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# LIME INDUCED CHANGES IN THE SURFACE AND SOIL SOLUTION CHEMISTRY OF VARIABLE CHARGE SOILS

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**Dissertation submitted to the**
**Davis College of Agriculture, Forestry, and Consumer Sciences**
**at West Virginia University**
**In partial fulfillment of the requirements for the degree of**

**Doctor of Philosophy**
**in**
**Plant and Soil Science**

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**Division of Plant and Soil Sciences**
**Morgantown, West Virginia**
**2008**

# ABSTRACT

## Lime induced changes in the surface and soil solution chemistry of variable charge soils

### Rajesh Chintala

The study was conducted to improve lime recommendations as well as to design better management practices for acidic grasslands of Appalachian region. These goals were achieved by two experiments. In the first experiment, the accuracy of lime predictions by quick tests were improved by accounting soil order and develop equation based lime correlations for acidic pasture soils of West Virginia. In order to achieve this objective, 26 surface soil samples (0 – 7.5 cm) from three most important soil orders for the state (Alfisols, Inceptisols, Ultisols) from each of the Major Land Resource Areas (MLRAs) in West Virginia with large proportions of pasture land were collected in cooperation with state soil scientists. Standard procedures for the determination of lime requirements by the Mehlich Buffer (MB), Adams-Evans Buffer (AEB) and Shoemaker-McLean-Pratt Single Buffer (SMPB) methods were used. Statistically significant improvements in lime recommendations for target pH 6.5 and 5.5 were achieved by accounting for soil order. Mehlich single buffer recommendations were better for Alfisols and Ultisols than for Entisols to achieve pH 6.5. Lime correlations were developed for all three chemical buffers by multiple regression where the independent variables were target pH and soil-buffer pH. The Adam-Evans buffer predicted lime rates better for target pH 5.5. Equation-based lime correlations were also developed for all three chemical buffers by multiple regressions where the independent variables are target pH and soil-buffer pH. The second experiment was conducted to quantify the critical growth factors such as water potential, pH, nitrogen, and phosphorus and their interactions to deduce a comprehensive prescription of site-specific management techniques to forage production in acidified hill land pastures of West Virginia. In order to achieve this objective, a pot experiment was set up with two water potentials, five pH levels, five N and P fertilizer rates were imposed on bluegrass (sole) and bluegrass + white clover mixture. The estimation of overall effects of these four factors showed that levels of water potential, pH, N fertilizer doses as well as their interactions significantly affected the bluegrass (sole) production ($p<0.05$). In case of bluegrass and white clover mixture cropping system, all four factors (water potential, pH, N and P levels) and their interactions exhibited significant influence on dry matter yield as well as nutrient concentration in shoot tissue. Nutrient concentrations also showed a synergistic relationship among each other as well as with dry matter yield in both bluegrass and bluegrass + white clover mixture. Response yield function was determined using significant factors and their interactions for blue grass (sole) and blue grass and white clover mixture.

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# CHAPTER I

## INTRODUCTION

### 1.1. Overview

In West Virginia, the total area of farm land is 1.40 million hectares (22.4% of the total land area) of which 0.21 million hectares of land is under pasture (National Agricultural Statistics Service, 2005) spread on undulating terrain. The soils on this rugged terrain range from Entisols and Inceptisols on recent deposits to Alfisols, Ultisols, Mollisols, and Spodosols on older, more stable surfaces. The hills and uplands of the Appalachian region have limitations on agricultural productivity because of climate, soil and physical features such as slope gradient and slope aspect. A forage-based cropping system allows economic use of land unsuitable for production of arable crops. Grassland is more efficient in reducing erosion because of the fibrous mass of roots that bind soil particles better than row crops. The growth of grasses promotes granulation of soil particles and crumb formation. The absorptive capacity of the soil for water and infiltration rate is also improved along with reduction in impact of rain drops. Finally the herbage on the surface offers mechanical obstruction to water moving over the soil and the velocity of runoff is greatly reduced. Together these make grass-based farming systems ideal for reducing runoff and erosion and improving sustainability of production on the soils of West Virginia.

State rainfall averages nearly 102 cm per anum that results in a removal rate of base cations that exceeds the rate of their liberation from non-exchangeable forms

(DeWalle et al., 1985). As a result of factors such as high precipitation and undulating topography, the pasture soils of West Virginia, though of mixed mineralogy, have a large variable charge mineral content (Ritchey and Snuffer, 2002). Rainfall is not uniformly distributed spatially or temporally across the state. This and the undulating topography create conditions where water potential can vary within a particular field or farm.

The goal of this research is to provide guidance for the way pasture soils are divided into management zones in the Appalachian region generally, and West Virginia in particular. The primary yield-liming factors were assumed to be available water (related to landscape position), and acidic soils. This was accomplished with two separate, but intimately related experiments. The first was designed to determine the best way to make lime recommendations for all soils in the state. The second was to determine the optimal pH, N and P needs as a function of water potential for bluegrass (alone) and a bluegrass and white clover mixture.

