0.40
	P	Min	4.8	3.6	0.59	4.8	4.7	0.63	4.6	3.0	0.47
		Max	4.7	2.8	0.49	4.8	3.3	0.46	4.8	4.1	0.70
2.2	A	Min	4.8	3.8	0.76	5.3	5.0	1.1	5.1	4.5	0.84
		Max	4.5	2.2	0.54	4.9	3.9	0.86	5.0	4.6	0.83
	P	Min	5.1	5.2	1.2	4.8	3.4	1.1	5.0	4.0	1.0
		Max	4.8	3.1	0.81	5.0	4.0	1.1	5.1	4.9	1.1
8.4	A	Min	5.4	5.8	0.79	5.5	7.3	0.89	5.6	7.5	0.95
		Max	5.4	6.1	0.81	5.3	5.5	0.84	5.4	7.0	0.87
	P	Min	5.3	5.6	0.91	5.2	5.9	0.79	5.3	6.4	1.0
		Max	5.2	6.0	0.84	5.5	6.8	0.85	5.4	7.4	0.89
14.6	A	Min	5.8	8.9	0.89	5.8	10.2	0.94	5.9	9.5	0.93
		Max	5.9	9.6	0.81	5.7	9.1	0.92	5.7	8.4	0.87
	P	Min	5.8	9.4	0.92	5.9	9.7	0.77	5.4	7.4	0.78
		Max	5.8	9.0	1.1	5.6	7.9	0.81	5.8	9.9	0.91

Appendix Table 6.

Soil Test (0-15 cm) Data for the 1980 Field Experiment on the Nekia Soil

Treatment No.	pH			Ca			Mg		
	R1	R2	R3	R1	R2	R3	R1	R2	R3
				------------cmol(+) kg^{-1} --------------					
1	4.7	5.1	4.9	2.6	4.2	2.9	0.28	0.56	0.37
2	5.1	5.1	5.4	4.5	3.4	6.0	0.50	0.34	0.64
3	5.8	5.9	6.3	9.6	8.8	11.0	0.60	0.47	0.59
4	6.1	6.5	6.4	11.8	15.4	14.5	0.39	0.50	0.48
5	4.9	5.1	5.1	2.6	3.1	3.7	0.61	0.89	0.96
6	5.6	5.4	5.4	6.3	5.6	5.7	1.10	0.66	0.78
7	5.7	6.4	6.1	7.3	12.1	8.9	0.44	0.91	0.95
8	6.3	6.8	6.3	12.2	13.4	13.6	0.67	0.69	0.70
9	5.3	5.6	5.7	5.6	5.6	6.9	0.70	0.92	0.92
10	5.6	5.9	5.8	7.2	8.4	8.4	0.76	0.70	0.95
11	6.5	6.3	6.4	13.3	11.6	13.6	0.71	0.76	0.83
12	6.5	6.8	6.8	13.0	19.8	16.2	0.75	0.94	0.87
13	5.7	6.1	5.8	7.8	9.6	7.5	0.80	0.89	0.85
14	6.1	6.0	5.9	11.1	8.9	9.7	0.86	0.80	0.86
15	6.3	6.5	6.7	12.8	13.4	14.2	0.76	0.67	0.78
16	7.1	6.9	7.0	19.8	18.1	20.0	0.67	0.69	0.67

Appendix Table 7.

Soil Test (0-15 cm) Data for the 1981 Field Experiment on the Nekia Soil

Treatment No.	pH			Ca			Mg		
	R1	R2	R3	R1	R2	R3	R1	R2	R3
				cmol(+) kg^{-1}					
1	4.6	5.2	5.1	1.6	3.3	2.2	0.18	0.49	0.22
2	5.3	5.2	5.5	4.4	4.0	5.6	0.45	0.37	0.55
3	5.9	6.1	6.2	8.3	8.7	9.0	0.53	0.54	0.68
4	6.4	6.9	6.2	11.9	15.7	10.4	0.46	0.55	0.56
5	5.2	5.1	5.3	2.1	2.7	4.2	0.37	0.53	0.67
6	5.5	5.6	5.6	5.9	5.3	6.1	0.69	0.78	0.77
7	6.0	6.8	6.3	7.9	18.3	11.1	0.49	0.67	0.87
8	6.8	6.8	6.3	14.4	14.8	12.0	0.66	0.78	0.69
9	5.6	5.5	5.8	5.7	5.6	6.8	0.62	0.67	0.84
10	5.8	6.0	6.0	7.0	8.6	8.3	0.68	0.87	0.86
11	6.5	6.3	6.6	11.5	10.5	12.6	0.68	0.72	0.77
12	6.6	7.0	6.9	14.9	15.3	17.4	0.75	0.63	0.80
13	5.8	5.9	5.8	8.5	8.6	7.9	0.83	0.79	0.82
14	6.2	6.1	6.1	10.7	8.5	10.3	0.80	0.81	0.85
15	6.6	6.5	7.1	13.5	11.8	16.5	0.73	0.68	0.75
16	7.2	7.3	7.6	17.0	19.5	23.4	0.58	0.60	0.58

Appendix Table 8.

Soil Test (0-15 cm) Data for the 1982 Field Experiment on the Nekia Soil

Treatment No.	pH			Ca			Mg		
	R1	R2	R3	R1	R2	R3	R1	R2	R3
				------------ cmol(+) kg^{-1} ------------					
1	4.56	5.09	4.80	1.8	3.7	2.6	0.23	0.45	0.26
2	5.35	5.02	5.23	4.6	2.7	4.4	0.49	0.32	0.49
3	6.03	6.04	6.23	9.0	8.4	9.6	0.72	0.60	0.72
4	6.42	6.75	6.12	12.0	14.3	9.6	0.70	0.75	0.54
5	5.04	5.14	5.26	2.6	3.2	4.4	0.49	0.78	0.74
6	5.58	5.56	5.64	5.9	5.2	5.9	0.86	0.81	0.73
7	6.06	6.51	5.85	8.2	11.8	7.8	0.66	0.69	0.92
8	6.47	6.66	6.10	11.9	12.8	9.9	0.73	0.85	0.74
9	5.54	5.44	5.72	5.4	5.2	7.1	0.60	0.60	0.81
10	5.72	5.96	5.84	6.5	7.9	8.1	0.77	0.82	0.79
11	6.27	6.17	6.39	10.1	9.5	12.8	0.72	0.77	0.88
12	6.26	6.90	6.85	11.1	16.1	16.7	0.86	0.77	0.68
13	5.76	6.03	5.57	7.5	9.6	6.5	0.77	0.91	0.76
14	5.98	5.94	6.17	8.8	8.3	10.0	0.74	0.80	0.89
15	6.40	6.48	6.70	11.4	12.4	13.8	0.77	0.78	0.76
16	6.92	7.09	7.20	16.1	17.4	19.4	0.75	0.61	0.59

Appendix Table 9.

