Surface Application vs. Incorporation of Limestone for No-Till Alfalfa Production

by

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(ABSTRACT)

No-till alfalfa (*Medicago sativa* L.) establishment is the only environmentally sound procedure for alfalfa production on erodable land. Surface limestone application is the only reasonable method of placement in no-till systems with pH below 6.5. The purpose of this research was to evaluate surface limestone application vs. incorporation throughout the plow layer for alfalfa production in acidic soils. In this study limestone placement included: 1. incorporation during tillage operations, 2. surface application after tillage and preparation of seedbed, and 3. surface application without tillage. Limestone was applied at 0, 1.25, 2.50, and 5.00 tons per acre with each placement method. Limestone treatments were imposed on 30 Sept. 1986 in Montgomery County, VA (37^{0} 11'N, 80^{0} 25'W and 1950 ft. elevation) on a Groseclose silt loam (clayey, mixed, mesic Typic Hapludult) having a pH of 5.6 in the top 9 inches. Limestone treatments were imposed at a second site on 25 Nov. 1986 in Orange County, VA (38^{0} 13'N, 70^{0} 7'W and 515 ft. elevation) on a Davidson clay loam (clayey, oxidic, thermic Rhodic Paleudult) having a pH of 5.7 in the top 9 inches. 'Cimmeron' alfalfa was planted using no-till procedures on 23 March 1987 in Montgomery County and on 26 Aug. 1987 in Orange County. Soil samples were taken about 2 years after limestone application at depths of 0 to 1, 1 to 2, 2 to 3, and 3 to 6 inches for surface applied treatments and 0 to 3, 3 to 6, and 6 to 9 inches for incorporated treatments. Soil samples were also taken at a depth of 18 to 24 inches where limestone was incorporated during tillage at 0 and 5 tons per acre. Four harvests were made in 1988. At both locations, limestone application increased yields by 114 to 300% as compared with the check where no limestone was applied. Yields from plots receiving surface limestone application were equal to plots with incorporation at both locations. Tillage did not increase yields as compared with no tillage except in Orange County

on plots where no limestone was applied. Soil pH increased from 5.6 to 6.8 at the 1- to 2-inch depths and from 5.6 to 6.3 at the 2- to 3-inch depths where 5 tons per acre of limestone were surface applied in Montgomery County. In Orange County, soil pH increased from 5.5 to 6.5 at the 1- to 2-inch depths and from 5.6 to 6.1 at the 2- to 3-inch depths where 5 tons per acre limestone were surface applied. Above pH 5.5, Al saturation was below 2.7% in Montgomery County and 0.7% in Orange County. Aluminum saturation averaged 9.0% and 4.6% where pH was between 5.0 and 5.5 in Montgomery and Orange Counties, respectively. At both locations, in the 18- to 24-inch depths a pH of 4.8 was not influenced by limestone incorporated at 5 tons per acre. Aluminum saturation at 18- to 24-inch depths was 51% and 62% in Montgomery and Orange Counties, respectively. These data indicate that surface applied limestone can produce first year alfalfa yields similar to yields obtained with incorporated limestone.

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Dedicated to

the two women in my life

my Mom and

Chapter I

Introduction

I. Justification

Acidic soils do not provide favorable conditions for alfalfa production. A pH below 6.0 decreases alfalfa yields by limiting dinitrogen fixation, inhibiting nutrient availability, and decreasing root penetration. Traditional methods for establishing alfalfa call for limestone to be incorporated when the pH is below 6.5. Tillage to incorporate limestone exposes soil to erosion and thus limits the acreage where alfalfa can be grown. Many acres of erodable land are suitable for alfalfa production if no-till methods are used in establishment. With current recommendations, no-till alfalfa should only be planted if soil pH is above 6.5 since limestone cannot be incorporated.

A layer of modified soil pH (6.5 or above) can be created in the soil profile when enough limestone is incorporated into the soil. This layer provides a favorable environment for dinitrogen fixation and roots of the alfalfa plant can penetrate through this layer to grow into acidic subsoil. In acidic soils where limestone is incorporated to a depth of 8 inches, alfalfa roots will penetrate deeper than the plow layer and into low pH subsoil. Without a layer of modified pH in the soil profile, dinitrogen fixation does not occur and roots can not penetrate into acidic subsoil. Poor yields in acid soils may be due in part to limited soil moisture supply. Previously the belief has been that a zone of modified pH needs to be to the depth of the plow layer (approximately 8 inches). Recently, research on surface-applied limestone at Virginia Tech has suggested that a modified pH zone of 2 inches can provide the plant with adequate nodulation to give yields equal to those resulting from incorporation throughout the plow layer. If methods of growing no-till alfalfa on acidic soils can be developed, many acres of land will become available for alfalfa production.

II. Hypothesis

The studies reported intend to provide data to indicate whether surface limestone application is a valid method of soil pH modification for alfalfa production on acidic soils.

Hypotheses, stated in their null form are:

1. There is no yield increase obtained with incorporated limestone application when compared with surface limestone application.
2. There is no yield increase due to increased limestone application rates (from 0 through 5 tons per acre).
3. There is no yield increase due to the depth of the soil pH modification. The three depths of soil pH modification are zero inches (check), two inches (surface limestone application), and six inches (incorporated limestone).
4. There is no change in pH below the surface due to surface limestone application.

Chapter II

Literature Review

Alfalfa is a highly productive and nutritious forage and can reduce N fertilizer inputs in rotational cropping systems. In combination with *Rhizobium meliloti* Dang., alfalfa (*Medicago sativa* L.) has the potential to fix more N than other legumes (Vance, 1978). Addition of N to the soil through fixation makes alfalfa a very energy-efficient crop. After three cuttings per year, alfalfa added an average of 57 pounds of N per acre to the soil (Kroontje and Kehr, 1956) in Virginia experiments. Residual N can be utilized by the succeeding crops and can reduce the need for N fertilizer (Heichel, 1978).

Low soil pH severely decreases growth and vigor of alfalfa. Among many factors influenced by soil pH are inhibition of dinitrogen fixation, decreased nutrient availability, and decreased root penetration. The main detrimental influence of low pH is a decrease in dinitrogen fixation and nodule formation (Munns et al., 1977a). The major influence of pH on dinitrogen fixation is believed to be an indirect effect of H^+ concentration rather than a direct effect. Subtoxic levels of Al and Mn available at pH 5.2 to 6.0 will decrease dinitrogen fixation without directly injuring the plant. Below pH 6.0 Mn content in plants sharply increase (Doerge et al., 1985) and below pH 6.0 Mo and P availability decrease. Lowered levels of Mo and P also indirectly reduce dinitrogen fixation. Reduced levels of P and Mo can inhibit dinitrogen fixation but not be low enough to directly cause nutrient deficiency symptoms (Doerge et al., 1985).

Aluminum Toxicity

Aluminum is mobile in low pH soil conditions. In most soils with pH below 5.5, exchangeable Al can be available in levels toxic to plants (Munns 1964). In highly weathered soils, Al can be available in toxic concentrations at a pH above 5.5. Aluminum has been found at toxic concentrations at pH 6.6 in Missions soils in Idaho (Mahler, 1983). Reduction of toxic levels of Al, can be accomplished by raising soil pH through limestone application. Increasing rates of limestone has been shown to decrease exchangeable Al in soils (Moschler et al., 1960) and to reduce Al concentrations in top and root tissue of alfalfa (Macleod and Jackson, 1965). Limestone application to increase pH to 5.3, reduce exchangeable Al to subtoxic levels (Maclean et al., 1972; Rice, 1975). Further reduction of Al in the soil solution can be accomplished through increasing rates of limestone. Limestone application to the pH range of 5.5 to 6.0 reduce exchangeable Al below measurable levels (Janghorbani et al., 1975).

Exchangeable Al in soils decreases alfalfa yields, with yield response correlated with pH, percent base saturation, and Al concentration (Hoyt and Nyborg, 1971). Other legumes have also shown severe growth reduction due to presence of high levels of exchangeable Al. High concentrations of Al reduces dry matter yield of clover (*Trifolium repens* L.) and lotus (*Lotus pedunculatus* Cav.) (Haynes and Ludcke, 1981). Restriction of root penetration is a direct effect of Al. Impairment of root growth observed in subhorizons is often due to toxic levels of exchangeable Al rather than soil structure (Macleod and Jackson, 1965). Aluminum tends to accumulate in soil subhorizons through illuviation.

Impairment of plants to utilize N is often caused by toxic levels of Al and Mn. Between pH 5.5 to 6.0 alfalfa will show signs of N deficiency due to lack of dinitrogen fixation, but this can be overcome by addition of nitrogen fertilizer. Below pH 5.2, alfalfa growth was greatly inhibited even when supplied with N fertilizer (Munns, 1964, Rice, 1975). Legumes are unable to translocate N at low pH. At pH 4.0, N accumulated in the roots of both white clover and lotus due to their inability to translocated N (Haynes and Ludecke, 1981).

Manganese Toxicity

Manganese toxicity is often associated with poor alfalfa growth on acidic soils. Manganese is highly available at pH below 5.3. The main cause of alfalfa yield depression in an acidic soil, low in Al, was Mn toxicity (Lanyon et al., 1977). At pH values above 6.0, exchangeable Mn availability is generally too low to injure alfalfa. Increasing soil pH through limestone application reduces exchangeable Mn concentration in soils (Buss et al., 1975a; Janghorbani et al., 1975; Lanyon et al., 1977; Maclean et al., 1972; Martini et al., 1974) and in plant tissue (Doerge et al., 1985; John et al., 1972). Reduction below toxic concentrations occurred by raising pH to 5.3 (Maclean et al., 1972). Application of limestone to obtain a specified base saturation could be more effective at reducing toxic levels of Mn than application of limestone to a specified pH. Limestone application to a specified base saturation reduces variation in exchangeable Mn due to variations in soil cation exchange capacity. In soil limed to 70% base saturation, exchangeable Mn can be reduced to subtoxic levels (John et al., 1972).

Soil pH

Decreased yields of many crops under low pH conditions are often associated with the indirect influences of low pH rather than direct H^+ion content (Bache and Crooke, 1981). However, H^+ion content can decrease legume growth at very low pH. At pH below 4.7 H^+ions can decrease soybean (*Glycine max* L) yields (Lund, 1970). Influence on yields between pH 5.0 to 6.0 are partially accompanied by direct influence of H^+ions on biological activity in the root nodules (Maclean et al., 1972). Alfalfa supplied with N did not respond to increasing pH, suggesting that an increase in yield in this pH range is primarily due to increased N fixation. As pH increases from 5.2 to 6.0, yield increases 250% when no fertilizer N is added; and yield increases 13% on treatments with N fertilizer added (Rice, 1975). In sand culture H^+ion content greatly influenced alfalfa growth and nodulation. Virtually no nodulation occurred, in sand cultures absent of Al, at pH 4 to 4.5 and required a pH of 6.0 to achieve 100% nodulation (Andrew, 1976).

Calcium

Calcium deficiency can occur in low-pH soils. Yields reduction due to Ca deficiency is more likely than is plant injury or death. Calcium deficiency has been shown to lower alfalfa yields (Lanyon et al.,1977). Exchangeable Ca influences plant growth directly by acting as a nutrient and indirectly by enhancing root nodulation. John et al., (1972) found exchangeable Ca concentrations in tops and roots of alfalfa increased significantly with limestone application. The increase was more for shoots than for roots. Elevated levels of exchangeable Al induced a ten-fold decrease in Ca transport to shoots. Reduced Al toxicity resulting from limestone application would increase Ca transport in plants and would explain why Ca concentrations increased more in roots than in shoots as pH increased. In roots, Ca concentrations were reduced by high levels of Mn. Increase in pH reduced Mn toxicity in roots (John et al., 1972). Another influence of exchangeable Ca on alfalfa growth is increased nodulation. (Munns, 1970; Andrew, 1976). Andrew (1976) found a 100% increase in nodulation when he increased exchangeable Ca at pH 5.0.

Magnesium

Low levels of exchangeable Mg in soil can reduce crop yields. Addition of dolomitic limestone increases pH, adds Mg to the soil, and when added to soils low in exchangeable Mg, can increase crop growth. Munns (1970) added Mg in the form of $MgSO_4$ to soils and found a slight but insignificant increase in nodulation. Addition of dolomitic limestone showed no significant advantage over calcitic limestone on alfalfa yields or on stand persistence for soils with sufficient Mg. However, there was a slight and consistent advantage in favor of dolomitic limestone in studies by Moschler et al. (1960).

At high rates of calcitic limestone, Mg can become deficient in plants. Application of calcitic limestone to 100% base saturation decreased Mg concentrations in alfalfa tops compared to that of unlimed soil (John et al., 1972).

Molybdenum

In many soils, Mo availability is high enough for proper crop growth at pH above 6.5. Under low pH conditions, Mo availability decreases. Reduced alfalfa yields at low pH are often caused by Mo deficiency. Molybdenum deficiency is associated more with the nitrogen fixing capability of the alfalfa rather than directly on plant growth. Poor alfalfa growth on well-nodulated plants due to N deficiency can be corrected by either increasing the soil pH to 6.5 or by supplying adequate Mo or nitrogen fertilizer (Doerge et al., 1985). Increase in yields, and increase in total N uptake result from application of Mo. Increased pH through limestone application can also increase Mo availability. John et al. (1972) found Mo concentrations in alfalfa tops and roots increased progressively with increased limestone application. A caution when correcting for Mo deficiency is that application of both limestone and Mo can result in excessive levels of Mo in plant tissue consumed by livestock. Mo accumulations in animals can be toxic to animals and to humans eating the animal (James et al., 1968; Petrie and Jackson, 1982).