## 1.2. Soil Acidity and Liming

### *1.2.1. Soil Acidification*

Soil acidification is a natural process which can be accelerated by the activity of humans and ameliorated with proper management. Soil acidity causes harmful effects to both plants and soil organisms (Runge and Rode, 1991). Acid soil infertility has been attributed to manganese and aluminum toxicity (Adams, 1984). The two most important acid generating processes in any natural ecosystem resulting from human activities are acid drainage from pyrite oxidation and acid deposition (Longhurst, 1991; Evangelou, 1995). In managed ecosystems, plant-induced processes such as carbon assimilation, uptake and assimilation of nitrogen and sulfur, and soil-mediated processes such as decomposition of organic matter, transformation of nitrogen (Table 1.2.1) and sulfur are important acid generating processes (Bolan et al., 2003). However, in West Virginia, the primary cause for the acidification of pasture soils is excess of rainfall over evopo-transpiration, the resulting leaching of base cations and the formation of acidic variable charge minerals in surface soils (Ritchey and Snuffer, 2002).

Table 1.2.1. Nitrogen reactions in soils and their net effect on $H^+$ production. (Bolan et al., 2003).

| Process | Reaction | $H^+$ ($mol_c.mol^{-1}$) |
|---|---|---|
| N fixation | $2N_2 + 2H_2O + 4ROH \rightarrow 4RNH_2 + 3O_2$ | 0 |
| Mineralization of organic N | $RNH_2 + H^+ + H_2O \rightarrow ROH + NH_4^+$ | -1 |
| Urea hydrolysis | $(NH_2)_2CO+3H_2O \rightarrow 2NH_4^+ + 2OH^- + CO_2$ | -1 |
| Ammonium assimilation | $NH_4^+ + ROH \rightarrow RNH_2 + H_2O + H^+$ | +1 |
| Ammonia volatilization | $NH_4^+ + OH^- \rightarrow NH_3 + H_2O$ | +1 |
| Nitrification | $NH_4^+ + 2O_2 \rightarrow NO_3^- + H_20 + 2H^+$ | +2 |
| Nitrate assimilation | $NO_3^- + 8H^+ + 8e^- \rightarrow NH_3 + 2H_2O + OH^-$ | -1 |
| Denitrification | $4NO_3^- + 4H^+ \rightarrow 2N_2 + 5O_2 + 2H_2O$ | -1 |

Minerals with pH-dependant surface charge (amphoteric minerals) include kaolinite, oxides and hydroxides of Fe and Al and their complexes with organic matter (Dahlgren et al., 1993; Parfitt, 1980; Zhang and Zhao, 1997). Variable charge arises from the protonation and deprotonation of functional groups at mineral surfaces and organic matter. In acid conditions, an excess of adsorbed $H^+$ results in a net positive charge at the oxygen and hydroxyl functional groups (Fig. 1.2.1a). At high pH condition oxygen deprotonation is induced along with the surface gaining a net negative charge (Fig. 1.2.1c). At some intermediate pH, the positive and negative charges are equal (Fig.

1.2.1b). This pH is referred to as the point of zero charge (PZC). Generally, the PZC represents the pH of maximum particle agglomeration and lowest potential mineral solubility (Parks and DeBruyn, 1962). As a result of variable charge dominant mineralogy and acidic pH, soils in West Virginia and the Appalachian region tend to have a low cation exchange capacity (3-21 $\mathrm{cmol_c\ kg^{-1}}$) (NRCS, 2004).