Soil Test (0-15 cm) Data for the 1983 Field Experiment on the Nekia Soil

Treatment No.	pH			Ca			Mg		
	R1	R2	R3	R1	R2	R3	R1	R2	R3
				------------cmol(+) kg^{-1}--------------					
1	4.75	5.16	4.90	1.3	4.2	1.8	0.14	0.52	0.24
2	5.16	4.94	5.43	4.1	2.7	4.8	0.60	0.28	0.93
3	5.93	5.85	6.07	8.8	8.1	9.1	0.72	0.63	0.73
4	5.98	6.47	5.94	10.1	12.6	8.6	0.69	0.76	0.61
5	5.00	5.12	5.28	2.6	3.0	3.9	0.39	0.55	0.73
6	5.55	5.41	5.43	6.0	5.3	5.1	0.82	0.72	0.66
7	5.80	6.47	5.99	7.3	12.0	8.1	0.88	0.77	0.88
8	6.28	6.48	6.12	12.0	12.1	9.6	0.83	0.89	0.72
9	5.42	5.40	5.74	5.2	4.7	6.5	0.61	0.59	0.83
10	5.48	5.78	5.86	6.6	7.9	7.6	0.71	0.84	0.81
11	6.08	6.04	6.15	10.2	9.0	9.4	0.78	0.74	0.77
12	6.11	6.87	6.79	9.8	14.6	13.2	0.81	0.87	0.87
13	5.67	5.97	5.62	7.7	8.4	7.5	0.78	0.87	0.89
14	5.94	5.95	6.05	8.4	8.2	8.8	0.73	0.82	0.87
15	6.22	6.22	6.41	11.3	10.8	10.9	0.84	0.76	0.84
16	6.57	6.77	6.90	13.6	14.5	15.1	0.91	0.88	0.92

Appendix Table 10.

Plot Identification for Field Experiment on the Woodburn Soil. 1972-1979.

2.2[1] Max[2] A[3]	2.2 Min A	2.2 Max P	11.2 Min P	
11.2 Max A	11.2 Min A	6.7 Max P	6.7 Min P	Rep 1
6.7 Max A	0 Min A	11.2 Max P	0 Min P	
0 Max A	6.7 Min A	0 Max P	2.2 Min P	
11.2 Min P	6.7 Max P	11.2 Min A	0 Max A	
0 Min P	2.2 Max P	6.7 Min A	11.2 Max A	Rep 2
6.7 Min P	11.2 Max P	2.2 Min A	6.7 Max A	
2.2 Min P	0 Max P	0 Min A	2.2 Max A	
6.7 Max A	6.7 Min A	2.2 Min P	2.2 Max P	
2.2 Max A	0 Min A	0 Min P	6.7 Max P	
11.2 Max A	2.2 Min A	6.7 Min P	11.2 Max P	Rep 3
0 Max A	11.2 Min A	11.2 Min P	0 Max P	

[1] Lime application rate in Mg ha^{-1}, applied 10/1971.

[2] Mixing treatment: Max = rototilled, Min = disced

[3] Crop type: P - perennial, A = annual

Appendix Table 11.

Plot Identification for Field Experiment on the Woodburn Soil. 1980-1983

2.2[1/]	8.4[2/]	8[3/]	2.2	5.0	7	2.2	0	5	11.2	5.0	15	Rep 1
11.2	8.4	16	11.2	0	13	6.7	8.4	12	6.7	5.0	11	
6.7	0	9	0	8.4	4	11.2	1.7	14	0	5.0	3	
0	1.7	2	6.7	1.7	10	0	0	1	2.2	1.7	6	

11.2	5.0	15	6.7	1.7	10	11.2	0	13	0	1.7	2	Rep 2
0	5.0	3	2.2	5.0	7	6.7	8.4	12	11.2	1.7	14	
6.7	0	9	11.2	8.4	16	2.2	1.7	6	6.7	5.0	11	
2.2	8.4	8	0	0	1	0	8.4	4	2.2	0	5	

6.7	8.4	12	6.7	5.0	11	2.2	5.0	7	2.2	8.4	8	Rep 3
2.2	1.7	6	0	5.0	3	0	1.7	2	6.7	1.7	10	
11.2	8.4	16	2.2	0	5	6.7	0	9	11.2	5.0	15	
0	0	1	11.2	1.7	14	11.2	0	13	0	8.4	4	

[1/] Lime application rate in Mg ha^{-1}; applied 10/1971.

[2/] Lime application rate in Mg ha^{-1}; applied 10/1979.

[3/] Treatment no.

Appendix Table 12.

Soil Test (0-15 cm) Data for the 1979 Field Experiment on the Woodburn Soil

Lime Rate	Crop Type	Mixing Treatment	pH			Ca		
			R1	R2	R3	R1	R2	R3
Mg ha-1						--cmol(+) kg^{-1}--		
0	A	Min	5.5	5.3	5.2	7.0	5.9	4.9
		Max	5.3	5.3	5.8	5.0	5.3	7.0
	P	Min	5.5	5.3	5.4	6.8	5.8	6.0
		Max.	5.5	5.5	5.6	6.2	6.3	6.9
2.2	A	Min.	6.1	5.5	5.6	9.4	6.0	6.9
		Max.	6.1	5.4	5.5	9.1	6.1	6.5
	P	Min.	5.5	5.5	5.5	6.3	6.0	6.2
		Max	6.1	5.6	5.5	10.0	6.9	6.8
6.7	A	Min	5.5	5.6	5.5	6.6	6.8	6.1
		Max	5.7	5.6	5.6	7.1	7.3	6.1
	P	Min	6.3	5.7	5.8	10.0	7.2	7.9
		Max	6.2	5.7	5.7	10.1	7.0	8.6
11.2	A	Min	6.4	5.8	6.3	10.3	7.8	10.5
		Max	6.4	6.0	5.8	11.1	8.6	7.2
	P	Min	6.5	5.9	6.3	11.6	8.8	9.9
		Max	6.3	6.1	6.1	10.0	8.9	9.5

Appendix Table 13.