Phosphorus deficiency and influence on yield

Phosphorus deficiency is often a cause of poor yields in many crops. As soil pH is lowered, P availability decreases and can decrease to a point of deficiency. Bache and Crooke (1981) worked with barley on soils that had adequate P at neutral pH. When pH was lowered, they observed P deficiency. The main cause of this P deficiency was believed to be Al toxicity inhibiting utilization of P. Under low pH conditions, P reacts with Al to form Al- phosphate, which is precipitated out of the soil solution and becomes unavailable for plant growth (Macleod and Jackson, 1965). As soil pH is increased up to 6.5, more P becomes available for plant growth (Maclean et al., 1972; Mahler, 1983; Martini et al., 1974).

Addition of P to the soil increases dinitrogen fixation, if soil pH is initially deficient, (measured by acetylene reduction) decreases exchangeable Al, (Bouton et al., 1981) and plant nutrition of P, which is vital for proper growth, is directly increased. Exchangeable Al is decreased when P is applied to soils with pH below 5.0 (Maclean et al., 1972; Bache and Crooke, 1981). In the presence of P, legumes have been found to withstand high concentrations of exchangeable Al (Janghorbani et al., 1975). Haynes and Ludecke (1981) found reduced levels of Al and Mn in both tops and roots of white clover with addition of P. This reduction is believed to occur within the plant, since soil Al and Mn is only slightly decreased by P addition. A limestone-P interaction was found especially at low pH (Bouton et al., 1981; Janghorbani et al., 1975). This interaction could be due to the limestones many influences including decreasing exchangeable Al which reacts with P to make it unavailable.

Potassium

Potassium is vital to alfalfa growth. Low K levels cause less photosynthesis in alfalfa. With less available photosynthate there will be less dinitrogen fixation. Increased rates of limestone tend to decrease exchangeable K (Moschler et al., 1960). This is most likely due to greater amounts of K removed from the soil by the increased crop growth.

Zinc

Increasing soil pH influences availability of many micronutrients including Zn. As soil pH increases, Zn becomes less available for plant growth (John et al., 1972). In soils with sufficient Zn levels, Zn deficiency can occur when pH is raised above neutrality. Reduction of Zn below a sufficient level for plant growth has been found in one soil with pH as low as 6.5 (Maclean et al., 1972). In most soils, Zn deficiency only occurs when pH is raised above neutrality, which is a potential danger that could result from excessive limestone. Application of micronutrients with limestone can provide higher concentrations of micronutrients, such as Zn, that become less available with increased pH. Indiscriminate application of micronutrients can do as much harm as good. In many soils, micronutrient levels are initially high and addition of more micronutrients can cause toxicities (Lanyon et al., 1977). Possibilities of Zn deficiencies due to limestone application vary with soils and need to be considered when making soil amendments.

Mineralization

Mineralization is the process in which nitrogen and other nutrients, from the organic sector of soil, change to a form available to plants. As pH increases from an acidic level to near neutral level, an environment more favorable to soil microbes is created. These microbes break down organic matter releasing the nitrogen into soil solution. This increased level of available N through mineralization does not contribute to plant growth. As pH increased from 5.3 to 6.5, the amount of N mineralized increased only slightly (Doerge et al., 1985). Even with this slight increase, mineralization is too slow to support significant increase in alfalfa growth due to increased soil pH (Munns et al., 1977b).

High temperature and dinitrogen fixation

Many experiments of various influences on dinitrogen fixation are confounded by factors not taken into account. Temperature can be one such factor. Dinitrogen fixation, measured by acetylene reduction, is greatly reduced under high temperature stress. Dinitrogen fixation was impaired by daily heating to 32 C. As much as 90% of the dinitrogen fixation disappeared in 1 hr at 40 C and after 4 hr at 36 C (Munns et al., 1977a). In greenhouse experiments, where alfalfa is grown in pots, temperatures in the root zone can often reach levels high enough to inhibit dinitrogen fixation. In temperate climates, field temperatures in the root zone will rarely reach levels high enough to severely inhibit N fixation. Munns et al. (1977a) found that only the top 2 inches of soil reached temperatures above 30 C. This zone contained less than 10% of the plant's nodules. Most nodules were in the 4 to 12 inch range where the temperature was relatively stable. A possibility is that most nodules are in the 4 to 12 inch range due to previous heating and drought killing nodules in the upper soil layers. The influence temperature has on dinitrogen fixation may need to be taken into account for experimentation on dinitrogen fixation, especially in pot studies.

Harvesting influences on dinitrogen fixation

Dinitrogen fixation in alfalfa can increase and decrease throughout the growing season due to many factors. An important factor influencing dinitrogen fixation is harvesting. Harvesting decreased dinitrogen fixation 78% after the first harvest of the season and 86% after the second harvest of the season (Cralle and Heichel, 1981). The period of decreased dinitrogen fixation started 2 days after harvest and lasted up to 21 days after harvest. This could be due to an interdependence of canopy growth and dinitrogen fixation in legumes. A high level of photosynthate is needed before dinitrogen fixation can reach full capacity. High levels of photosynthate cannot be provided by a plant, such as alfalfa, with little photosynthetic area immediately after a harvest. Shortly after harvest, remobilized nonstructural carbohydrate becomes available from root reserves. Some of the carbohydrate is available to root nodules until photosynthesis can provide carbohydrate. Nodules are a weak sink for carbohydrate in comparison to top growth (Cralle and Heichel, 1981). Most of the remobilized carbohydrate is transported to plant tops. Lack of dinitrogen fixation after a harvest demonstrates that root nodules are not at their full-nitrogen-fixing potential throughout the entire growing season.

Stand longevity

Stand longevity of alfalfa is reduced in acidic soils. In some soils, alfalfa populations may flourish the first year and than rapidly decrease. Under low pH conditions, plant number decreased during the year of establishment and losses continued into following years (Moschler et al., 1960). This reduction in stand quickly leaves an alfalfa field sparse and uneconomical for production. In addition to yield of alfalfa, field experiments involving alfalfa production should also determine stand longevity.

Drought

Acidic soils limit rooting depth and increase alfalfa drought sensitivity. Under proper growing conditions, alfalfa tends to be drought tolerant due to a deep rooting system, which allows plants access to reserve moisture from soil depths (Devine et al., 1976). Roots without proper nutrient supply cannot penetrate deeply into acidic subsoils. Shallow roots decrease yields under droughty conditions for they are unable to obtain water (Rechcigl et al., 1985). Additionally, droughty alfalfa plants will have decreased dinitrogen fixation. Nitrogenase activity was found to decline as water potential decreased (Carter and Sheaffer, 1983). Root nodules were able to resume activity when soil moisture levels were restored.

Root hair infection

Nodule formation is severely inhibited under low pH conditions. Nodules are more sensitive to soil acidity and Ca deficiencies than are host plants (Munns, 1970b). Failure at any stage in the nodule development process can prevent nodules from reaching a stage capable of dinitrogen fixation. Root hair infection is the first step of association (Peterson and Barnes, 1981). Although sufficient rhizobia may be present in the soil, root hair curling is inhibited at low pH (Munns, 1968a). After root hair curling is initiated, a pectolytic enzyme, that breaks down the pectin in the root cell walls, is mobilized in the root. The pectin in the root cell walls must be broken down prior to entry of rhizobia. Between pH 4.5 and 5.5, this pectolytic enzyme is unable to break down pectin (Munns, 1969). Pectin breakdown may be the most acid-sensitive stage in nodule formation. In one study, infection of rhizobia occurred at pH 6.0, after which the pH was reduced to 4.5 without inhibiting nodule formation (Munns, 1968a). The pH dependence of pectin breakdown by the pectolytic enzyme closely resembles the pH dependence of root nodulation. There is uncertainty whether the enzyme action is affected by H^+ion content or exchangeable Ca. Possibly there is a dual influence of both H^+ion content and exchangeable Ca on the enzyme's action. Munns (1970) found initiation of infection to be the most Ca-demanding stage of the nodulation process. Munns also found an interaction between Ca and pH on nodulation in solution. Lowering pH from 5.6 to 4.8 increased Ca concentration required for nodulation. Below pH 4.6, no nodules formed at any Ca concentration. Below 0.2 mM Ca, nodulation was inhibited even at pH 6.0. However, a Ca level low enough to inhibit nodulation inhibited root and root hair growth.

If any step of nodule formation is inhibited active nodules will not occur. Although any step can be inhibited by low pH, breakdown of the root wall to allow infection to occur appears to be the most acid sensitive stage in nodulation.

The influence of nodules on nodulation

Alfalfa root nodulation will occur under proper soil inoculation and pH conditions. Nodules begin to form in the top layers of the soil profile as roots grow into the soil. Roots will penetrate deeply into the soil, and nodules existing in the top of the soil profile will inhibit nodulation deeper in the soil profile. At this point, no more nodules can form until other nodules either die or are removed (Munns, 1970). In culture solution at pH 6.5, seedling alfalfa plants formed nodules mostly in the top 2 inches of solutions (Munns, 1970). An older plant can have nodule distribution related to the depth of the environment favorable for nodulation. Nodule's inhibition of further nodulation would explain why, in a neutral pH environment, most nodules will form in the top layer of the soil. Alfalfa growing on acidic soils with only a narrow layer of the soil profile modified to a favorable pH will have root nodulation only in that layer.

The influence of N on nodulation

Root nodules can supply sufficient levels of N for alfalfa growing under favorable conditions. In environments unfavorable to dinitrogen fixation, alfalfa growth can be increased by addition of N fertilizer. Modifying the soil environment to favor dinitrogen fixation will show little to no increase in yield when N fertilizer is present. Andrews (1976) created an environment favorable for dinitrogen fixation by raising pH and Ca concentration in sand culture. In the presence of fertilizer N only small increases in yield resulted as pH increased. When plants have all the N needed for growth, alfalfa root nodules will not produce N. Therefore, high levels of nitrate in the soil will decrease dinitrogen fixation. Reduced nodulation may be a primary cause of reduced dinitrogen fixation due to the presence of high levels of nitrate. Plants grown in solution cultures with N concentrations of 2mM had decreased nodulation due to lack of root hair curling (Munns, 1968b). Inhibition is believed to be due to the response of the host plant to nitrate. In the presence of N, indole 3 acetate (IAA) is not produced in the plant and then transferred to the roots to initiate root hair curling.

Alfalfa can be grown without addition of N fertilizer. However, a soil environment favorable for dinitrogen fixation needs to be provided. Under proper conditions, addition of N fertilizer to soil supporting alfalfa is not necessary, is wasteful, and causes decreased nodulation. If N fertilizer is applied, plant growth can be lower than without N fertilizer. This is due to reduced nodulation which produces a plant that is dependant on N fertilizer.

Influence of inoculation on alfalfa growth

Low soil pH reduces the presence of effective *Rhizobium meliloti.* With few effective rhizobia under low pH treatments, few healthy nodules were able to form and dinitrogen fixation was reduced (Mahler, 1983). Reduced pH possibly alters effective rhizobia to ineffective rhizobia (Rice, 1975). Ineffective strains of rhizobia can compete with effective rhizobia for nodulation sites on the root complex. Strains differed in competitiveness for nodulation sites in soybeans (John et al.son et al., 1965). When low pH soil is inoculated with *Rhizobia* at time of planting, soybean yields increase. Rice (1975) found a significant increase in effective nodulation resulted by inoculating soil with *Rhizobia.*

Genetic improvement

Developing plant species genetically adapted to poor environments is a viable method for increasing yields in growing environments unable to be altered. Many crop species and varieties that are used today are resistant to diseases, insects, soil deficiencies, and toxicities. New varieties of alfalfa are being tested each season and commercial development of alfalfa strains capable of high yields under low pH conditions is possible in the future. Different clones of alfalfa have been found to yield differently under low pH conditions (Buss et al., 1975; Vance and John et al.son, 1983). Many clones with variance in effective nodulation exist. Five clones of alfalfa capable of only producing non-effective nodules were found, and one clone was found to produce no nodules in the presence of effective Rhizobia strains (Peterson and Barnes, 1981). A more positive outlook could be seen with the discovery of viable strains resistant to low pH and accompanied toxicities. Varieties of alfalfa capable of high yields under toxicities of Al (Devine et al., 1976) and tolerance to

Mn (Dessureaux and Ouellette, 1958) exist, and these traits have been found to be heritible. Drought-resistant varieties also may benefit agriculture for soils restricting root growth. Rumbaugh and Johnson et al., (1981) found subspecies slightly tolerant of drought in the seedling stages. Alternative strains of rhizobia that can survive well under unfavorable conditions could have the potential to fix high rates of N under low pH conditions (Williams and Phillips, 1983; Thomas et al., 1983). Discovery of a strain of rhizobia capable of high levels of nitrogen fixation under acidic conditions can be facilitated by creating a new strain. A strain capable of high dinitrogen fixation in pea was created by plasmid transfer into *Rhizobium leguminosorum* (DeJong et al., 1981).