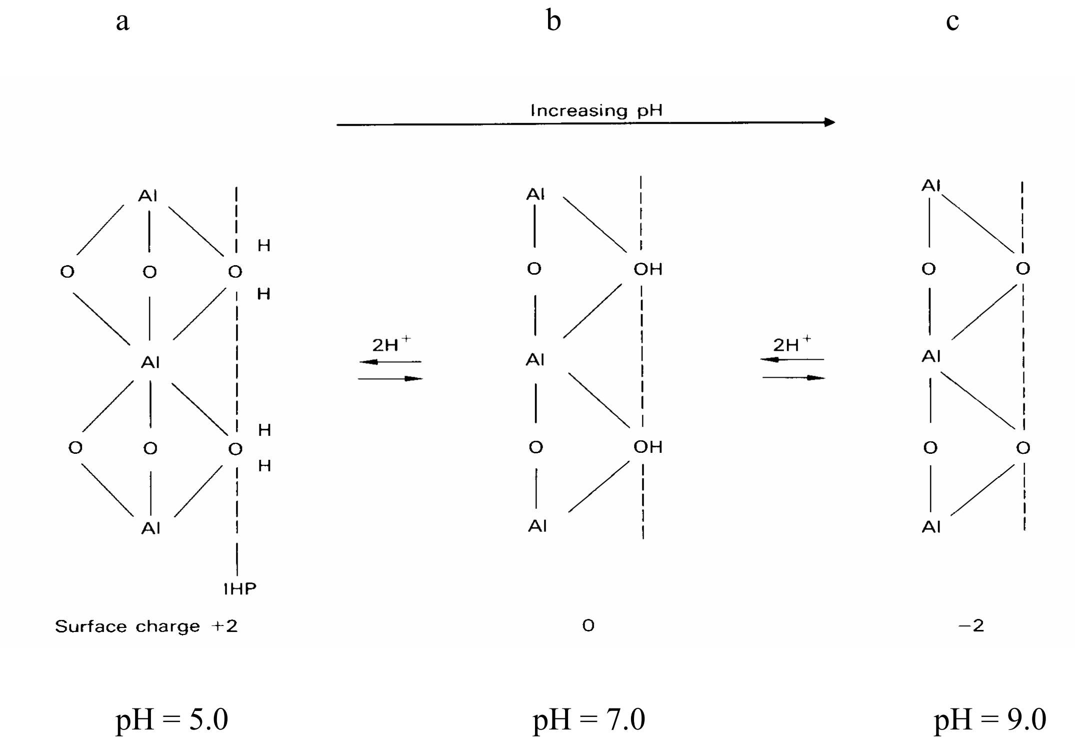

Fig. 1.2.1. Schematic representation of the terminal edge of an aluminium oxide crystal under three pH conditions. (Brady and Weil, 1990).

The metal most commonly associated with soil acidification is $Al^{3+}$ which occupies a greater proportion of cation exchange sites and reduces base saturation (Jenny and Overstreet, 1939). Soil acidification changes the equilibrium, partitioning and speciation of metals in the soil solution. In general, the solubility and mobility of most metals increases with decreasing pH. Aluminum ions on mineral surfaces hydrolyze to produce $H^+$, which in turn attacks the clay surfaces to produce more acidity (Eq. [1.2.1]), (Bolan et al., 2003),

$$Al^{3+} + nH_2O \leftrightarrow Al(OH)_3^{n-3} + nH^+ \qquad [1.2.1]$$

In addition to the direct toxicity of $Al^{3+}$, especially to growing root tips, soil aluminum reduces the available pool of alkali and alkali earth elements (base cations) (Ulrich, 1994). Al toxicity can also have a substantial inhibitory effect on the uptake and translocation of P (Chen and Barber, 1990). Soil acidification also decreases the number of plant species in natural grassland (Goulding and Annis, 1998; Tilman et al., 1994).

### *1.2.2. Lime Requirement*

The oldest definition of a lime requirement (McBride, 1994) was the amount of $CaCO_3$ (or its equivalent in any other alkaline material needed to neutralize all exchangeable acidity and bring the soil to 100 percent base saturation. More modern definitions of lime requirement are variations of McLean (1973) “the amount of liming material which must be applied to a soil to raise its pH from an initial acid condition to a level selected for near optimum plant growth”. The soil physico-chemical factors that have been shown to influence LR include CEC, clay type and content, organic matter content, buffer capacity, total and exchangeable acidity (Machacha, 2004). Lime requirement values are correlated negatively with soil pH and positively with total acidity and exchangeable Al (Halder and Mandal, 1985). The most direct method to determine lime requirement is by direct incubation with $CaCO_3$. However, this approach is not practical for routine soil test laboratory recommendations. Therefore, various chemical methods (quick tests) have been developed to determine lime requirements for acid soils (McLean and Brown 1984). These include:

(a). Titration of the soil with $Ca(OH)_2$ which allows soil pH to be raised to any chosen value (Abruna et al.,1955)

(b). Single chemical buffer methods of Woodruff (1948), Shoemaker, McLean, and Pratt (SMP) (1961), Adams and Evans buffer method (AEB) (1962), and Mehlich single buffer method (MB) (1976). Single buffer methods are based on the principle that the pH of a buffer solution when mixed with soil will decrease linearly in response to the exchangeable hydrogen ($H^+$) content of the soil solution (Alabi et al., 1986)

(c). Improved double buffer methods of McLean et al., (1978) and Yuan (1974), which possess greater sensitivity and takes into account the buffering capacity of the soil

(d). Exchangeable Al extracted with an unbuffered salt such as potassium chloride (Kamprath, 1970).

The choice of a quick test (buffer method) and its lime requirement depends on the soil properties such as amount of exchangeable aluminum, cation exchange capacity, and amorphous Al content of the soil (Bolan et al., 2003). The lime requirements of acidic soils were highly correlated with exchangeable Al and total acidity (Patiram and Prasad, 1991). However, soil components such as organic carbon and clay minerals were more important in controlling the magnitude of lime requirement of acid soils with the same degree of weathering (Chen and Lin, 1994).