Soil Test (0-15 cm) Data for the Field Experiment on the Woodburn Soil, 1980-1981

Treat-ment No.	1980						1981					
	pH			Ca			pH			Ca		
	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3
				cmol(+) kg^{-1}						cmol(+) kg^{-1}		
1	5.7	5.9	5.9	6.2	6.7	7.3	5.6	5.6	5.8	6.2	6.7	7.5
2	5.8	5.9	5.9	7.1	6.8	6.8	5.6	5.7	5.7	6.7	6.9	7.0
3	6.4	6.3	5.9	9.0	8.6	7.3	6.1	5.8	5.7	8.5	7.1	6.9
4	6.7	6.4	6.7	11.4	9.5	11.5	6.5	6.2	6.5	9.8	9.4	10.2
5	6.4	5.7	5.6	10.3	6.2	6.2	6.2	5.4	5.6	9.4	6.1	7.1
6	6.0	6.0	5.9	7.1	7.6	7.2	5.8	5.6	5.9	6.9	7.3	7.3
7	6.9	6.4	6.3	12.9	9.0	9.7	6.8	6.2	6.3	12.0	9.1	9.9
8	7.0	6.5	6.4	14.0	9.9	10.9	7.1	6.4	6.5	12.7	9.5	9.8
9	6.0	5.9	5.8	7.8	7.2	7.4	5.7	5.7	5.8	7.4	7.0	8.0
10	6.1	6.0	6.1	8.0	7.6	8.6	6.0	5.8	6.0	7.6	7.6	8.7
11	6.8	6.3	6.1	11.4	9.1	8.4	6.7	6.0	6.1	10.9	8.6	8.1
12	6.9	6.6	6.3	12.6	10.4	9.8	7.0	6.5	6.3	11.6	10.4	9.2
13	6.6	6.1	6.3	10.5	7.9	9.8	6.3	5.9	6.4	9.9	8.1	9.8
14	6.5	6.4	6.3	9.8	9.2	9.0	6.3	6.0	6.3	9.5	8.5	9.4
15	6.9	6.5	6.3	13.5	9.9	10.4	7.0	6.4	6.5	11.9	9.9	10.5
16	7.1	6.8	6.3	13.6	11.4	9.4	7.3	6.6	6.3	14.3	11.2	9.5

Appendix Table 14

Soil Test (0-15 cm) Data for the Field Experiment on the Woodburn Soil, 1982-1983

Treatment No.	1982						1983					
	pH			Ca			pH			Ca		
	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3
					cmol(+) kg^{-1}						cmol(+) kg^{-1}	
1	5.53	5.55	5.69	5.3	5.7	6.2	5.42	5.63	5.67	5.7	6.3	6.6
2	5.53	5.53	5.65	5.3	5.7	6.4	5.51	5.36	5.69	6.3	5.9	6.7
3	6.12	6.00	5.86	7.9	7.4	7.0	6.04	5.71	5.67	8.4	7.0	6.8
4	6.16	6.38	6.32	8.6	9.1	9.6	6.17	6.15	6.36	9.2	8.6	9.8
5	6.14	5.45	5.62	9.5	5.6	6.5	6.01	5.53	5.54	9.8	6.1	6.6
6	5.75	5.63	5.83	6.5	6.2	7.1	5.70	5.68	5.67	6.4	7.0	6.5
7	6.74	6.03	6.00	10.8	7.8	9.3	6.72	5.98	5.84	11.5	8.2	8.9
8	6.93	6.07	6.31	11.9	7.8	10.0	6.91	5.99	6.28	12.3	8.5	10.0
9	5.73	5.71	5.71	6.5	6.6	7.2	5.70	5.74	5.68	7.6	6.7	7.4
10	5.77	5.84	5.92	6.8	6.6	8.5	5.71	5.83	5.85	7.1	7.5	8.7
11	6.66	5.85	5.95	10.5	7.8	7.3	6.46	5.91	5.95	10.2	8.2	8.3
12	6.86	6.34	6.27	12.1	9.3	9.4	6.82	6.16	6.28	11.6	9.1	9.2
13	6.32	5.90	6.35	9.5	7.5	10.2	6.13	5.78	6.25	9.6	7.5	9.8
14	6.21	5.86	6.30	9.1	8.3	9.5	6.24	5.95	6.23	9.5	8.4	9.3
15	6.80	6.22	6.25	11.4	8.7	10.2	6.71	6.28	6.15	11.1	9.5	10.1
16	7.07	6.51	6.41	12.2	10.6	9.2	6.75	6.45	6.17	11.6	10.1	9.2

Appendix Table 15.

Ion Concentrations in Saturated Paste Extracts from 1983 Nekia and Woodburn Soils

Soil	Treatment No.	Rep	Cations					Anions		
			Ca	Mg	K	Na	NH_4	NO_3	Cl	SO_4
			-------- mmol(+) L^{-1} --------					- mmol(-) L^{-1} -		
Nekia	1	1	0.45	0.06	0.33	0.35	0.18	0.74	0.64	0.25
		2	0.90	0.18	0.15	0.30	0.12	1.17	0.62	0.05
		3	0.60	0.11	0.28	0.30	0.11	0.98	0.59	0.05
	9	1	1.15	0.21	0.21	0.39	0.06	1.44	0.55	0.05
		2	0.80	0.15	0.23	0.26	0.11	1.12	0.58	0.09
		3	1.05	0.24	0.13	0.26	0.11	1.35	0.86	0.08
	11	1	2.10	0.28	0.13	0.35	0.12	2.38	0.64	0.05
		2	1.75	0.24	0.13	0.26	0.09	2.00	0.53	0.05
		3	1.95	0.30	0.13	0.26	0.08	1.78	0.80	0.09
	16	1	2.35	0.27	0.15	0.30	0.09	2.38	0.88	0.24
		2	2.40	0.23	0.08	0.13	0.03	2.14	0.76	0.09
		3	2.45	0.23	0.10	0.17	0.04	2.00	0.79	0.17
Woodburn	1	1	0.80	0.20	0.10	0.40	0.03	0.58	0.70	0.25
		2	0.81	0.21	0.08	0.26	0.04	0.66	0.64	0.38
		3	1.00	0.17	0.18	0.65	0.05	0.81	0.75	0.41
	9	1	1.05	0.20	0.05	0.30	0.03	0.97	0.61	0.29
		2	0.75	0.17	0.08	0.26	0.03	0.63	0.68	0.21
		3	0.90	0.18	0.03	0.30	0.03	0.88	0.59	0.29
	11	1	1.50	0.22	0.05	0.22	0.03	1.26	0.75	0.54
		2	1.25	0.18	0.01	0.22	0.01	0.96	0.55	0.29
		3	1.45	0.22	0.05	0.26	0.01	1.04	0.57	0.38
	16	1	1.55	0.18	0.03	0.56	0.01	0.90	0.47	0.29
		2	1.25	0.25	0.05	0.26	0.01	1.20	0.72	0.41
		3	1.45	0.18	0.05	0.26	0.01	1.21	0.64	0.38