Time and movement of limestone

Limestone requires time to increase soil pH. Limestone applied as ground calcitic limestone needs to break down and become active in the soil solution. Limestone applied to the surface will take time to move into the soil profile.

Proper amendment of the soil pH requires application of limestone several months or possibly several years prior to planting. For limestone to be active in the soil reaction, the limestone must be broken down into mineral components (Ca and CO_3). Once $CaCO_3$ is in the soil, time is needed to overcome the buffering action of the reserve soil acidity.

Limestone movement through the soil is very slow (Brown, 1930; Macleod and Jackson, 1965). Due to mass water movement through the top few inches of soil, surface limestone will move more rapidly in the soil profile than will limestone at 6 inches depth. Limestone penetration into subsurface layers from the plow layer requires many years.

Limestone incorporation does not neutralize subsoil acidity (Devine et al., 1976; Macleod and Jackson, 1965). Roots of alfalfa grown on acidic soils with either surface limestone application or incorporated limestone will have to penetrate into acidic subsoils after going through a layer of modified pH in the soil profile. Incorporation of limestone into subsurface horizons is possible but not economically feasible.

Surface limestone application

Conventional methods for establishing alfalfa, on soils with pH below 6.5, require limestone to be incorporated into the soils (White et al., 1982). Recommendations for soil with a pH below 6.0 include application of one-half the recommended limestone before deep plowing to incorporate the limestone. Then the remaining one-half of the limestone is applied, and incorporation is completed by disking. With current recommendations, no-till alfalfa could be planted only where soil pH is above 6.5, since limestone cannot be incorporated. Tillage to incorporate limestone exposes soil to erosion and thus limits the acreage where alfalfa can be grown. Many acres would be suitable for alfalfa production except for low soil pH if no-till methods were used in establishment.

Surface limestone application creates a layer of modified pH in the top few inches of the soil profile. Rechcigl et al. (1985) found surface-applied limestone modified soil pH to a depth of 3 inches after 1 year. This zone of modified pH can provide adequate depth to enable proper nodulation and root growth in alfalfa. Most nodules occur in the zone in which limestone is applied (Pohlman,1946; Watenpaugh, 1936). A zone of modified soil pH at three different depths was examined. High pH layers were 0 to 8 inches, 8 to 16 inches, and 16 to 24 inches in the soil profile. In all three depths most nodules and feeder roots were confined to the layer of modified pH (Pohlman, 1946). Surface limestone application can result in yields equal to that resulting from incorporated limestone (Rechcigl, 1988; Watenpaugh, 1936). Alfalfa roots are able to absorb proper levels of nutrients and fix nitrogen through root nodules in a smaller zone of modified pH created by surface application of limestone as well as a larger zone created by incorporation of limestone. The nutrients and dinitrogen fixation obtained by the plant in the layer of modified soil pH enables the roots to penetrate deeply into the soil profile (Rechcigl and Reneau, 1984; Rechcigl et al., 1985; Watenpaugh, 1936). Whether limestone is incorporated or surface-applied, roots will penetrate the layer of modified pH, and can be influenced by Al toxicities in the subsoils. Rechcigl et al (1985) observed red-violet roots below 6 inches, indicating Al toxicity.

Limestone recommendations are based on the incorporation of the limestone to 6 inches in the soil profile. Surface limestone application will generally influence the pH in the topmost 3 inches of the soil profile. Less soil volume is modified with surface limestone applications; therefore, less limestone should be needed to properly modify the pH. Rechcigl et al. (1988) found no significant difference in the alfalfa yields between one-half and the full recommended rate of limestone.

Some factors may limit the use of surface limestone application. Variability of soils will cause surface limestone application to be more effective on some soils than on others. Severity of pH and Al saturation also strongly influence surface limestone practicality. Mahler (1983) found high exchangeable Al in Missions soils up to pH 6.6. In this soil, surface-applied limestone could not provide sufficient rooting depth. Pohlman, (1946) while working with soils of pH 4.8, found increased pH in only the top 3 inches was less effective, at increasing yields, than liming to the the top 8 inches of soil. Surface limestone application can be very effective on most soils and can expand acres available for alfalfa production to include highly erodable and non-plowable land.

Conclusion

Low soil pH severely reduces growth of alfalfa and many other crops. Many factors are associated with growth reduction due to low pH. Decreased dinitrogen fixation, decreased nutrient availability, and limited rooting depth are the main factors associated with low pH. Where limestone cannot be incorporated, researchers have found several alternatives for increasing plant growth. Increased growth can result from improvement through genetics, application of deficient nutrients, and alternative methods of limestone application, especially surface limestone application. Research in the area of crop improvement on low pH soils is desperately needed. As world growth claims highly productive agricultural lands for living and working environments, research is needed to expand potential acreage to utilize less favorable land for crop growth.

References

Andrew, C.S. 1976. Effect of Ca, pH, and nitrogen on the growth and chemical composition of some tropical and temperate pasture legumes. I. Nodulation and growth. Aust. J. Agric. Res. 27:611-623.

Bache, B.W. and W.M. Crooke. 1981. Interactions between aluminum, phosphorous, and pH in the response of barley to soil acidity. Plant Soil 61:365-375.

Bouton, J.H., J.K. Syers, and M.E. Sumner. 1981. Alfalfa, *Medicago sativa* L., in highly weathered acid soils. I. Effect of lime and P application on yield and acetylene reduction (N-fixation) of young plants. Plant Soil 59:455-463.

Brown, B.A. 1930. Fertilizer experiments with alfalfa. Storrs Exp. Sta. Bull. 363.

Buss, G.R., J.A. Lutz Jr., and G.W. Hawkins. 1975a. Effect of soil pH on plant genotype and uptake by alfalfa. Crop Sci. 15:614-616.

Buss, G.R., J.A. Lutz Jr., and G.W. Hawkins. 1975b. Yield response of alfalfa cultivars and clones to several pH levels in Tatum subsoil. Agron. J. 67:331-334.

Carter, P.R., and C.C. Sheaffer. 1983. Alfalfa response to soil water deficits. III. Nodulation and N fixation. Crop Sci. 23:985-990.

Cralle, H.T., and G.H. Heichel. 1981. Nitrogen fixation and vegetative regrowth of alfalfa and birdsfoot trefoil after successive harvests or floral debudding. Plant Physiol. 67:898-905.

DeJong, T.M., N.J. Brewin, W.B. Johnston, and D.A. Phillips. 1981. Improvement of symbiotic properties in *Rhizobium leguminosarum* by plasmid transfer. J. Gen. Micro. 128:1829-1838.

Dessureaux, L., and G.J. Ouellette. 1958. Tolerance of alfalfa to manganese toxicity in sand culture. Can. J. Soil Sci. 38:8-13.

Devine, T.E., C.D. Foy, A.L. Fleming, C.H. Hanson, T.A. Campbell, J.E. McMurtrey, III, and J.W. Schwartz. 1976. Development of alfalfa strains with differential tolerance to aluminum toxicity. Plant Soil 44:73-79.

Doerge, T.A., P.J. Bottomley, and E.H. Gardner. 1985. Molybdenum limitations to alfalfa growth and nitrogen content on a moderately acid, high phosphorus soil. Agron. J. 77:895-901.

Fribourge, H.A. and I.J. Johnson. 1955. Dry matter and nitrogen yields of legume tops and roots in the fall of the seeding year. Agron. J. 47:73-77.

Haynes, R.J., and T.E. Ludecke. 1981. Yield, root morphology and chemical composition of two pasture legumes as affected by lime and phosphorus application to an acid soil. Plant Soil. 62:241-254.

Heichel, G.H. 1978. Energy analysis of alfalfa production. Proc. 8th Annual Alfalfa Symp. Bloomington, MN. p. 16-22.

Hoyt, P.B., and M. Nyborg. 1971. Toxic metals in acid soil: I. Estimation of plant available aluminum. Soil Sci. Soc. Amer. Proc. 35:236-240.

James, D.W., T.L. Jackson, and M.E. Harward. 1968. Effect of molybdenum and lime on the growth and molybdenum content of alfalfa grown on acid soils. Soil Sci. 105:397-402.

Janghorbani, M., S. Roberts, and T.C. Jackson. 1975. Relationship of exchangeable acidity to yield and chemical composition of alfalfa. Agron. J. 67: 350-354.

John, M.K., G.W. Eaton, V.W. Case, and H.H. Chuah. 1972. Liming of alfalfa (*Medicago sativa L.*) II. Effect on mineral composition. Plant Soil 37:363-374.

Johnson, W.J., U.M. Means, and C.R. Weber. 1965. Competition for nodule sites of *Rhizobium japonicum* applied as inoculum and strains in the soil. Agron. J. 57:179-185.

Kroontje, W., and W.R. Kehr. 1956. Legume top and root yields in the year of seeding and subsequent barley yield. Agron. J. 48:127-131.

Lanyon, L,E., B. Naghshineh-Pour, and E.O. McLean. 1977. Effect of pH level on yields and composition of pearl millet and alfalfa in soils with differing degrees of weathering. Soil Sci. Soc. Am. J. 41:389-394.

Lund, Z.F. 1970. The effect of calcium and it's relation to several cations in soybean root growth. Soil Sci. Soc. Am. Proc. 34:456-459.

Maclean, A.J., R.L. Halstead, and B.J. Finn. 1972. Effects of lime on extractable aluminum and other soil properties on barley and alfalfa growth in pot tests. Can. J. Soil Sci. 52:427-438.

Macleod, L.B., and L.P. Jackson. 1965. Effect of concentration of the aluminum ion on root development and establishment of legume seedlings. Can. J. Soil Sci. 45:221-234.

Mahler, R.L. 1983. Influence of pH on yield and N and P nutrition of alfalfa grown on an acidic Mission silt loam. Agron. J. 75:731-735.

Martini, J.A., R.A. Kochhann, O.J. Siqueira, and C.M. Borkert. 1974. Response of soybeans to liming as related to soil acidity, Al and Mn toxicities and P in some oxisols in Brazil. Soil Sci. Soc. Am. Proc. 38:616-620.

Moschler, W.W., G.D. Jones, and G.W. Thomas. 1960. Lime and soil acidity effects on alfalfa growth in a red-yellow podozolic soil. Soil Sci. Soc. Am. Proc. 24:507-509.

Munns, D.N. 1964. Soil acidity and growth of a legume. I. interactions of lime with nitrogen and phosphate on growth of *Medicago sativa* L. and *Trifolium subterraneum* L. Aust. J. Agric. Res. 16:733-741.

Munns, D.N. 1968a. Nodulation of *Medicago sativa* in solution culture. I. acid sensitive steps. Plant Soil 28:129-146.

Munns, D.N. 1968b. Nodulation of *Medicago sativa* in solution culture. III. effects of nitrate on root hairs and infection. Plant Soil 29:33-47.

Munns, D.N. 1969. Short communication. Enzyme breakdown of pectin and acid inhibition of the infection of *Medicago* roots by *Rhizobium*. Plant Soil. 30:117-119.

Munns, D.N. 1970. Nodulation of *Medicago sativa* in solution culture. V. Calcium and pH requirements during infection. Plant Soil 32:90-102.

Munns, D.N., V.W. Fogle, and B.G. Hallock. 1977a. Alfalfa root nodule distribution and inhibition of nitrogen fixation by heat. Agron. J. 69:377-380.

Munns, D.N., R.L. Fox, and B.L. Koch. 1977b. Influence of lime on nitrogen fixation by tropical and temperate legumes. Plant Soil 46:591-601.

Peterson, M.A. and D.K. Barnes. 1981. Inheritance of ineffective nodulation and non-nodulation traits in alfalfa. Crop Sci. 21:611-616.

Petrie, S.E. and T.L. Jackson. 1982. Effects of lime, P and Mo applications on Mo concentration in subclover. Agron. J. 74:1077-1081.

Pohlman, G.G. 1946. Effect of liming different soil layers on yield of alfalfa and on root development and nodulation. Soil Sci. 62:255-266.

Rechcigl, J.E. and R.B. Reneau, Jr. 1984. Effect of subsurface amendments and irrigation on alfalfa growth. Agron. J. 77:72-75.

Rechcigl, J.E., D.D. Wolf, R.B. Reneau, Jr., and W. Kroontje. 1985. Influence of surface liming on yield and nutrient concentration of alfalfa established using no-tillage techniques. Agron. J. 77:856-959.

Rechcigl, J.E., K.L. Edmisten, D.D. Wolf, and R.B.Reneau, Jr. 1988. Response of alfalfa grown on acid soil to different chemical amendments. Agron. J. 80:515-518.

Rice, W.A. 1975. Effects of $CaCO_3$ inoculum on nodulation and growth of alfalfa in an acid soil. Can. J. Soil Sci. 55:245-250.

Rumbaugh, M.D. and D.A. Johnson. 1981. Screening alfalfa germplasm for seedling drought resistance. Crop Sci. 21:709-713.

Thomas, R.J., K. Jokinen, and L.E. Schrader. 1983. Effect of *Rhizobium japonicum* mutants with enhanced nitrogen fixation activity on nitrogen transport and photosynthesis of soybeans during vegetative growth. Crop Sci. 23:453-456.