Comparative studies of different methods for estimating lime requirement have been carried out all over the world to determine the suitability of the selected method. Webber et al. (1977) observed that the Woodruff and SMP methods gave lime requirement values that were highly correlated with values from the incubation method for 39 soils from Canada, whereas Curtin et al. (1984) found that the SMP method underestimated the lime requirement for Saskachevan soils. The SMP method was recommended as the diagnostic tool to predict the lime requirement of acid Ghanaian soils due to its simplicity and shorter analytical time (Owusu-Bennoah et al., 1995). However, Brown and Cisco (1984) found that the SMP buffer method underestimated the lime requirement for low buffer capacity soils and overestimated it for high lime requirement soils. Therefore, the double buffer SMP method was introduced to improve the sensitivity for low buffer capacity soils. The SMP double buffer method gave the best results for both high and low lime requirement soils and was particularly impressive at the lower pH targets of low buffered soils (Shoemaker et al., 1961). Daniel et al. (1989) found that the double buffer method of McLean (1978) was more accurate for soils with a low lime requirement, and the SMP single buffer method was more accurate for soils with a high lime requirement. The Mehlich single-buffer method worked well in two different soil pH conditions and demonstrated good correlations with lime requirements to pH 5.5 ($R^2 = 0.78$) and pH 6.69 ($R^2 = 0.80$). Compared with the double-buffer methods (which need two pH measurements), the single-buffer methods were better correlated with lime requirements and easier for laboratories that handle numerous samples (Aitken et al., 1990).

Lime incubation with calcium carbonate is an accurate reference method for comparative studies of chemical buffers to predict lime requirements for soil. However, lime incubations are also time and labor intensive tests. Fortunately direct titration with $Ca(OH)_2$ has been shown to be an accurate substitute (Alabi et al., 1986) (Fig. 1.2.2).

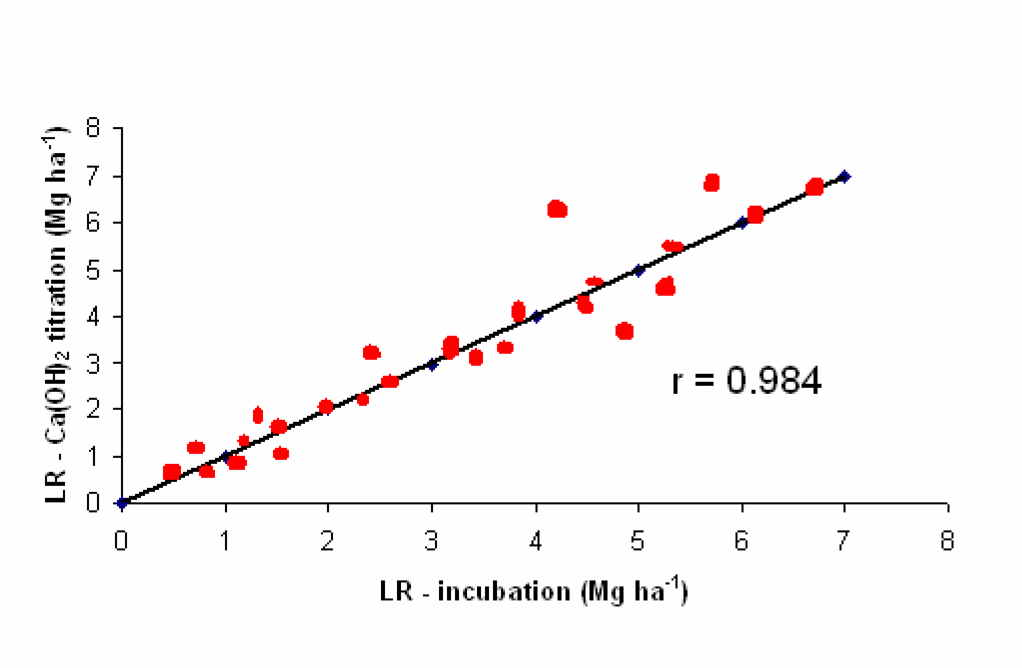

Fig. 1.2.2. Relationship of lime requirements (LR) determined by $Ca(OH)_2$ titration with those determined by incubation. Equation: $Y = 0.889X + 0.057$ (Alabi et al., 1986).