Appendix Table 16.

Yield Data from Field Experiment on the Nekia Soil, 1980-1983

Treatment No.	1980 Wheat Yield			1981 Wheat Yield			1982 Red Clover Yield						1983 Wheat Yield		
							Cut 1			Cut 2					
	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3
	$Mg\ ha^{-1}$														
1	0.90	5.02	1.15	1.81	2.07	4.18	0.01	0.07	0.01	0.08	0.39	0.22	0.22	4.54	1.24
2	4.63	4.39	4.43	2.55	3.95	2.76	0.26	0.09	0.53	0.95	0.62	1.52	6.77	2.86	5.67
3	3.51	4.07	6.30	1.82	0.98	0.61	1.53	1.61	1.00	2.23	2.18	2.62	6.33	4.45	5.26
4	5.34	3.10	4.08	1.16	1.72	1.50	1.43	1.38	1.32	2.66	2.65	3.01	6.04	7.28	5.11
5	3.39	4.01	4.85	3.05	2.26	3.52	0.08	0.09	0.25	0.22	0.72	0.88	1.65	1.67	3.43
6	3.62	3.85	4.49	2.56	2.02	2.40	0.26	0.48	0.56	1.36	2.22	1.24	5.62	5.52	4.20
7	5.40	3.26	3.67	2.07	1.26	1.17	1.04	1.01	1.00	1.69	1.96	2.35	4.88	5.68	5.88
8	2.79	4.03	3.75	0.49	1.05	1.64	2.01	1.40	0.86	2.40	3.15	3.36	5.39	6.21	4.96
9	4.90	4.41	5.88	2.12	2.47	2.68	0.34	0.94	0.74	1.32	2.22	2.58	5.23	5.43	5.55
10	5.26	3.89	3.04	1.26	0.77	1.68	0.98	0.95	0.53	1.74	2.24	2.35	5.67	5.47	6.98
11	2.99	4.69	4.26	1.26	1.45	1.58	0.89	1.46	1.34	2.12	3.40	3.09	6.27	5.90	5.04
12	2.59	3.00	1.69	0.73	0.49	1.42	0.82	0.91	1.01	2.01	2.59	2.54	6.18	4.34	5.50
13	4.37	3.74	3.35	1.79	1.99	1.98	0.77	0.62	1.11	2.54	2.33	2.38	5.58	6.69	4.86
14	3.75	3.55	2.99	0.42	1.12	1.06	0.97	1.09	0.88	2.71	2.54	3.01	5.67	6.86	5.12
15	2.60	2.99	3.76	0.59	1.11	0.86	1.82	1.74	0.73	2.12	2.74	2.59	5.32	5.65	3.95
16	2.58	2.93	3.97	0.75	1.17	1.17	1.65	0.89	0.74	3.57	2.71	3.20	5.42	5.07	4.72

Appendix Table 17.

Yield Data from Field Experiment on the Woodburn Soil, 1980-1982

Treatment No.	1980 Wheat Yield			1981 Alfalfa Yield			1982 Alfalfa Yield											
				Cut 2			Cut 1			Cut 2			Cut 3			Cut 4		
	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3
	Mg ha^{-1}																	
1	5.74	4.70	3.33	0.30	0.38	1.25	0.68	0.51	1.32	0.62	0.56	1.14	0.27	0.23	0.60	0.26	0.33	0.65
2	6.42	4.69	6.99	0.84	1.24	0.36	1.81	1.79	0.65	1.40	1.85	0.53	1.34	0.76	0.18	1.19	0.80	0.44
3	7.12	5.52	4.32	1.92	1.26	1.76	2.70	3.03	2.74	2.87	1.75	3.23	1.87	1.50	1.32	1.69	1.26	1.72
4	5.82	4.21	3.64	2.42	2.21	2.32	3.29	2.72	3.14	3.17	2.88	4.04	2.17	1.42	1.85	1.80	1.74	2.67
5	6.97	3.88	6.40	1.12	0.64	1.18	2.09	0.38	1.24	2.06	0.62	0.89	0.80	0.48	0.68	0.96	0.48	0.68
6	6.89	5.37	4.96	0.34	1.37	1.53	0.91	1.85	2.98	0.79	1.76	2.36	0.33	0.82	1.24	0.52	0.93	1.09
7	7.19	4.65	4.44	2.39	1.67	1.68	2.69	2.68	2.89	2.87	3.21	2.86	1.66	1.82	1.13	1.60	1.56	1.52
8	5.56	5.30	3.94	2.83	1.48	1.94	2.29	2.68	3.63	2.29	2.23	3.95	1.75	1.29	1.94	1.55	1.73	1.89
9	5.66	5.42	6.54	1.27	0.35	0.70	1.40	0.56	1.42	1.56	0.68	1.58	0.85	0.40	0.76	0.89	0.36	0.82
10	6.08	6.88	6.39	1.36	0.84	0.62	2.19	1.55	1.46	1.62	1.36	1.56	1.44	0.61	0.72	1.36	0.66	0.96
11	5.85	5.38	5.46	2.30	1.84	1.86	2.64	3.42	3.00	3.19	3.15	2.69	1.64	1.92	1.52	1.76	2.19	1.93
12	7.34	5.43	5.31	2.63	2.80	2.19	3.36	3.95	3.31	3.59	4.11	2.73	1.55	1.72	1.01	1.78	2.04	1.69
13	6.20	4.05	5.37	2.12	1.29	2.44	2.79	2.84	2.63	2.89	2.52	3.15	1.33	1.15	1.81	1.95	1.46	1.76
14	6.22	5.66	3.53	2.64	2.18	2.78	3.10	3.70	2.97	3.55	3.39	3.85	2.00	1.81	2.27	2.07	2.18	2.30
15	6.28	7.63	4.78	2.77	1.92	2.34	3.12	3.28	3.04	2.03	3.72	3.34	1.87	2.18	2.00	2.22	1.77	2.58
16	6.12	4.15	3.13	2.93	3.15	2.45	2.40	3.53	3.27	3.01	3.14	3.62	1.44	1.78	2.19	1.39	2.13	2.26

Appendix Table 18.