Vance, C.P. 1978. Nitrogen fixation in alfalfa: An overview. Proc. 8th Annual Alfalfa Symp. Bloomington, MN.

Vance, C.P. and L.E.B. Johnson. 1983. Plant determined ineffective nodules in alfalfa (*Medicago sativa* L.): Strucural and biochemical comparisons. Can. J. Bot. 61:93-106.

Watenpaugh, H.N. 1936. The influence of the reaction of soil strata upon the root development of alfalfa. Soil Sci. 41:449-468.

White, H.E., D.D. Wolf, H.T. Bryant, E.S. Hagood, J.M. Luna, and E.S. Smith. 1982. No-till establishment of alfalfa. Virginia Coop. Ext. Serv. Pub. 418-263 Blacksburg, VA.

Williams, L.E. and D.A. Phillips. 1983. Increased soybean productivity with a *Rhizobium japonicum* mutant. Crop Sci. 23:246-250.

Surface Application vs. Incorporation of Limestone for No-Till Alfalfa Production

ABSTRACT

No-till alfalfa (*Medicago sativa* L.) establishment is the only environmentally sound procedure for alfalfa production on erodable land. Surface limestone application is the only reasonable method of placement in no-till systems with pH below 6.5. The purpose of this research was to evaluate surface limestone application vs. incorporation throughout the plow layer for alfalfa production in acidic soils. In this study limestone placement included: 1. incorporation during tillage operations, 2. surface application after tillage and preparation of seedbed, and 3. surface application without tillage. Limestone was applied at 0, 1.25, 2.50, and 5.00 tons per acre with each placement method. Limestone treatments were imposed on 30 Sept. 1986 in Montgomery County, VA (37^0 11′N, 80^0 25′W and 1950 ft. elevation) on a Groseclose silt loam (clayey, mixed, mesic Typic Hapludult) having a pH of 5.6 in the top 9 inches. Limestone treatments were imposed at a second site on 25 Nov. 1986 in Orange County, VA (38^0 13′N, 70^0 7′W and 515 ft. elevation) on a Davidson clay loam (clayey, oxidic, thermic Rhodic Paleudult) having a pH of 5.7 in the top

9 inches. 'Cimmeron' alfalfa was planted using no-till procedures on 23 March 1987 in Montgomery County and on 26 Aug. 1987 in Orange County. Soil samples were taken about 2 years after limestone application at depths of 0 to 1, 1 to 2, 2 to 3, and 3 to 6 inches for surface applied treatments and 0 to 3, 3 to 6, and 6 to 9 inches for incorporated treatments. Soil samples were also taken at a depth of 18 to 24 inches where limestone was incorporated during tillage at 0 and 5 tons per acre. Four harvests were made in 1988. At both locations, limestone application increased yields by 114 to 300% as compared with the check where no limestone was applied. Yields from plots receiving surface limestone application were equal to plots with incorporation at both locations. Tillage did not increase yields as compared with no tillage except in Orange County on plots where no limestone was applied. Soil pH increased from 5.6 to 6.8 at the 1- to 2-inch depths and from 5.6 to 6.3 at the 2- to 3-inch depths where 5 tons per acre of limestone were surface applied in Montgomery County. In Orange County, soil pH increased from 5.5 to 6.5 at the 1- to 2-inch depths and from 5.6 to 6.1 at the 2- to 3-inch depths where 5 tons per acre limestone were surface applied. Above pH 5.5, Al saturation was below 2.7% in Montgomery County and 0.7% in Orange County. Aluminum saturation averaged 9.0% and 4.6% where pH was between 5.0 and 5.5 in Montgomery and Orange Counties, respectively. At both locations, in the 18- to 24-inch depths a pH of 4.8 was not influenced by limestone incorporated at 5 tons per acre. Aluminum saturation at 18- to 24-inch depths was 51% and 62% in Montgomery and Orange Counties, respectively. These data indicate that surface applied limestone can produce first year alfalfa yields similar to yields obtained with incorporated limestone.

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Additional Index Words: Establishment, Incorporated limestone, Protein, Nutrient elements, Surface-applied.

Acidic soils are not favorable for alfalfa (*Medicago sativa* L.) production. Low pH hinders alfalfa growth in part by causing Al and Mn toxicity but the main detrimental effect of low pH may be decreased dinitrogen fixation (Munns et al., 1977). Current recommendations suggest a pH of 6.5 to 6.8 is optimal for alfalfa growth. Recommendations to modify acidity, when pH is above 6.0, include incorporating limestone into the surface layer with heavy disking. With a pH below 6.0, recommendations include application of one-half of the limestone followed by disking and deep plowing. The remaining one-half is applied and incorporated with a disk. The requirement to incorporated limestone restricts alfalfa production on erodable land, requires large amounts of fuel, and is time-consuming. Under many circumstances, an alternative to incorporation of limestone may be surface application in a no-till system. Use of limestone application without incorporation will increase as the need to grow alfalfa in no-till systems increases. Surface application of limestone has been found to benefit alfalfa growth the same as limestone conventionally incorporated into soil (Rechcigl, 1985).

The ability to provide available N through a symbiotic relationship with *Rhizobia* bacteria is one of the important aspects of production of a legume such as alfalfa. Low pH severely inhibits dinitrogen fixation by creating unfavorable conditions for nodule formation and dinitrogen fixation. Below a pH of 5.0, nodulation cannot occur due to inhibition of an enzyme that normally breaks down the root cell walls to allow rhizobial infections to occur (Munns, 1969). Inhibition may be by direct influence of pH on the enzyme or by influence of Ca on plant root development (Munns, 1970). Nodulation can occur between pH 5.0 and 6.0; however, nitrogenase activity is negligible below pH 6.0.

The major influence of pH on nodulation and dinitrogen fixation is believed to be an indirect influence of H^+ion concentration rather than a direct effect. This indirect influence of pH on dinitrogen fixation is due to increased levels of Al and Mn in the soil solution at low pH. Subtoxic levels of Al and Mn will decrease dinitrogen fixation. Below pH 6.0, Mn concentrations in plants increase sharply (Doerge et al., 1985). Below pH 6.0, Mo and P availability decrease and cause decreased dinitrogen fixation and plant growth (Doerge et al., 1985).

Mature alfalfa plants had 93% of nodules in the layer of soil amended to a pH of 6.5 or above (Carter and Sheaffer, 1983). In seedlings grown in solution with pH of 6.5, 80% of the nodules were formed in the top 2 inches (Munns, 1970). When limestone has been surface applied, nodule formation occurs mainly in the top 2 inches of soil (Webel, 1976). When incorporated into the soil, limestone is diluted through the plow layer. Under these dilute conditions downward movement of limestone is less than one-fourth inch per year (Brown, 1940). However, when the same amount of limestone is surface applied, there is a high concentration on the surface. More rainfall movement will occur in the top of the soil profile and will move more limestone in the soil than at 6 inches, resulting in surface-applied limestone movement of greater than 1 inch in the first year. Additionally with surface application a smaller volume of soil is amended which may possibly require less limestone to make the proper pH correction.

Alfalfa root nodulation will occur under proper soil inoculation and pH conditions. Nodules begin to form in the top layers of the soil profile as roots grow into the soil. Roots will penetrate deeply into the soil and nodules existing in the top of the soil profile will inhibit nodulation deeper in the soil profile. At this point, no more nodules can form until other nodules either die or are removed (Munns, 1970). In culture solution at pH 6.5 seedling alfalfa plants formed nodules mostly in the top 2 inches of solutions (Munns, 1970). An older plant can have nodule distribution related to the depth of the environment favorable for nodulation. Inhibition of further nodulation by existing nodules would explain why most nodules will form in the top layer of the soil, in a neutral pH environment. Alfalfa growing on acidic soils with only a narrow layer of the soil profile modified to a favorable pH will have root nodulation only in that layer.

The objective of this study was to compare alfalfa yields where limestone was applied on the surface with incorporated limestone. Data were collected at two geographic locations on soils with original pH values of less than 5.7 to a depth of 24 inches. Yields and soil pH were used to indicate the degree of success of surface limestone application and to predict recommended rates needed to adequately modify soil pH.

MATERIALS AND METHODS

Alfalfa performance as influenced by placement and rates of limestone, was studied at two locations in Virginia. Limestone placement included: 1. incorporation during conventional tillage operations, and 2. surface application after tillage and seedbed preparation. To account for influences on alfalfa growth due to tillage, a third treatment was included in which limestone was surface applied without tillage. Where incorporated, one-half of the limestone was applied and disked into the top layer before being tilled to approximately 6 inches. The remaining one-half of the limestone was applied and incorporated by disking before preparing a seedbed. Where limestone was surface applied to a conventionally prepared seedbed, tillage procedures were the same as where limestone was incorporated, but the limestone was applied after final seedbed preparation. Limestone applied to the surface without tillage was similar to no-till planting recommendations (Wolf et al., 1985). Limestone applications included 0, 1.25, 2.50, and 5.00 tons per acre. Nitrogen, P, and K were surface applied at 22, 74, and 108 lb/acre, respectively, for both locations after limestone treatments were completed.

Montgomery County

The soil was a Groseclose silt loam (clayey, mixed, mesic Typic Hapludult) with 7% slope at the Agronomy Research Farm (37 ° 11'N, 80 ° 25'W and 1950 ft. elevation). Initial soil tests indicated a pH of 5.6, a P level of 7 ppm, and a K level of 73 ppm (double-acid extraction, Donohue and Gettier, 1979) in the top 6 inches. Limestone treatments were made on 30 Sept. 1986. Spring oats (*Avena sativa* L) were planted as a winter cover crop on 2 Oct. 1986. 'Cimmeron' alfalfa was planted with no-till procedures on 23 March 1987 at 15 lb/acre. Plot dimensions were 15 ft. by 25 ft.

Orange County

The soil was a Davidson clay loam (clayey, oxidic, thermic, Rhodic Paleudult) with 9 to 11% slope at the Northern Virginia Piedmont Research Farm (38 ^{0} 13'N, 70 ^{0} 7'W and 515 ft. elevation). Initial soil tests indicated a pH of 5.7, a P level of 3 ppm, and a K level of 80 ppm in the top 6 inches. Limestone treatments were made on 25 Nov. 1986. Rye (*Secale cereale* L) was planted for a winter cover crop. A 10-ft. wide strip of wood-fiber netting was placed at the downhill end of all plots in order to minimize possible soil and limestone movement while a vegetative cover was established. In spring of 1987, rye was removed for hay and the area was sprayed with glyphosate [*N* -(phosphono-methyl) glycine]. German millet (*Setaria italica* L) was planted in late May and removed as hay in early August 1987. The area was sprayed with paraquat (1,1'-dimethyl-4, 4'-bipyridium ion) prior to seeding. Cimmeron alfalfa was planted with no-till procedures at 15 lb/acre on 26 Aug. 1987. Plot dimensions were 7 ft. by 20 ft.

Data collection and analyses

Yields were determined in mid-May, early-July, early-August, and mid-September of 1988 at both locations. Soil samples were taken approximately 2 yr after limestone application at depths of 0 to 1, 1 to 2, 2 to 3, and 3 to 6 inches in plots with surface-applied limestone and 0 to 3, 3 to 6, and 6 to 9 inches in incorporated treatments. Soil samples were also taken between 18 to 24 inches from the incorporated treatments with 0 and 5 tons per acre. At the late May and September harvests, tissue samples of alfalfa were collected, dried, ground, and analyzed for crude protein (Association of Official Analytical Chemists, 1975). Soil pH was determined on 1:1 soil to water slurries. Plant-available Ca, Mg, and Mn were determined with an inductively coupled plasma spectrophotometer (ICP) after extraction with ammonium acetate (Council on Soil Testing and Plant Analysis, 1980). Cation exchange capacity (CEC) of soils in non-limed plots was calculated according to Horn et al., (1982) as the sum of K, Ca, Mg, and Na concentrations as determined from ammonium acetate extracts of soils and Al from KCl extracts. Also Al concentration was determined on all samples having a pH below 5.5 and a few with a pH of about 6.0. Fifty ml of 1 N KCl was added to 5 g of soil, shaken for 30 min., and analyzed for Al using an ICP (Page et al., 1982). Percentage Al saturation was calculated by dividing Al concentration by CEC.

A randomized complete block within a split-plot design included four replications at each location. Methods of limestone placement were blocked as main effects and limestone rates were randomized within application methods. Data are presented for each location because differences in magnitude of response resulted in significant interactions between treatments and locations for most measured variables. Fisher's protected least significant difference test for mean separation was used for all measured variables as outlined by Zar (1984). Multiple regression was used to analyze data relating to limestone rates (Kleinbaum et al., 1988). Yields and soil pH were considered random variables. Limestone rates and placement methods were fixed variables.