### *1.2.3. Lime Response*

Liming is the most common practice used to overcome the impact of soil acidification in agricultural soils. However, an integrated approach involving liming, cultural practices and plant tolerance will probably be necessary, particularly where the acidification potential is high and its effect is likely to extend into the subsoil (Bolan et al., 2003). A range of liming materials is available, which vary in their ability to neutralize acidity. These include calcite ($CaCO_3$), burnt lime (CaO), slaked lime ($Ca(OH)_2$), dolomite ($Ca\ Mg\ (CO_3)_2$) and slag ($CaSiO_3$). The acid neutralizing value of liming materials is expressed in terms of its calcium carbonate equivalent (CCE), defined as the acid neutralizing capacity of liming materials expressed as a weight percentage of pure $CaCO_3$. The amount of liming material required to rectify soil acidity depends on the neutralizing value of the liming material and the pH buffering capacity of the soil. Lime neutralizes acidity by reacting with free $H^+$ (Eq. [1.2.2]),

$$2H^+ + CaCO_3 \rightarrow Ca^{2+} + H_2O + CO_2 \qquad [1.2.2]$$

Free $H^+$ results from aluminum hydrolysis (Eq. [1.2.1]), dissociation from organic matter functional groups (Eq. [1.2.3]),

$$R - COOH \leftrightarrow R - COO^- + H^+ \qquad [1.2.3]$$

or from any other reaction that produces a proton. The complete neutralization reaction can be written as

$$ExAl + \frac{3}{2}CaCO_3 + \frac{1}{2}H_2O \xrightarrow{H_2O} Al(OH)_3 + \frac{3}{2}ExCa + \frac{3}{2}CO_2 \qquad [1.2.4]$$

The net result of all these reactions is to increase the soil pH and base saturation (Fig. 1.2.3) and displace the $Al^{3+}$ from the exchangeable complex and precipitate it as unavailable hydroxides. Curtin and Smillie (1983) limed three acid soils with $CaCO_3$ and incubated them for 52 weeks at field capacity and observed that the activity of $Al^{3+}$ was linearly correlated with solution pH. There was a significant decrease in Al solubility with time (increase of slope of $pAl^{3+}/pH$) due to slow crystallization of the Al precipitate (hydroxides of Al) and the proportion of total Al increased in organic complexes increased with pH in 27 and 52 weeks (Fig. 1.2.4).

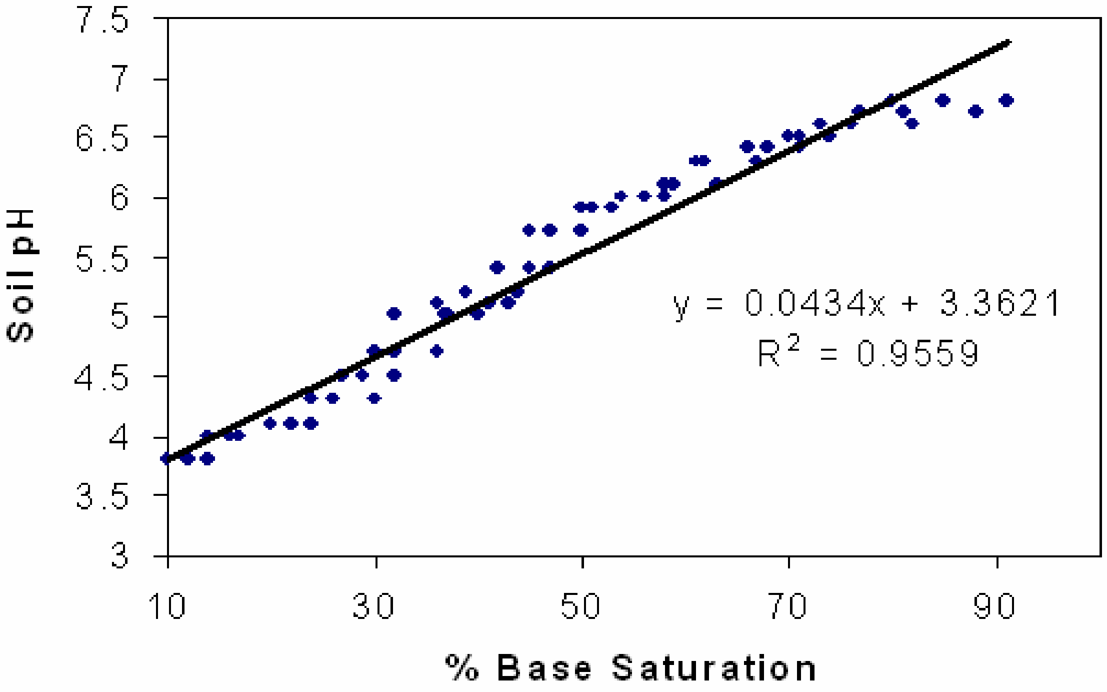

Fig. 1.2.3. Relationship between soil suspension pH and percent base saturation (Magdoff and Bartlett, 1985).