Plant Tissue Analysis Data for the Upper Two-Thirds of Alfalfa Tops at One-Tenth Bloom from the Second 1982 Harvest, 24 June

Treatment No.	Rep 1						Rep 2						Rep 3					
	N	P	Ca	Mg	Mn	Mo[1]	N	P	Ca	Mg	Mn	Mo	N	P	Ca	Mg	Mn	Mo
	---------- $g\ kg^{-1}$ ----------				-- $mg\ kg^{-1}$ --		---------- $g\ kg^{-1}$ ----------				-- $mg\ kg^{-1}$ --		---------- $g\ kg^{-1}$ ----------				-- $mg\ kg^{-1}$ --	
1	19.1	3.5	17.9	3.2	87	0.89	18.4	3.1	16.2	3.0	77	-	27.6	2.7	14.6	2.7	47	-
2	27.4	2.5	14.2	2.5	46	0.82	23.6	2.8	17.0	2.7	57	-	19.4	3.1	16.4	2.9	65	-
3	33.2	3.3	14.5	2.7	49	0.59	26.8	3.0	13.8	2.2	48	-	34.5	3.0	15.3	3.0	43	-
4	33.8	2.9	13.9	2.4	41	0.74	36.4	3.3	15.3	2.9	55	-	38.2	3.4	16.8	2.9	48	-
5	29.3	2.9	16.2	2.8	49	0.74	22.3	2.9	16.6	2.9	55	-	22.5	2.6	16.6	2.9	56	-
6	20.4	2.9	14.6	2.5	63	1.05	26.1	3.1	15.4	2.8	55	-	34.5	3.3	15.4	2.9	47	-
7	37.0	2.9	15.5	2.5	48	0.89	26.1	3.0	13.6	2.5	51	-	34.5	3.3	17.4	3.4	67	-
8	35.7	3.1	15.3	2.4	48	1.20	36.4	3.4	14.4	2.7	49	-	33.8	3.3	16.9	3.2	57	-
9	28.7	2.8	13.9	2.3	40	1.42	19.1	3.5	15.7	2.8	81	-	26.3	2.9	16.6	3.1	60	-
10	31.9	3.2	14.4	2.4	41	0.97	20.6	3.0	14.5	2.8	60	-	25.7	2.9	17.6	2.8	56	-
11	37.7	3.0	16.5	2.7	47	0.89	36.4	3.1	14.5	2.9	39	-	35.1	3.1	15.0	3.0	46	-
12	35.7	3.1	16.5	2.9	58	1.12	35.1	3.1	13.9	2.8	39	-	36.4	3.3	14.0	2.7	34	-
13	38.3	3.2	17.3	2.7	46	1.12	28.2	3.0	13.7	2.6	39	-	35.7	2.9	18.3	3.3	56	-
14	37.0	3.3	16.3	3.0	54	0.89	32.6	3.2	14.5	2.6	40	-	34.5	3.0	14.7	2.6	52	-
15	37.0	3.0	15.9	2.4	45	1.50	32.6	2.9	14.2	2.5	38	-	38.2	3.3	20.6	3.3	58	-
16	40.9	3.2	16.2	2.7	51	0.67	33.8	2.7	15.2	2.6	41	-	35.1	3.1	15.8	2.7	37	-

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[1] Mo values are for composite samples of Reps 1, 2, and 3.

Appendix Table 19.

Dry Matter Yield of Alfalfa in 1983 on the Field Experiment on the Woodburn Soil

Treatment No.	Cut 1						Cut 2						Cut 3					
	Rep 1		Rep 2		Rep 3		Rep 1		Rep 2		Rep 3		Rep 1		Rep 2		Rep 3	
	N_0	N_1	N_0	N_1	N_0	N_1	N_0	N_1	N_0	N_1	N_0	N_1	N_0	N_1	N_0	N_1	N_0	N_1
	$Mg\ ha^{-1}$																	
1	1.01	4.04	0.79	5.05	2.09	5.57	1.19	2.96	1.03	3.32	1.86	3.43	1.03	3.82	0.87	3.41	1.08	4.48
2	2.42	5.05	2.74	5.39	1.06	4.67	1.03	3.19	2.29	3.97	1.57	3.50	1.85	4.32	1.99	4.48	1.17	3.59
3	6.11	6.38	2.67	5.68	4.42	5.32	3.08	3.50	1.57	3.70	3.43	4.02	3.35	5.50	2.73	4.12	3.03	3.68
4	5.25	5.43	4.38	5.66	4.13	4.69	2.81	3.32	3.17	3.91	2.69	4.18	4.87	5.17	3.77	4.57	4.21	3.77
5	3.77	5.05	0.97	5.21	1.21	5.79	2.87	4.27	1.50	3.97	1.50	4.13	3.90	4.58	0.82	4.03	1.05	4.98
6	0.92	5.32	3.66	4.78	3.23	5.90	0.63	2.76	2.69	3.66	3.43	3.43	0.80	4.12	2.97	4.30	2.88	4.12
7	3.32	5.23	3.50	5.84	4.29	5.03	2.60	3.97	2.20	3.19	2.92	3.59	4.64	4.05	3.80	3.94	2.91	3.80
8	3.52	4.78	4.04	4.96	4.53	5.75	3.39	4.38	3.08	3.75	2.81	3.75	5.04	4.59	3.94	4.30	3.80	4.62
9	3.30	4.67	1.77	5.14	1.98	5.70	2.45	3.32	1.14	3.48	1.62	3.79	2.28	4.63	1.22	4.48	1.82	4.39
10	3.10	5.12	2.92	4.96	2.94	5.21	2.13	3.95	2.02	3.50	2.18	3.91	2.01	3.96	1.40	4.57	2.53	4.33
11	6.20	6.71	5.48	6.42	5.05	5.72	3.59	3.79	2.85	4.65	3.03	3.66	3.26	4.49	4.24	4.89	4.92	3.83
12	5.79	5.77	5.30	5.93	4.13	5.79	3.35	4.11	2.76	4.02	2.81	3.32	4.01	4.25	4.77	4.51	4.03	4.51
13	4.92	7.03	3.03	5.95	4.45	5.86	3.82	4.74	2.40	4.18	2.92	3.97	4.83	5.03	2.97	4.54	3.44	4.54
14	4.65	5.93	5.07	5.99	4.71	5.97	3.03	3.82	3.19	3.55	3.01	3.66	4.49	4.87	4.45	4.03	4.09	4.42
15	6.60	6.22	4.31	5.77	3.59	5.39	4.27	4.49	2.40	2.87	2.49	3.39	5.16	3.70	4.89	3.97	4.18	4.77
16	5.61	5.50	4.67	6.17	5.01	5.14	4.65	4.33	3.48	3.86	2.56	2.85	4.32	4.79	5.52	5.34	4.62	4.60