RESULTS AND DISCUSSION

Soil Factors

Soil pH increased to greater than 6.5 at a depth of 2 inches for surface application and at a depth of 6 inches for incorporated treatments with increasing quantities of limestone (Table 1). Soil pH was increased from 5.5 to above 6.8 in Orange County and from 5.8 to 7.5 in the 0- to 1-inch sample from surface limestone treatments in Montgomery County with 5 ton of limestone per acre. Even at the 2- to 3-inch depth, pH was greater than 6.0 with 5 tons/acre of surface-applied limestone. Soil pH was increased from 5.5 to above 6.5 in Orange County and from 5.6 to 6.8 in the 1- to 2-inch sample from surface limestone treatments in Montgomery County with 5 tons of limestone per acre. Soil pH increased from 5.8 to above 7.0 in the 0- to 3-inch depth incorporated limestone treatments in Orange County and from 5.7 to 7.3 in the 0- to 3-inch sample from incorporated limestone treatments in Montgomery County with 5 tons of limestone per acre. Soil pH increased from 5.8 to above 6.7 in the 0- to 6-inch depth incorporated limestone treatments in Orange County and from 5.7 to 6.8 in the 0- to 6-inch sample from incorporated limestone treatments in Montgomery County with 5 tons of limestone per acre. In the 6- to 9-inch layer of the soil profile, pH was not increased by any limestone level at either location. This suggests that the incorporation process effectively mixed limestone to a depth of 6 inches and movement did not occur below 6 inches.

Soil pH was increased to a depth of 3 inches by surface-applied limestone applications. Any increase in pH below the soil surface could be caused only by movement of limestone into the soil profile. This suggests that limestone movement by illuviation through the soil profile, is more rapid when limestone is surface-applied than when incorporated (Brown, 1930; Macleod and Jackson, 1965). Even though samples were not taken from the 6- to 9-inch depth below surface-applied treatments, we can assume pH was the same (5.7 and 5.6 for Montgomery and Orange

Counties, respectively) as were measured below incorporated treatments. This assumption would seem valid since no increase in pH occurred even in the 3- to 6-inch layer for surface limestone application.

Sampling to a depth of the plow layer is recommended by Tisdale et al. (1985) for conventional tillage. Sampling to a 2-inch depth is recommended for non-tilled fields. Soil pH was calculated in this study for the 0- to 2-inch depth using data from the 0- to 1- and 1- to 2-inch sample of the surface-applied limestone treatments. Soil pH was calculated for the 0- to 6-inch depth using data from the 0- to 3- and 3- to 6-inch sample of the incorporated limestone treatments. Calculations were made using the antilog of the pH values and determining weighted averages. Concentrations were then converted to pH values. Multiple regressions using pH and limestone rates were used to calculate limestone required to achieve a pH of 6.5. When limestone was surface-applied, 1.9 tons per acre limestone were needed to modify the 0- to 2-inch layer from a pH of 5.5 to a pH of 6.5 at the Montgomery County location (Fig. 1). With incorporated limestone, 4.0 tons per acre were needed to modify the 0- to 6-inch layer from pH 5.5 to pH 6.5 at the Montgomery County location. The Orange County location did not have similar trends to the Montgomery County location for 0- to 2-inch and 0- to 6-inch soil sampling depths. If the 0- to 1-inch soil sample was used in Orange County for the surface-applied limestone soil sample results would have been similar to Orange County. The Orange County location did not have as long of a time period as the Montgomery County location for limestone to break down and move in the soil. The authors believe one more winter and spring of weathering will influence the 0- to 2-inch soil layer in Orange County to require less limestone to obtain the same pH as the 0- to 6-inch layer. When current limestone recommendations are calculated, enough limestone to modify 6 inches of soil depth is considered. When using surface application approximately 2 inches of soil depth are being modified, and two-thirds less limestone is needed to modify the pH due to the decreased volume of soil.

Soil test data indicated differences among Ca, Mg, and Mn concentrations due to treatments; however, all levels were within tolerances for alfalfa growth and are not presented in detail. Data from check plots indicated that ammonium acetate extractable Ca was 500 and 1061 ppm, Mg was 93 and 193 ppm, and K was 125 and 212 ppm, in Montgomery and Orange Counties, respectively (Table 2). Aluminum saturation averaged 4.6 and 9.0% for soils with pH values between pH 5.0 and 5.5 in Orange and Montgomery Counties, respectively. For samples with pH greater than 5.5, percentage Al saturation was below 0.7 and 2.7% in Orange and Montgomery Counties, respectively. Saturation below 9% does not severely limit crop growth according to Kamprath (1970). Soil samples taken between the 18- and 24-inch depth showed no differences in pH with 5 tons per acre incorporated limestone. Soil pH values at this depth were 4.8 in both Montgomery and Orange Counties. Percentage Al saturation at the 18- to 24-inch depth did not differ due to limestone incorporation in Montgomery County and averaged 51%. In Orange County, Al saturation unexplainably increased from 57 to 67% with incorporation of 5 tons limestone per acre when compared with the treatment where no limestone was added. Aluminum saturation in the soil above 20% may be detrimental to many crops, including alfalfa (Kamprath, 1970). Rooting depth was not determined; however, a yield of 5 tons/per acre could not be achieved with roots only in pH-modified soil. Thus we can assume that root activity into high-Al acid soils was sufficient to obtain considerable water supply. These data suggest that neither incorporation of limestone to a 6-inch depth nor surface-applied limestone influences the soil to a depth of 18 to 24 inches one year after application.

Herbage

Limestone placement on the surface or by incorporation resulted in similar yields at all rates at both locations (Table 3). This shows that alfalfa can be grown on acidic soils with surface-applied limestone and is in agreement with data reported by Rechcigl et al. (1985). Tillage of soil did not increase yields as compared with no tillage at any limestone rate in Montgomery County. At the Orange County location, tillage did affect yield where no limestone was applied. In both counties, alfalfa yields were greater with 1.25 tons limestone per acre as compared with the check for both placement methods (Table 3). Between 1.25 and 5 tons limestone per acre alfalfa yields did not increase in Montgomery County. In Orange County for both placement methods, yields increased between 1.25 and 2.50 tons limestone per acre, but between 2.5 and 5.0 tons limestone per acre yields did not increase. Differences between the amount of limestone needed for maximum alfalfa yields demonstrates variation of response due to soil types.

Plant tissue protein levels were similar between surface-applied and incorporated limestone placement at all rates at both locations (Table 4). In Montgomery County, percentage protein was less in the check than when 1.25 tons per acre were applied. However, between 1.25 and 5 tons of limestone per acre percentage protein did not change. In Orange County, percentage protein increased from zero to 5 tons per acre of limestone. Tillage of soil did not influence percentage protein as compared with no tillage in Montgomery County. At the Orange County location, percentage protein was higher in plots with tillage than plots without tillage except when limestone rate was 5 tons per acre. In the check where no limestone was applied, protein was 15.4 and 13.5% for plots with tillage and plots with no tillage, respectively. At 5 tons limestone per acre, alfalfa protein was 21.9 and 21.2% for plots with tillage and plots with no tillage, respectively. This increase in protein due to limestone application, would be expected since N was supplied from dinitrogen fixation in soils with favorable pH.

CONCLUSIONS

Surface limestone applications can be a viable method for no-till alfalfa grown on acidic soils. Surface limestone applications and incorporation of limestone on acidic soils resulted in similar alfalfa yields at two locations. When surface-applied limestone is used, lower rates of limestone can produce yields similar to higher rates of limestone in incorporated treatments. This difference in limestone placement is due to less volume of modified soil with surface-applied limestone. Current recommendations which consider growing alfalfa on non-acidic soils unless limestone is incorporated, may need to be altered. Even soils with a pH as low as 5.6 can be recommended for alfalfa production if surface limestone is applied. Stand persistence of alfalfa grown with surface-applied limestone and incorporated limestone needs to be studied.

Table 1. Soil pH at several soil depths as influenced by rates and placement of limestone and by tillage of soil in Montgomery and Orange Counties.

Soil	Limestone†		Rate (tons/acre)				Parameters‡			
prep.	placement	Depth	0	1.25	2.50	5.00	a	b	c	R^2
		Inches	pH				× 10^{-1}			%
			Montgomery County							
Tilled	Incorp.	0-3	5.71	6.62	6.59	7.28	5.81*	4.9*	-0.41*	89*
		3-6	5.70	6.13	6.22	6.81	5.74*	2.4*	-0.05	74*
		6-9	5.78	5.67	5.56	6.04	5.80*	2.1	0.51	15
	LSD§ 0.05 = 0.62									
	Surface	0-1	5.75	6.97	7.32	7.47	5.81*	9.8*	-1.29*	90*
		1-2	5.61	6.27	6.64	6.79	5.62*	5.9*	-0.72*	82*
		2-3	5.62	5.68	6.18	6.26	5.56*	2.6*	-0.23	57*
		3-6	5.68	5.61	5.97	5.96	5.62*	1.2	-0.10	38*
	LSD§ 0.05 = 0.36									
None	Surface	0-1	5.95	6.79	7.02	7.30	6.00*	6.3*	-0.75*	88*
		1-2	5.45	6.07	6.21	6.45	5.49*	4.5*	-0.52*	83*
		2-3	5.52	5.66	5.89	5.94	5.50*	2.0*	-0.21	54*
		3-6	5.57	5.45	5.68	5.78	5.53*	0.1	0.10	37*
	LSD§ 0.05 = 0.27									
			Orange County							
Tilled	Incorp.	0-3	5.82	6.05	6.59	6.99	5.78*	3.3*	-0.18	81*
		3-6	5.78	5.83	6.45	6.70	5.70*	2.7*	-0.14	73*
		6-9	5.55	5.40	5.78	5.36	5.47*	1.4	-0.32	6
	LSD§ 0.05 = 0.48									
	Surface	0-1	5.47	6.25	6.44	6.79	5.52*	5.6*	-0.62*	94*
		1-2	5.51	5.93	6.04	6.50	5.54*	2.6*	-0.14	85*
		2-3	5.59	5.75	5.90	6.14	5.59*	1.4	-0.05	51*
		3-6	5.52	5.59	5.65	5.73	5.52*	0.7	-0.05	20
	LSD§ 0.05 = 0.22									
None	Surface	0-1	5.64	6.01	6.41	6.70	5.63*	3.8*	-0.33*	91*
		1-2	5.45	5.75	6.07	6.25	5.44*	3.2*	-0.31*	84*
		2-3	5.47	5.91	6.13	6.18	5.48*	4.0*	-0.51*	78*
		3-6	5.35	5.64	5.66	6.09	5.38*	1.3	0.01	58*
	LSD§ 0.05 = 0.61									

*Indicates significance at the 0.1 level or lower.
†Incorporation during tillage, surface applied after tillage and surface applied without tillage.
‡Models: Yield = a + b • Limestone applied + c • Limestone applied^2.
§Compares means within columns.

Table 2. Nutrient elements, pH, cation exchange capacity (CEC), and Al saturation of non-limed plots at several depths in Montgomery and Orange Counties.

Soil depth	pH	Nutrient elements‡ K	Ca	Mg	CEC	Al sat.
Inches		----- ppm -----			meq/100g	%
		Montgomery County				
0-3	5.7	125	500	93	4.0	7.0
3-6	5.7	59	475	90	3.7	8.5
6-9	5.8	61	687	129	5.7	12.5
18-24	4.8	142	865	204	13.3	51.0
		Orange County				
0-3	5.8	212	1061	193	7.5	1.5
3-6	5.8	81	912	177	6.6	4.8
6-9	5.6	40	704	167	5.4	7.3
18-24	4.8	106	166	72	4.3	62.0

†Soil analysis used tilled check plots one year after incorporation of zero tons per acre limestone. P and K were applied to the surface after tillage was completed.

‡Elements were obtained by treating soil samples with ammonium acetate and then analyzing extractant with an ICP unit.

Table 3. Total alfalfa yields from four harvests in 1988 as influenced by rates and placement of limestone and by tillage of soil in Montgomery and Orange Counties.