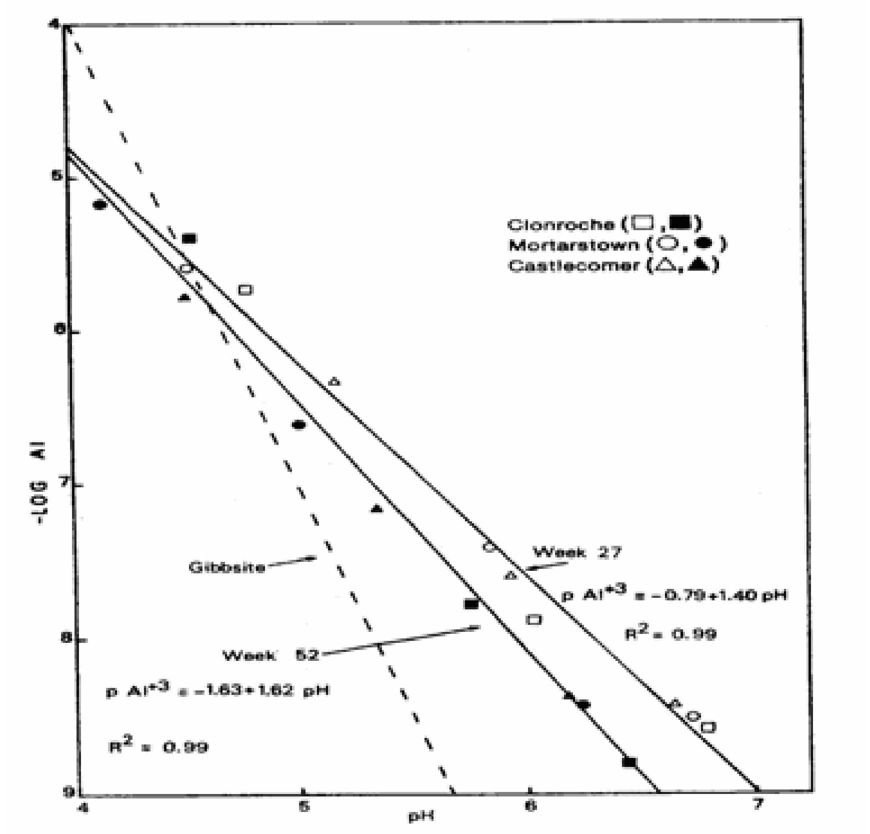

Fig. 1.2.4. Changes in $pAl^{3+}$ with pH for Clonroche, Mortarstown and Castlecomer soil solutions obtained after 27 and 52 weeks of incubation. Solubility of gibbsite was calculated using a solubility product value of $10^{-34.05}$ (Curtin and Smillie, 1983).

Although it is widely accepted that the pH at which maximum plant yield occurs may vary depending on soil characteristics, the reasons for this differential responses are not well understood (Bolan et al., 2003). Although lime is an inexpensive soil amendment, because economic returns to pastures are relatively low and lime applications can be difficult on the steep soils of the region, it is important that lime application accurately reflect lime need especially for low input cropping systems.

## 1.3. Nitrogen and Phosphorus

Nitrogen and phosphorus are the most frequently recommended fertilizers and limestone is the most commonly recommended soil amendment for agricultural soils. Most university soil testing laboratories, and many private laboratories, make fertilizer and soil amendment recommendations based on sufficiency levels (Eckert, 1987). Limestone is routinely prescribed at rates to increase soil pH to the range 6.2 to 6.6 and sufficiency level recommendations for phosphorus assume that soil pH is in the prescribed range. Therefore, it is important that lime recommendations made by soil test calibrations are accurate.

### *1.3.1. Crop Response to Nitrogen and Phosphorus*

Overman and Scholtz (2003) developed relationships (response curves) among applied nitrogen, dry matter yield and plant N uptake and plant nitrogen concentration for bermudagrass (Fig.1.3.1).