Appendix Table 20.

Nitrogen Content of Whole Alfalfa Tops in 1983
from the Field Experiment on the Woodburn Soil

Treatment No.	Cut 1[1]						Cut 2[2]						Cut 3[3]					
	Rep 1		Rep 2		Rep 3		Rep 1		Rep 2		Rep 3		Rep 1		Rep 2		Rep 3	
	N_0	N_1	N_0	N_1	N_0	N_1	N_0	N_1	N_0	N_1	N_0	N_1	N_0	N_1	N_0	N_1	N_0	N_1
	g N kg^{-1}																	
1	16.8	37.0	18.5	31.6	33.0	46.6	21.4	29.9	22.0	32.2	23.2	36.0	17.8	30.2	19.5	26.3	22.3	26.7
2	24.8	37.6	19.6	44.8	21.8	44.2	20.2	30.5	22.6	26.6	19.8	34.9	18.9	23.0	21.8	28.6	15.9	26.7
3	22.9	37.0	22.9	40.0	34.7	43.0	23.2	29.4	25.0	31.6	28.2	34.9	23.5	29.1	24.6	31.3	26.3	27.8
4	34.1	40.0	31.3	39.4	34.1	41.2	27.8	24.8	31.4	31.6	25.4	31.0	24.0	31.8	28.6	29.7	26.9	28.4
5	28.5	37.0	19.0	38.8	24.0	45.4	26.1	29.4	20.2	28.7	18.6	31.5	24.6	26.9	17.8	25.2	19.7	27.8
6	21.2	40.0	25.7	43.0	28.5	49.6	20.8	32.2	25.0	29.2	29.4	32.0	17.2	27.4	24.0	27.8	26.3	27.3
7	36.3	35.2	23.5	43.0	29.1	41.8	28.4	29.4	27.3	36.0	24.2	32.6	28.0	24.1	25.2	26.2	28.5	25.0
8	37.5	43.0	32.4	40.6	35.8	35.2	27.3	33.3	30.2	32.6	28.8	36.0	27.4	31.8	24.0	31.3	28.5	27.8
9	25.2	38.8	20.7	42.4	26.3	43.6	25.5	28.8	19.6	31.0	20.9	31.5	25.7	23.6	18.4	27.3	20.8	29.6
10	22.9	37.6	23.5	38.8	28.0	37.0	23.2	27.6	22.0	33.2	23.2	37.7	20.1	26.3	20.6	22.7	23.0	30.7
11	33.5	44.8	29.6	35.8	33.0	43.0	32.6	28.8	27.3	32.9	24.2	33.2	25.2	26.9	27.4	24.4	24.1	27.3
12	32.4	40.0	30.2	31.0	30.2	43.0	30.2	28.8	27.3	32.0	29.4	36.0	27.4	24.1	28.0	29.6	24.7	30.2
13	31.9	44.8	24.6	43.0	31.3	34.4	29.0	32.2	27.8	33.2	28.2	40.0	28.6	26.9	20.6	27.3	26.3	31.0
14	25.2	33.4	28.0	40.6	36.9	37.2	27.8	32.2	30.8	32.6	31.0	28.7	26.9	28.0	25.4	31.8	26.3	25.5
15	33.0	41.2	30.2	36.4	28.0	40.5	28.4	34.4	31.4	29.8	28.3	31.6	30.3	24.1	28.6	30.7	29.1	28.8
16	33.5	38.8	33.0	43.6	34.6	47.2	30.8	31.0	28.4	31.5	32.2	30.5	26.9	30.7	25.2	26.2	28.5	27.7

Appendix Table 21.

Total Uptake of N in Alfalfa Tops in the Three 1983 Harvests from the Field Experiment on the Woodburn Soil

	Rep 1		Rep 2		Rep 3	
Treatment No.	N_0	N_1	N_0	N_1	N_0	N_1
	kg N ha^{-1}					
1	60.6	352	54.2	355	136	502
2	115	385	148	474	72.5	424
3	289	498	168	472	329	471
4	374	463	344	480	322	429
5	278	435	63.1	400	77.3	530
6	46.0	414	232	431	268	514
7	324	397	237	468	278	421
8	362	497	318	457	351	465
9	204	385	81.3	447	123	496
10	161	405	142	412	191	472
11	406	530	355	501	357	484
12	397	450	368	445	306	504
13	405	601	202	517	311	500
14	322	456	352	487	374	439
15	494	498	345	417	292	461
16	447	494	391	530	387	456

Appendix Table 22.