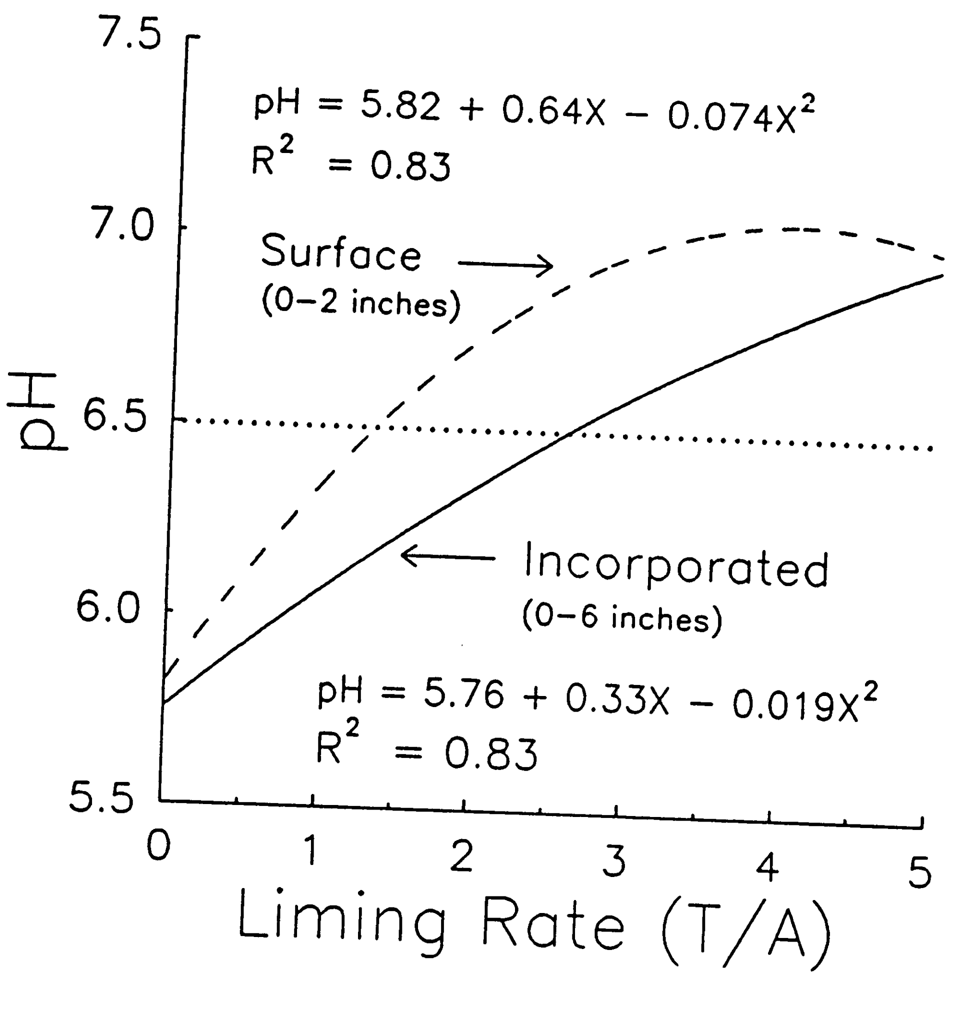
Soil† prep.	Limestone placement	Rate (tons/acre) 0	1.25	2.50	5.00	Parameters‡ a	b	c	R^2
		-------tons/acre-------				--- x10^{-1}---			%
				Montgomery County					
Tilled	Incorp.	1.57	4.27	3.95	4.14	1.84*	168*	-24.7*	73*
	Surface	0.91	4.12	4.10	4.35	1.18*	216*	-30.9*	76*
None	Surface	2.04	4.29	3.73	4.89	1.83*	148*	-17.8*	56*
	LSD§ 0.05 = 0.93								
				Orange County					
Tilled	Incorp.	2.32	4.27	5.21	4.62	2.34*	186*	-28.1*	76*
	Surface	1.74	4.25	5.15	4.93	1.82*	217*	-31.0*	76*
None	Surface	0.93	3.55	4.64	4.86	1.01*	226*	-29.8*	82*
	LSD§ 0.05 = 0.64								

*Indicates significance at the 0.1 level or lower.
†Incorporation during tillage, surface applied after tillage and surface applied without tillage.
‡Models: Yield = a + b • Limestone applied + c • Limestone applied^2.
§Compares means within columns.

Table 4. Protein concentration in alfalfa as influenced by rates and placement of limestone and by tillage of soil in Montgomery and Orange Counties.

Soil prep.	Limestone† placement	Rate (Tons/acre) 0	1.25	2.50	5.00	Parameters‡ a	b	c	R^2
		------------ %			--------------				%
					Montgomery County				
Tilled	Incorp.	20.9	22.8	23.0	23.1	20.2*	1.6*	-0.23	20*
	Surface	20.0	22.2	22.7	23.0	19.4*	2.1*	-0.28	24*
None	Surface	20.4	22.3	22.4	22.0	20.4*	1.1	-0.19	6
	LSD§ 0.05 = 1.2								
					Orange County				
Tilled	Incorp.	15.7	20.4	21.3	21.1	16.0*	3.6*	-0.53*	69*
	Surface	15.4	20.1	21.2	21.9	15.7*	3.6*	-0.48*	66*
None	Surface	13.5	17.6	20.1	21.2	13.6*	3.7*	-0.44*	78*
	LSD§ 0.05 = 1.0								

*Indicates significance at the 0.1 level or lower.
†Incorporation during tillage, surface applied after tillage and surface applied without tillage.
‡Models: Yield = a + b • Limestone applied + c • Limestone applied^2.
§Compares means within columns.



Appendix Fig.2. Soil pH as influenced by rate and placement of limestone in Orange County. Soil pH was calculated for 0 to 2 inches for surface limestone treatments and 0 to 6 inches for incorporated limestone treatments.

REFERENCES

Association of Official Analytical Chemists. 1975. Official methods of analysis. 12th ed. Association of Official Analytical Chemists, Washington D.C.

Brown, B.A. 1930. Fertilizer experiments with alfalfa. Storrs Exp. Sta. Bull. 363.

Buss, G.R., J.A. Lutz Jr., and G.W. Hawkins. 1975. Effect of soil pH on plant genotype and uptake by alfalfa. Crop Sci. 15:614-616.

Buss, G.R., J.A. Lutz Jr., and G.W. Hawkins. 1975. Yield response of alfalfa cultivars and clones to several pH levels in Tatum subsoil. Agron. J. 67:331-334.

Carter, P.R., and C.C. Sheaffer. 1983. Alfalfa response to soil water deficits. III. Nodulation and N fixation. Crop Sci. 23:985-990.

Council on Soil Testing and Plant Analysis. 1980. Handbook on methods for soil testing. Athens, Georgia.

Doerge, T.A., P.J. Bottomley, and E.H. Gardner. 1985. Molybdenum limitations to alfalfa growth and nitrogen content on a moderately acid, high phosphorus soil. Agron. J. 77:895-901.

Donohue, S.J. and S.W. Gettier. 1979. Laboratory procedures, Virginia Polytechnic Institute and State University Soil Testing and Plant Analysis Laboratory. Virginia Polytechnic Institute and State University Pub. 853.

Horn, D.P., M.M. Alley, and P.M. Bertsch. 1982. Cation exchange capacity measurements. Commun. In Soil Sci. Plant Anal. 13(10):851-862.

Janghorbani, M., S. Roberts, and T.C. Jackson. 1975. Relationship of exchangeable acidity to yield and chemical composition of alfalfa. Agron. J. 67: 350-354.

Kamprath, E.J. 1970. Exchangeable aluminum as a criterion for liming leached mineral soils. Soil Sci. Amer. Proc. 34:252-254.

Kleinbaum, D.G., L.L. Kupper, and K.E. Muller. 1988. Applied regression analysis and other multivariable methods. 2nd ed. PWS-Kent, Boston, MA.

Macleod, L.B., and L.P. Jackson. 1965. Effect of concentration of the aluminum ion on root development and establishment of legume seedlings. Can. J. Soil Sci. 45:221-234.

Munns, D.N. 1969. Short communication. Enzyme breakdown of pectin and acid inhibition of the infection of *Medicago* roots by *Rhizobium*. Plant Soil. 30:117-119.

Munns, D.N. 1970. Nodulation of *Medicago sativa* in solution culture. V. Calcium and pH requirements during infection. Plant Soil 32:90-102.

Munns, D.N., V.W. Fogle, and B.G. Hallock. 1977. Alfalfa root nodule distribution and inhibition of nitrogen fixation by heat. Agron. J. 69:377-380.

Munns, D.N., R.L. Fox, and B.L. Koch. 1977. Influence of lime on nitrogen fixation by tropical and temperate legumes. Plant Soil 46:591-601.

Page, A.L., R.H. Miller, and D.R. Keeney. 1982. Methods of soil analysis. Part 2. Chemical and microbial properties. Amer. Soc. of Agron., Madison, WI.

Rechcigl, J.E., K.L. Edmisten, D.D. Wolf, and R.B.Reneau, Jr. 1988. Response of alfalfa grown on acid soil to different chemical amendments. Agron. J. 80:515-518.

Rechcigl, J.E., D.D. Wolf, R.B. Reneau, Jr., and W. Kroontje. 1985. Influence of surface liming on yield and nutrient concentration of alfalfa established using no-tillage techniques. Agron. J. 77:856-959.

Rice, W.A. 1975. Effects of $CaCO_3$ and inoculum levels on nodulation and growth of alfalfa in an acid soil. Can. J. Soil Sci. 55:245-250.

Tisdale, S.L., W.L. Nelson, and J.D. Beaton. 1985. Soil fertility and fertilizers. 4th ed. Macmillan Publishing Company, New York, NY.

Wolf, D.D., E.S. Hagood,Jr., and M. Lentner. 1985. No-till alfalfa establishment as influenced by previous cover crop. Can. J. Plant Sci. 65:609-613.

Zar, J.H. 1984. Multiple comparisons p. 185-205 *In* Biostatistical analysis. Prentice Hall, Englewood Cliffs, NJ.

Webel D. 1976. Lime and phosphorus response of alfalfa and red clover under minimum tillage pasture renovation. Masters Thesis. Ohio State University.

Appendix A

Significant Variations

Many unexpected results occurred in the surface applied limestone studies. Some plots with no limestone applied produced yields similar to those on plots with 5 tons limestone per acre. Other plots had portions of the plot producing in high yields, while other portions of the plot had low yields. Soil samples were taken to determine the causes of these unexpected results.

In the Orange County location, the fourth replication and the downhill side of the plots in the first replication produced high yields on all treatments. Preliminary soil samples in the top 2 inches of the soil profile indicated pH to be 5.9 in the plots receiving no limestone. Samples taken at 0- to 1-inch depths, indicated pH similar to soil samples taken in the 0- to 2-inch depth. Extensive soil sampling indicated the factor causing the unexpectedly high yields was high pH deep in the soil profile. In part of the fourth replication, soil samples revealed pH between 3 to 9 inches in the soil profile to be higher in some plots than in others. Between plots 401 and 405, the average pH at 3 to 6 inch depth in the soil profile was 5.46. Between plots 406 and 411, pH at the same depth averaged 7.02. This pH trend did not appear to be influenced by limestone application treatments. In plot 410, the treatment was 0 tons limestone per acre incorporated and the pH at the 6 to 9 inch depth in the soil profile was 7.45. Research station records showed limestone was applied to the area of plots 406 through 411 38 years ago in a study of crown vetch (*Coronilla varia* L) During 38 years, the pH in the upper 3 inches of the soil profile was acidified through natural processes. Below 3 inches in the soil profile, not enough time has passed for natural processes to decrease soil pH. Limestone movement in the soil profile could have occurred, but records do not show the depth of limestone placement 38 years ago.

In the downhill side of the plots in the first replication of the Orange County location, soil samples indicated an elevated pH in the subsoil areas of the soil profile. Samples taken on the 0 tons limestone per acre treatments revealed the following pH values: between 0 and 6 inches, pH was 6.20; between 6 and 12 inches, pH was 6.86; between 12 and 18 inches, pH was 6.78, and between 18 to 24 inches pH was 5.62. This experiment is on a 11% slope. We hypothesize that soil transported downhill over many years has accumulated at the area that is now the bottom part of the first replication.

A consistently higher yield occurred on tilled, unlimed plots than on non-tilled, unlimed plots at the Orange County location. As the limestone rate was increased, the tillage difference disappeared. This difference at 0 limestone rate is believed to be due to increased root penetration due to tillage on this clayey soil. Another theory suggests that S can be released in the soil due to tillage increasing mineralization of organic matter with subsequent release of S to plants.

The Montgomery County location had several 0 tons limestone per acre plots in which approximately 2 feet on one side produced high yields. During seedbed preparation, limestone could have been dragged onto these high yielding areas. Soil samples were taken at 0- to 2-inch depth, comparing high yield areas and low yield areas of these 0 tons limestone per acre plots. Soil pH in the high yielding areas averaged 6.6, suggesting limestone was accidentally placed in those areas, and pH in the low yielding areas averaged 5.5. Additionally, Ca levels were higher in the high yielding areas.

The results discussed in this section are further evidence that, if a layer of high pH is somewhere in the soil profile, alfalfa can produce high yields.

Appendix B

Additional Information

The following tables contain data that could be useful in research on surface limestone and nutrient application.

Exchangeable Ca increased with increased rate of limestone, as would be expected, due to Ca being a component of the limestone. As depth increased, exchangeable Ca decreased consistently in all treatments in Orange County (Appendix Table 5). In Montgomery County, exchangeable Ca decreased with depth in the surface-applied treatments but not in the incorporated treatments. Exchangeable Ca levels were slightly and consistently increased to a depth of 3 inches in the surface applied treatments due to movement of Ca into the soil profile. In the incorporated treatments at the Montgomery County location, exchangeable Ca levels were high in the 6 to 9 inch depths. Calcium movement into the 6 to 9 inch depth would increase exchangeable Ca levels such that a decreasing level of exchangeable Ca from 0 to 9 inches in the soil profile would not be observed. Due to differences in soils and time, samples taken after limestone application at the Orange County location did not have a similar response in the 6 to 9 inch soil layer to the Montgomery County location. A soil sample below 9 inches depth might show a decrease in exchangeable Ca.

Exchangeable Mg increased slightly with increased limestone rates. With increased depth, exchangeable Mg levels slightly decreased (Appendix Table 6). High levels of exchangeable Mg in the soil prior to limestone application could explain the lack of response to the Mg that was added through application of dolomitic limestone.

Exchangeable Mn decreased with increased rates of limestone (Appendix Table 7) as has been shown by other authors (Buss et al.,1975; Janghorbani et al.,1975). Decreased levels of exchangeable Mn occurred consistently to a depth of 3 inches and inconsistently to a depth of 6 inches in surface-applied limestone treatments. In incorporated limestone treatments, exchangeable Mn decreased from 0- to 6-inches depth and slightly lowered between 6- to 9-inches depth in the soil profile. The trends in exchangeable Mn are inversely related to pH trends in these soil layers, providing further evidence of an inverse relationship between pH and Mn.