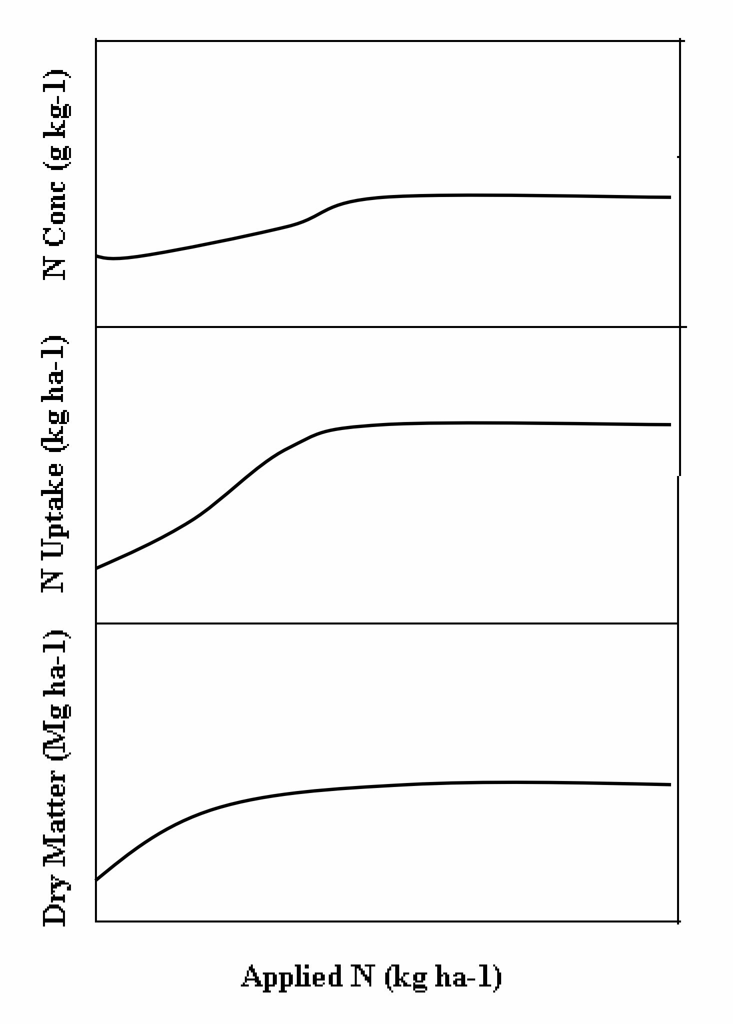

Fig.1.3.1. Dependence of dry matter, plant N uptake, and plant N concentration on applied nitrogen for coastal Bermudagrass grown at Holland, VA (Overman and Scholtz , 2003)

Burman et al. (2004) found the synergistic effect of P and thiourea enhanced the net photosynthesis, leaf area, chlorophyll content and nitrogen metabolism leading to significant improvement in plant growth and seed yield of cluster bean under water stress conditions (Table 1.3.1). The decline in seed yield was consistently lower in P treated cluster beans as compared to untreated plants. In a similar way, thiourea increased the seed yield of both control and water stressed plants. The combined application of P and thiourea exhibited the synergistic effects as seed yield and shoot dry mass increased by 34.2 and 27.3% respectively in water stressed treatments. Both P nutrition and thiourea application had a significant and favorable influence on plant growth and yield under drought conditions. Other studies have also shown that P nutrition under water deficits increased drought resistance and improved growth and yield (Gutierrez-Boem and Thomas 1998, Singh and Sale 2000).

Table 1.3.1. Influence of P and thiourea (TH) on seed yield and shoot dry matter (DM) of clusterbean under water stress (D) (Burman et al., 2004)

| Treatments | | Seed yield (g plant$^{-1}$) | | Shoot DM (g plant$^{-1}$) | |
|---|---|---|---|---|---|
| | | $P_o$ | $P_{40}$ | $P_o$ | $P_{40}$ |
| Control | -TH | 3.71 | 4.38 | 11.41 | 13.20 |
| | +TH | 4.46 | 4.91 | 12.72 | 13.94 |
| Drought | -TH | 3.15 | 3.15 | 7.77 | 9.02 |
| | +TH | 3.42 | 3.42 | 9.01 | 9.92 |
| $LSD_{0.05}$D | | | 0.27 | | 0.54 |
| $LSD_{0.05}$P | | | 0.27 | | 0.54 |
| $LSD_{0.05}$TH | | | 0.27 | | 0.54 |
| D X P | | | NS | | NS |
| D X TH | | | NS | | NS |
| P X TH | | | NS | | NS |

### *1.3.2. Nitrogen by Phosphorus Interactions*

The decrease in the P supply reduced both organic and inorganic phosphate concentration of tomato leaves (Fig. 1.3.2a) while the concentrations of total and reduced leaf N continued to decrease with reduction of N supply (Fig. 1.3.2b).

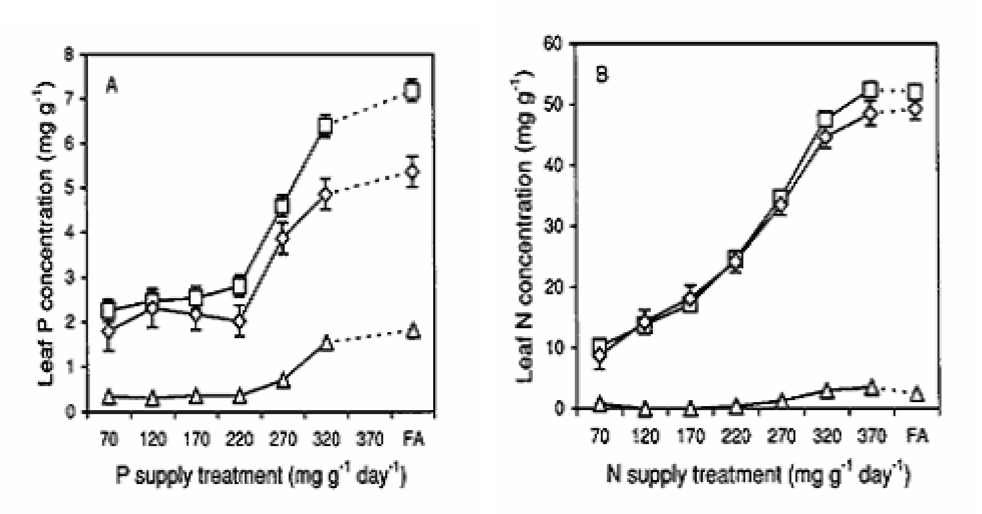

Fig. 1.3.2. Effect of N and P nutrition on leaf concentration of tomato leaves (Corine et al., 2003).