Dry Matter Yield of Alfalfa in pH-Ca-N Greenhouse Experiment

KC Rate	Ca Rate	N Rate	Dry Matter Yield															
			Cut 1				Cut 2				Cut 3				Cut 4			
			R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4
			$g\ pot^{-1}$															
0	0	0	0.17	0.19	0.30	0.21	0.46	0.43	0.42	0.44	0.42	0.20	0.43	0.54	0.42	0.43	0.36	0.63
0	0	1	0.12	0.22	0.33	0.17	1.03	1.14	2.02	1.36	2.39	2.61	3.42	2.54	3.20	2.87	3.41	2.55
0	1	0	0.16	0.26	0.24	0.15	0.36	0.46	0.43	0.48	0.31	0.27	0.37	0.59	0.38	0.40	0.43	0.40
0	1	1	0.15	0.27	0.23	0.19	1.36	1.55	1.20	1.52	2.51	2.54	2.13	3.21	2.58	2.78	2.60	3.41
0	2	0	0.15	0.20	0.22	0.13	0.47	0.30	0.47	0.29	0.52	0.13	0.45	0.41	0.54	0.25	0.53	0.32
0	2	1	0.11	0.27	0.22	0.14	1.25	1.56	1.52	1.20	2.19	2.55	2.18	2.15	2.73	2.71	3.11	2.58
1	0	0	0.33	0.40	0.30	0.28	0.84	0.80	0.85	0.93	1.26	1.05	1.19	1.32	1.72	1.19	1.32	1.18
1	0	1	0.41	0.38	0.35	0.33	2.64	2.11	1.88	1.81	3.87	3.85	3.39	2.92	3.28	3.57	3.47	2.67
1	1	0	0.22	0.32	0.37	0.32	0.58	0.84	0.87	1.03	0.92	1.01	1.39	1.14	1.19	1.02	1.40	1.17
1	1	1	0.21	0.25	0.38	0.34	1.93	1.87	1.83	2.04	3.35	3.17	3.35	3.17	3.25	2.99	3.71	3.36
1	2	0	0.31	0.31	0.32	0.33	0.59	1.01	0.71	0.76	0.82	1.29	1.38	1.03	0.92	1.31	1.53	1.05
1	2	1	0.30	0.32	0.33	0.33	1.89	2.03	1.80	2.27	3.63	3.18	3.50	3.74	3.55	3.07	3.18	3.56
2	0	0	0.33	0.39	0.46	0.40	1.86	1.13	1.63	2.02	2.95	1.55	2.75	3.04	3.31	1.71	2.72	2.82
2	0	1	0.36	0.44	0.44	0.36	2.02	2.59	1.95	1.92	3.32	3.83	3.12	3.74	3.74	3.77	3.64	3.89
2	1	0	0.40	0.38	0.39	0.39	1.48	1.60	1.54	1.54	2.65	2.77	2.52	1.88	2.88	3.02	2.95	2.00
2	1	1	0.41	0.41	0.45	0.49	2.02	2.56	2.27	2.77	2.94	4.00	4.04	4.13	3.77	3.70	3.11	3.60
2	2	0	0.38	0.53	0.40	0.34	1.90	2.00	1.30	1.81	3.13	2.97	2.03	2.55	3.09	3.02	2.45	2.90
2	2	1	0.51	0.39	0.39	0.36	2.22	2.01	2.47	2.25	3.49	3.86	4.41	3.58	3.59	3.34	3.99	3.33

Appendix Table 23.

Average N Content, Total N Uptake and Nodulation for Alfalfa from pH-Ca-N Greenhouse Experiment, N_0 Treatments

KC Rate	Ca Rate	N Content[1/]				N Uptake[2/]				Nodules/Plant				Nodules/g root			
		Rep				Rep				Rep				Rep			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
		---------- $g\ kg^{-1}$ ----------				---------- $g\ pot^{-1}$ ----------											
0	0	22.3	21.2	24.3	29.3	0.043	0.048	0.058	0.065	21.3	15.3	24.7	36.0	68.1	61.3	110.0	127.0
0	1	28.0	21.9	23.0	19.8	0.049	0.044	0.051	0.052	18.7	10.3	29.3	70.0	43.8	33.7	110.0	168.0
0	2	27.7	31.0	26.5	21.2	0.061	0.064	0.051	0.039	36.7	19.7	40.0	76.7	126.4	85.5	106.0	288.0
1	0	25.3	23.3	27.0	26.1	0.168	0.112	0.138	0.133	83.3	39.0	69.3	67.7	75.5	55.2	85.6	93.1
1	1	27.7	25.6	25.7	23.7	0.111	0.143	0.134	0.114	32.7	71.0	56.0	60.7	51.3	78.3	77.1	88.3
1	2	26.0	28.3	28.2	24.9	0.087	0.158	0.155	0.099	63.3	70.3	63.7	71.0	155.7	69.0	63.0	121.0
2	0	29.2	34.2	27.3	27.4	0.319	0.299	0.291	0.288	43.3	44.0	53.3	83.0	30.3	58.4	37.0	62.9
2	1	28.6	28.0	30.4	30.9	0.297	0.295	0.302	0.216	46.7	47.0	81.3	95.7	26.2	27.2	58.7	118.0
2	2	28.0	27.5	28.9	26.7	0.327	0.256	0.244	0.274	88.3	61.7	71.0	91.7	45.5	37.1	64.2	68.6

[1/] Average of all 4 cuttings

[2/] Includes roots and all 4 cuttings

Appendix Table 24.

Yield and N Content and Total N Uptake by Alfalfa in Mo Greenhouse Experiment

Rep	Mo Rate	D.M. Yield tops[1/]	D.M. Yield roots	N Content tops[1/]	N Content roots	N Uptake
		---g pot^{-1}---		---g kg^{-1}---		g pot^{-1}
1	-	1.59	1.01	20.2	9.7	0.042
	+	4.67	3.24	28.0	14.9	0.179
2	-	1.75	1.29	19.0	8.6	0.044
	+	7.66	2.93	23.8	12.6	0.219
3	-	1.92	1.26	22.0	12.0	0.057
	+	6.14	3.06	27.4	12.6	0.207
4	-	1.86	1.16	21.4	9.2	0.050
	+	7.63	4.17	26.8	12.6	0.257

[1/] Reflects data from all four harvests

Appendix Table 25

Soil Series Profile Descriptions,[1]

Nekia Series

These soils are on low, red foothills that are dissected by drainage channels and streams.

Ap - 0 to 9 inches, dark reddish-brown (5 YR 2/2) silty clay loam, reddish brown (5 YR 4/3) when dry; moderate, medium and fine, granular structure; friable, slightly hard, plastic and sticky; many roots; many, fine, interstitial pores; medium acid (pH 5.6); abrupt, wavy boundary. (5 to 10 inches thick.)