Exchangeable K was highest in the upper soil samples in Montgomery County (Appendix Table 8) and decreased with depth. With increased limestone rate, exchangeable K did not increase. At some of the sampling depths, exchangeable K decreased with increased limestone application. Exchangeable K was highest in the upper soil samples in Orange County (Appendix Table 9) and decreased with depth. In some of the sampling depths, exchangeable K decreased with increased limestone application.

Appendix Table 10 contains data on percent protein of alfalfa for limestone application treatments. Alfalfa samples were taken at some harvest dates and analyzed for protein. Percent protein did not differ in the Montgomery County treatments. In Orange County, percent protein was lower in the plots with surface limestone no-till treatments than in plots where limestone was incorporated or surface-applied after tillage. This influence apparently was due to some factor related to tillage of soil and not to placement of limestone, since similar protein levels resulted between the incorporated and surface applied after tillage treatments.

Appendix Table 11 contains alfalfa yield data for each harvest date in 1988 in Montgomery County. Alfalfa yields increased with higher rates of limestone for all application methods. Similar yields resulted between all limestone application methods. Appendix Table 12 contains alfalfa yield data for all harvest dates in 1988 in Orange County. Increased alfalfa yields resulted with increased limestone rates for all application methods. Limestone application methods did not affect yield. Tillage of the soil influenced yield at the zero limestone rate. As rate of limestone increased, no difference in yield due to tillage was apparent.

Appendix Figure 2 illustrates total alfalfa yield in 1988 in Montgomery County for limestone application treatments at increasing limestone rates. As limestone rate increased from 0 to 2.5 tons per acre alfalfa yields increased. Between 2.5 and 5 tons limestone per acre, alfalfa yields did not increase. All three limestone application treatments produced similar yields.

Appendix Figure 3 illustrates soil pH as influenced by limestone rate in Orange County. Soil pH for surface-applied limestone, was calculated for a 0- to 2-inch depth and incorporated limestone was calculated for a 0- to 6-inch depth. Both treatment's response to limestone was similar.

Appendix Table 5. Exchangeable calcium as influenced by rates and placement of limestone and by tillage of soil in Montgomery and Orange Counties.

Soil prep.	Limestone† placement	Depth	Rate (tons/acre) 0	1.25	2.50	5.00	Parameters‡ a	b	c	R^2
		Inches	ppm							%
			Montgomery County							
Tilled	Incorp.	0-3	500	720	854	909	501*	203 *	-24.3*	80*
		3-6	475	613	783	796	463*	170 *	-20.6*	63*
		6-9	687	716	909	845	662*	118	-16.0	16
		LSD§ 0.05 =	224							
	Surface	0-1	613	703	963	900	583*	191 *	-25.1	31*
		1-2	611	553	740	674	579*	57	-7.1	8
		2-3	628	481	632	544	593*	-17	2.0	1
		3-6	642	457	605	506	583*	-27	2.8	3
		LSD§ 0.05 =	199							
None	Surface	0-1	723	763	996	998	694*	133 *	-14.2	51*
		1-2	583	702	752	566	581*	136 *	-27.8*	49*
		2-3	561	440	685	454	511*	68	-15.1	11
		3-6	642	425	649	409	588*	-7	-5.0	14
		LSD§ 0.05 =	210							
			Orange County							
Tilled	Incorp.	0-3	1061	1100	1237	1546	1054*	36	12.5	57*
		3-6	912	930	1056	1064	896*	69	-6.8	23
		6-9	704	670	782	702	684*	41	-7.2	5
		LSD§ 0.05 =	215							
	Surface	0-1	899	1290	1095	1613	972*	91	6.4	26
		1-2	859	1071	1200	1041	856*	233	-39.1	19
		2-3	932	1071	984	1161	960*	26	2.5	38*
		3-6	772	858	662	818	810*	-57	11.2	9
		LSD§ 0.05 =	480							
None	Surface	0-1	1317	1493	1841	2202	1294*	218 *	-6.9	75*
		1-2	876	917	1111	1156	854*	109 *	-9.5	62*
		2-3	812	946	1057	790	801*	188 *	-37.9*	34
		3-6	667	850	769	835	695*	77	-10.3	15
		LSD§ 0.05 =	199							

*Indicates significance at the 0.1 level or lower.
†Incorporation during tillage, surface applied after tillage and surface applied without tillage.
‡Models: Yield = a + b • Limestone applied + c • Limestone applied^2.
§Compares means within columns.

Appendix Table 6. Exchangeable magnesium as influenced by rates and placement of limestone and by tillage of soil in Montgomery and Orange Counties.

Soil prep.	Limestone† placement	Depth	Rate (tons/acre) 0	1.25	2.50	5.00	Parameters‡ a	b	c	R^2
		Inches	----------- ppm	-----------						%
			Montgomery County							
Tilled	Incorp.	0-3	93	176	205	190	95*	73*	-10.8*	86*
		3-6	90	150	183	171	90*	58*	-8.5*	76*
		6-9	129	155	193	172	125*	39	-5.8	25
	LSD§ 0.05 = 43									
	Surface	0-1	129	138	174	151	124*	26	-4.2	15
		1-2	121	127	149	141	118*	16	-2.2	8
		2-3	124	103	134	125	118*	1	0.2	1
		3-6	125	91	122	115	117*	-8	1.5	2
	LSD§ 0.05 = 42									
None	Surface	0-1	146	177	214	151	141*	50*	-9.5*	40*
		1-2	132	144	187	131	125*	38*	-7.2*	34
		2-3	123	108	156	110	114*	19	-3.9	11
		3-6	132	89	139	88	121*	1	-1.4	10
	LSD§ 0.05 = 56									
			Orange County							
Tilled	Incorp.	0-3	193	238	271	318	193*	39*	-2.7*	62*
		3-6	177	213	240	228	176*	39*	-5.8*	41*
		6-9	167	159	191	173	162*	12	-1.9	7
	LSD§ 0.05 = 46									
	Surface	0-1	158	221	171	201	170*	16	-2.1	12
		1-2	166	201	199	160	168*	30	-6.4*	28
		2-3	176	194	185	196	178*	7	-0.7	34*
		3-6	164	179	145	175	171*	-11	-2.3	10
	LSD§ 0.05 = 37									
None	Surface	0-1	220	231	279	241	214*	36*	-6.0	24
		1-2	169	189	215	196	167*	29*	-4.6*	44*
		2-3	160	179	223	152	154*	45*	-9.0*	46*
		3-6	148	170	173	173	149*	16*	-2.3	29
	LSD§ 0.05 = 40									

*Indicates significance at the 0.1 level or lower.
†Incorporation during tillage, surface applied after tillage and surface applied without tillage.
‡Models: Yield = a + b • Limestone applied + c • Limestone applied^2.
§Compares means within columns.

Appendix Table 7. Exchangeable manganese as influenced by rates and placement of limestone and by tillage of soil in Montgomery and Orange Counties.

Soil prep.	Limestone† placement	Depth	Rate (tons/acre) 0	1.25	2.50	5.00	Parameters‡ a	b	c	R^2
		Inches	ppm					×0.01		%
			Montgomery County							
Tilled	Incorp.	0-3	6.9	3.2	2.9	1.6	6.6*	-247*	29.7*	86*
		3-6	7.2	4.8	3.8	2.2	7.1*	-184*	17.3*	81*
		6-9	4.9	3.7	3.5	2.1	4.8*	-72	3.8	45*
	LSD§ 0.05 = 1.5									
	Surface	0-1	6.6	2.5	2.0	1.3	6.3*	-289*	38.2*	75*
		1-2	6.5	4.2	3.4	2.0	6.4*	-171*	16.6	67*
		2-3	6.2	6.6	4.3	4.3	6.5*	-79	6.4	29
		3-6	5.9	7.4	6.2	5.2	6.1*	66	-17.4	12
	LSD§ 0.05 = 2.3									
None	Surface	0-1	7.0	2.6	2.9	1.6	6.5*	-264*	33.5*	75*
		1-2	9.3	5.0	4.7	3.1	9.0*	-284*	34.1*	81*
		2-3	8.4	6.8	6.7	5.0	8.2*	-85	4.5	55*
		3-6	8.4	7.5	7.2	5.6	8.3*	-52	-0.4	50*
	LSD§ 0.05 = 1.3									
			Orange County							
Tilled	Incorp.	0-3	8.0	4.4	3.1	1.5	7.8*	-277*	30.5*	79*
		3-6	6.4	3.8	2.8	3.6	6.4*	-237*	36.7*	34
		6-9	2.3	1.4	2.4	1.2	2.0*	4	-3.9	7
	LSD§ 0.05 = 2.7									
	Surface	0-1	11.9	5.5	7.0	3.7	11.2*	-306*	32.4	61*
		1-2	1.6	6.7	6.7	5.3	11.2*	-313*	39.7*	62*
		2-3	10.8	7.6	7.8	4.9	10.4*	-160*	10.5	67*
		3-6	7.6	4.5	8.7	4.5	6.7*	50	-17.3	16
	LSD§ 0.05 = 2.2									
None	Surface	0-1	9.2	7.1	4.2	2.9	9.4*	-257*	24.5	67*
		1-2	11.2	9.7	5.7	4.7	11.6*	-267	25.2	37
		2-3	11.1	6.7	4.2	6.0	11.1*	-442*	68.0*	61*
		3-6	7.6	7.2	5.0	4.7	7.8*	-117	10.5	30
	LSD§ 0.05 = 4.1									

*Indicates significance at the 0.1 level or lower.
†Incorporation during tillage, surface applied after tillage and surface applied without tillage.
‡Models: Yield = a + b • Limestone applied + c • Limestone applied^2.

Appendix Table 8. Exchangeable potassium as influenced by rates and placement of limestone and by soil tillage in Montgomery County.

Soil prep.	Limestone† placement	Depth	Rate (tons/acre) 0	1.25	2.50	5.00	Parameters‡ a	b	c	R^2
		Inches	ppm							%
Tilled	Incorp.	0-3	125	103	102	95	123*	-14.1	1.71	27
		3-6	59	53	52	45	59*	-3.2	0.08	18
		6-9	61	58	65	50	59*	3.5	-1.07	11
	LSD§ 0.05 =		21							
Tilled	Surface	0-1	204	166	165	155	201*	-25.5	3.30	32
		1-2	94	67	63	62	92*	-20.5	2.89	39*
		2-3	79	48	49	49	76*	-20.7	3.12	40*
		3-6	69	58	44	44	70*	-13.9	1.73	34*
	LSD§ 0.05 =		35							
None	Surface	0-1	240	205	193	181	229*	-20.3	2.15	40*
		1-2	126	82	69	83	125*	-38.7*	6.08*	61*
		2-3	103	58	54	132	102*	-46.4	10.51	29
		3-6	72	89	43	58	80*	-11.3	1.29	14
	LSD§ 0.05 =		58							

*Indicates significance at the 0.1 level or lower.
†Incorporation during tillage, surface applied after tillage and surface applied without tillage.
‡Models: Yield = a + b • Limestone applied + c • Limestone applied^2.
§Compares means within columns.

Appendix Table 9. Exchangeable potassium as influenced by rates and placement of limestone and by soil tillage in Orange County.

Soil prep.	Limestone† placement	Depth	Rate (tons/acre) 0	1.25	2.50	5.00	Parameters‡ a	b	c	R^2
		Inches	ppm							%
Tilled	Incorp.	0-3	212	145	170	160	203*	-32.9	4.98	28
		3-6	81	79	81	58	80*	3.8	-1.63	47*
		6-9	40	40	47	66	40*	-0.1	1.07	26
	LSD§ 0.05 = 41									
Tilled	Surface	0-1	255	262	506	186	214*	170.6	-34.67	19
		1-2	118	129	130	93	117*	14.5	-3.86	32
		2-3	107	86	82	84	106*	-16.7	2.47	28
		3-6	67	67	47	50	70*	-10.1	1.17	28
	LSD§ 0.05 = 181									
None	Surface	0-1	364	245	207	202	359*	-98.2*	13.41	49*
		1-2	163	155	93	77	170*	-31.4	2.49	54*
		2-3	116	94	71	85	118*	-27.3*	4.25	41*
		3-6	66	82	47	127	74	-18.2	5.65	18
	LSD§ 0.05 = 72									

*Indicates significance at the 0.1 level or lower.
†Incorporation during tillage, surface applied after tillage and surface applied without tillage.
‡Models: Yield = a + b•Limestone applied + c•Limestone applied^2.
§Compares means within columns.

Appendix Table 10. Protein concentration in alfalfa as influenced by rates and placement of limestone and by soil tillage in Montgomery and Orange Counties.

Soil prep.	Limestone† placement	Rate (tons/acre) 0	1.25	2.50	5.00	Parameters‡ a	b	c	R^2
		%							%
Montgomery County									
			5/19/88						
Tilled	Incorp.	19.0	20.5	21.0	20.1	19.0*	1.5*	-0.25*	29
Tilled	Surface	17.4	19.8	20.8	20.9	17.4*	2.1*	-0.28	40*
None	Surface	17.9	19.3	19.9	20.9	18.0*	1.0*	-0.09	54*
	LSD§ 0.05 is 2.19								
			8/05/88						
Tilled	Incorp.	21.3	23.5	24.3	24.8	21.4*	1.8*	-0.22	74*
Tilled	Surface	21.1	24.6	24.0	24.8	20.5*	2.0*	-0.28*	61*
None	Surface	22.7	24.3	23.9	22.0	22.8*	1.3*	-0.28	23
	LSD§ 0.05 is 2.31								
			9/20/88						
Tilled	Incorp.	22.6	22.9	23.8	24.3	22.5*	0.5	-0.33	45*
Tilled	Surface	21.6	22.3	23.4	23.2	21.4*	1.1	-0.14	31
None	Surface	20.5	23.4	23.5	23.0	20.6*	2.1*	-0.33*	32
	LSD§ 0.05 is 2.67								
Orange County									
			5/23/88						
Tilled	Incorp.	13.8	19.6	20.4	20.4	14.1*	4.3*	-0.62*	89*
Tilled	Surface	13.1	19.4	20.3	20.5	13.5*	4.7*	-0.67*	86*
None	Surface	10.8	17.7	19.6	20.9	11.2*	5.4*	-0.68*	96*
	LSD§ 0.05 is 1.25								
			8/04/88						
Tilled	Incorp.	17.7	21.2	22.2	21.8	17.8*	3.0*	-0.43*	83*
Tilled	Surface	17.8	22.8	22.1	23.2	17.9*	2.5*	-0.29*	87*
None	Surface	16.3	17.5	20.5	21.5	16.0*	2.1*	-0.19*	82*
	LSD§ 0.05 is 1.61								

*Indicates significance at the 0.1 level or lower.
†Incorporation during tillage, surface applied after tillage and surface applied without tillage.
‡Models: Yield = a + b • Limestone applied + c • Limestone applied^2.
§Compares means within columns.

Appendix Table 11. Alfalfa yields from four harvests in 1988 as influenced by rates and placement of limestone and by soil tillage in Montgomery County.

Soil prep.	Limestone† placement	Rate (tons/acre) 0	1.25	2.50	5.00	Parameters‡ a	b	c	R^2
		--------tons per acre--------				------ x0.01 -------			%
					5/19/88				
Tilled	Incorp.	0.47	1.41	1.03	1.11	0.58*	0.410*	-0.0607*	82*
Tilled	Surface	0.23	1.29	1.28	1.32	0.27*	0.716*	-0.0935*	91*
None	Surface	0.65	1.46	1.13	1.62	0.81*	0.296*	-0.0300	60*
	LSD§ 0.05 is 0.48								
					6/29/88				
Tilled	Incorp.	0.31	0.57	0.57	0.55	0.33*	0.184*	-0.0283*	78*
Tilled	Surface	0.19	0.58	0.52	0.48	0.24*	0.217*	-0.0269*	87*
None	Surface	0.20	0.45	0.48	0.65	0.20*	0.172*	-0.0167*	95*
	LSD§ 0.05 is 0.13								
					8/05/88				
Tilled	Incorp.	0.37	1.12	0.99	1.08	0.46*	0.438*	-0.0636*	80*
Tilled	Surface	0.33	1.12	1.16	1.02	0.40*	0.542*	-0.0754*	93*
None	Surface	0.51	1.11	1.06	1.23	0.43*	0.471*	-0.0629*	89*
	LSD§ 0.05 is 0.31								
					9/20/88				
Tilled	Incorp.	0.44	1.25	1.42	1.36	0.48*	0.648*	-0.0951*	95*
Tilled	Surface	0.22	1.13	1.15	1.25	0.28*	0.685*	-0.1140*	83*
None	Surface	0.49	1.19	1.13	1.41	0.39*	0.537*	-0.0678*	89*
	LSD§ 0.05 is 0.28								
					Total				
Tilled	Incorp.	1.57	4.27	3.95	4.14	1.84*	1.680*	-0.2477*	92*
Tilled	Surface	0.90	4.12	4.10	4.01	1.18*	2.160*	-0.3089*	95*
None	Surface	2.04	4.29	3.73	4.89	1.83*	1.475*	-0.1777*	85*
	LSD§ 0.05 is 0.93								

*Indicates significance at the 0.1 level or lower.
†Incorporation during tillage, surface applied after tillage and surface applied without tillage.
‡Models: Yield = a + b • Limestone applied + c • Limestone applied^2.
§Compares means within columns.

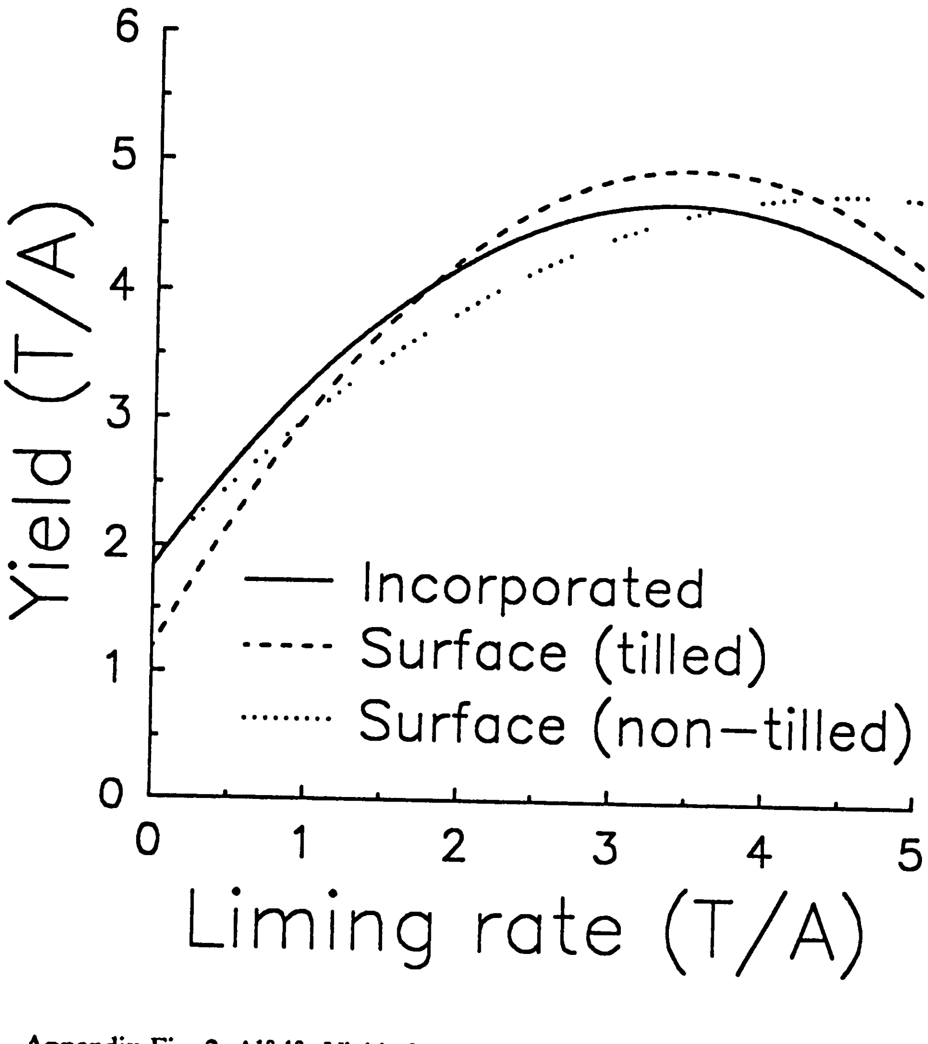
Appendix Table 12. Alfalfa yields from four harvests in 1988 as influenced by rates and placement of limestone and by soil tillage in Orange County.

Soil prep.	Limestone† placement	Rate (tons/acre) 0	1.25	2.50	5.00	Parameters‡ a	b	c	R^2
		------tons per acre------							%
					5/23/88				
Tilled	Incorp.	0.91	1.81	2.18	1.91	0.92*	0.831*	-0.1268*	85*
Tilled	Surface	0.76	1.87	2.18	2.00	0.80*	0.941*	-0.1408*	95*
None	Surface	0.41	1.54	2.08	2.11	0.43*	1.015*	-0.1358*	96*
	LSD§ 0.05 is 0.24								
					6/30/88				
Tilled	Incorp.	0.65	1.24	1.45	1.33	0.67*	0.526*	-0.0788*	86*
Tilled	Surface	0.42	1.16	1.42	1.41	0.45*	0.628*	-0.0875*	97*
None	Surface	0.16	0.98	1.28	1.42	0.19*	0.673*	-0.0861*	96*
	LSD§ 0.05 is 0.15								
					8/04/88				
Tilled	Incorp.	0.68	0.98	1.22	1.06	0.67*	0.345*	-0.0530*	91*
Tilled	Surface	0.51	0.98	1.45	1.10	0.52*	0.408*	-0.0585*	97*
None	Surface	0.35	0.83	0.95	1.01	0.37*	0.373*	-0.0493*	94*
	LSD§ 0.05 is 0.10								
					9/13/88				
Tilled	Incorp.	0.09	0.24	0.35	0.32	0.09*	0.160*	-0.0227*	51*
Tilled	Surface	0.05	0.23	0.40	0.41	0.05*	0.192*	-0.0237*	55*
None	Surface	0.01	0.21	0.33	0.32	0.01*	0.194*	-0.0267*	62*
	LSD§ 0.05 is 0.07								
					Total				
Tilled	Incorp.	2.32	4.27	5.21	4.62	2.34*	1.862*	-0.2813*	76*
Tilled	Surface	1.74	4.25	5.15	4.93	1.82*	2.170*	-0.3104*	76*
None	Surface	0.93	3.55	4.64	4.86	1.07*	2.256*	-0.2979*	82*
	LSD§ 0.05 is 0.64								

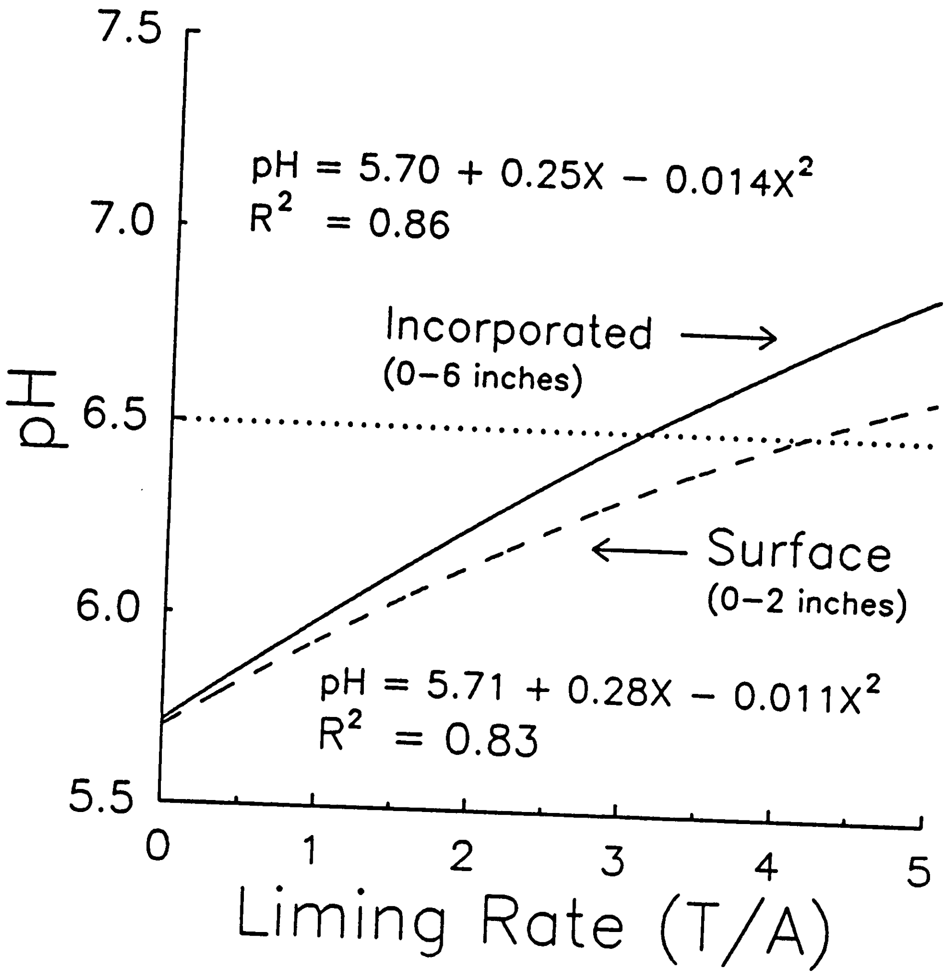
*Indicates significance at the 0.1 level or lower.

†Incorporation during tillage, surface applied after tillage and surface applied without tillage.

‡Models: Yield = a + b • Limestone applied + c • Limestone applied^2.



Appendix Fig. 2. Alfalfa Yields for rate and placement of limestone in Montgomery County.



Appendix Fig. 3. Soil pH as influenced by rate and placement of limestone in Orange County. Soil pH was calculated for 0 to 2 inches for the surface limestone treatment and 0 to 6 inches for the incorporated limestone treatment.

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