B1 - 9 to 18 inches, dark reddish-brown (5 YR 3/3) clay, reddish brown (5 YR 4/4) when dry; weak, medium, prismatic structure breaking to weak, very fine, granular structure; friable, slightly hard, plastic and sticky; common roots; many, very fine, tubular pores; strongly acid (pH 5.5)y; clear, smooth boundary. (3 to 12 inches thick.)

B21t - 18 to 24 inches, dark reddish-brown (5 YR 3/3) clay, reddish brown (5 YR 4/4) when dry; weak, very coarse, prismatic structure breaking to moderate, fine and very fine, subangular

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[1] All profile descriptions are those of the National Cooperative Soil Survey as reported in the <u>Soil Survey of Marion County Area, Oregon</u>. 1972.

blocky structure; friable, hard, plastic and sticky; common roots; many, very fine, tubular pores; few thin clay films on ped surfaces and in pores; strongly acid (pH 5.4); clear, smooth boundary. (4 to 18 inches thick.)

B22t - 24 to 36 inches, dark reddish-brown (5 YR 3/4) clay, yellowish red (5 YR 4/6) when dry; very weak, coarse, prismatic structure breaking to moderate, fine and very fine, subangular blocky structure; firm, hard, very plastic and very sticky; few roots; many, very fine, tubular pores; many moderately thick clay films on ped surfaces and in pores; very few, faint, black coatings on ped surfaces; very few, fine, black concretions; many, corase, sand-size fragments; strongly acid (pH 5.3); clear, wavy boundary. (8 to 18 inches thick.)

R1 - 36 to 45 inches, fractured bedrock, the fractures filled with reddish-brown (5 YR 4/4) clay, reddish brown (5 YR 5/3) when dry; weak, fine and very fine, subangular blocky structure; firm, hard, very plastic and very sticky; few large roots; many, very fine, tubular pores; few thick clay films on stone surfaces and in pores; variegations in color caused by weathering of the fragments of rock; many, medium, black coatings on stone surfaces; few, medium, black concretions; 90 percent of horizon is fractured, hard rock; strongly acid (pH 5.3); clear, wavy boundary.

R2 - 45 inches, basalt bedrock.

Color of the A horizon ranges from dark brown to dark reddish brown. Color of the B2 horizon ranges from dark reddish brown to yellowish red, but it is dominantly dark-reddish brown. In places the B2 horizon is silty clay. The content of coarse fragments of hard basalt in the A horizon ranges from 0 to 15 percent, but the content of coarse fragments in the B22t horizon is as high as 50 percent. Depth to bedrock ranges from 20 to 40 inches. Bedrock is at a depth of more than 30 inches in most places.

Woodburn Series

These soils are on braod valley terraces.

Ap - 0 to 9 inches, very dark brown (10 YR 2/2) silt loam, brown (10 YR 5/3) when dry; cloddy and has very weak, subangular blocky structure; friable, slightly hard, slightly sticky and slightly plastic; many roots; many, fine and very fine, tubular pores; few, fine, interstitial pores; common, medium and fine, reddish-brown and black concretions; medium acid (pH 5.9); abrupt, smooth boundary. (6 to 10 inches thick.)

A1 - 9 to 17 inches, dark-brown (10 YR 3/3) silt loam, brown (10 YR 5/3) when dry; moderate, medium, subangular blocky structure; friable, hard, slightly sticky and slightly plastic; common clean silt and sand grains on ped surfaces; many roots; many, very fine, tubular pores; few, thin, darker (10 YR 2/2) coatings on ped surfaces; few reddish-brown and black concretions; slightly acid (pH 6.2); clear, smooth boundary. (3 to 8 inches thick.)

B21t - 17 to 25 inches, dark yellowish-brown (10 UR 3/4) silty clay loam, brown (7.5 YR 5/4) when dry; moderate, coarse and medium, subangular blocky structure; friable, hard, sticky and plastic; common roots; many, very fine, tubular pores; few thin clay films on peds; few reddish-brown and black concretions; few black stains on ped surfaces; medium acid (pH 6.0); clear, smooth boundary. (7 to 9 inches thick).

B22t - 25 to 32 inches, dark-brown silty clay loam, brown (10 YR 5/3) when dry; few, fine and medium, distinct, dark-gray (10 YR 4/1) mottles, light brownish gray (10 YR 6/2) when dry; moderate, medium and coarse, subangular blocky structure; friable, hard, brittle, sticky and plastic; common roots; many, very fine, tubular pores; continuous, moderately thick clay films on ped surfaces and in pores; few, fine, black concretions and stains on ped surfaces; medium acid (pH 5.8); abrupt, smooth boundary. (6 to 10 inches thick.)

B31t - 32 to 39 inches, dark-brown (10 YR 4/3) silt loam, brown (10 YR 5/3) when dry; distinct, dark grayish-brown (10 YR 4/2) mottles in a few root channels; thin, dark grayish-brown (10 YR 4/2) coatings on plane surfaces, light gray (10 YR 7/2) when dry; nearly massive; some planes of weakness that are indistinct; vertical planes are more distinct than horizontal planes; very firm, very hard, brittle, slightly sticky and slightly plastic; few roots; many, fine and very fine, tubular pores;

continuous, moderately thick clay films on plane surfaces and in some root channels and pores; few, fine and medium, black concretions and few, black coatings on plane surfaces; medium acid (pH 5.7); gradual, smooth boundary. (7 to 10 inches thick.)

B32t - 39 to 54 inches, dark-brown (10 YR 4/3) silt loam, pale brown (10 YR 6/3) when dry; nearly massive, and has some indistinct vertical planes of weakness; very firm, very hard, brittle, slightly sticky and slightly plastic; no roots; many, fine and very fine, and few, medium, tubular pores; continuous, thin clay films in pores and in old root channels; few black concretions, and some patchy, black coatings on plane surfaces; medium acid (pH 5.9); gradual, wavy boundary. (11 to 17 inches thick.)

C - 54 to 68 inches, dark-brown (10 YR 4/3) silt loam, pale brown (10 YR 6/3) when dry; massive; very firm, very hard, brittle, slightly sticky and slightly plastic; no roots; many, very fine, tubular pores; common moderately thick clay films in larger pores and in old root channels or worm channels; few black coatings in pores and in channels; medium acid (pH 5.9); gradual, wavy boundary. (14 to 16 inches thick.)