The relative growth rate (RGR) in tomato plants initially increased sharply with increasing plant P concentration but leveled off at higher plant N concentrations. But RGR increased gradually with increasing plant N concentration before it leveled off at higher Plant N concentrations (Corine et al., 2003).

Plant N concentration was also decreased with increasing P limitation (Fig. 1.3.3a). But there was a consistent increase in plant P concentration and stem P concentration with decreasing N supply (Fig. 1.3.3b). The explanation for the differences in response is mainly due to different roles of N and P in plant's energy metabolism.

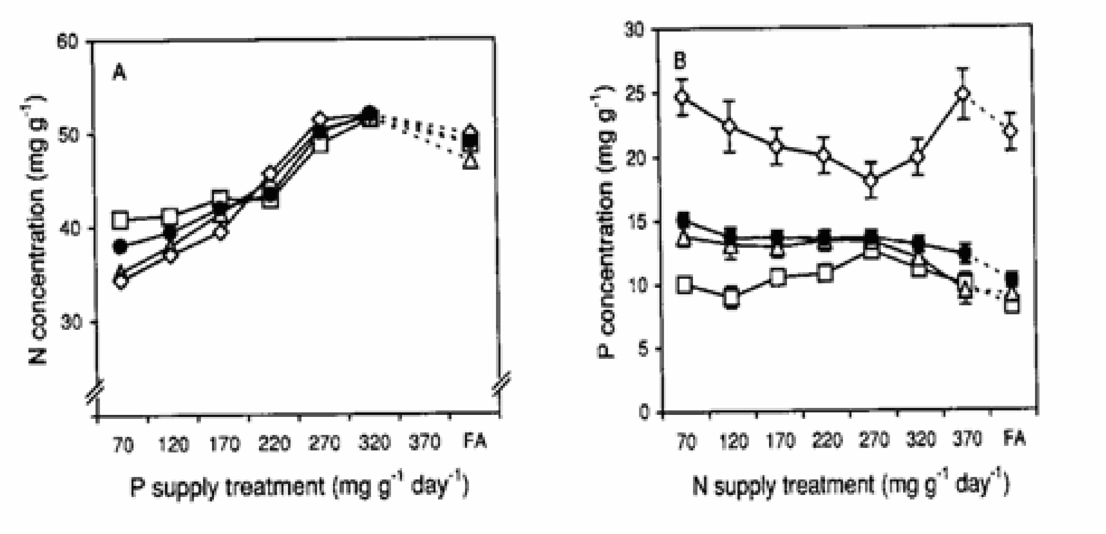

Fig. 1.3.3. Interactive effects of N and P nutrition in tomato leaves (Corine et al., 2003).

Mengel and Kirkby (1987) found that the accumulated inorganic phosphate and nitrate do not increase RGR but did increase the plant P and N concentration. An increase in P nutrition improved symbiotic $N_2$ fixation in bean only at low N concentrations (Leidi and Navarro, 2000).

### ***1.3.3. Lime by Nitrogen Interactions***

Pasture growth and N-accumulation responded to changes in soil acidity at the Bungendore site. There was also an increase in subterranean clover N yields, and pasture clover contents by addition of superphosphate in presence of lime at Bungendore site (Peoples et al., 1995) (Table1.3.2).

Table1.3.2. Effect of lime and supersphosphate applications on pasture growth and accumulation of N in 1991. For each measurement, values followed by the same superscript letter do not differ significantly (P = 0.05).

| Site and treatment | Phosphorus applied (kg P ha$^{-1}$) | Pasture dry matter production (t ha$^{-1}$) | Non-clover N yield (kg P ha$^{-1}$) | Subterranean clover N yield (kg P ha$^{-1}$ ) | Pasture clover content* ( % N basis) | Total pasture N (kg P ha$^{-1}$ ) |
|---|---|---|---|---|---|---|
| Bungendore | | | | | | |
| Nil | 0 | 3.19$^{a}$ | 33$^{a}$ | 23$^{a}$ | 41$^{a}$ | 56$^{a}$ |
| | 10 | 3.11$^{a}$ | 29$^{a}$ | 29$^{a}$ | 50$^{ab}$ | 58$^{a}$ |
| | 20 | 3.26$^{a}$ | 28$^{a}$ | 39$^{a}$ | 58$^{b}$ | 67$^{a}$ |
| Lime | 0 | 4.61$^{b}$ | 46$^{b}$ | 38$^{a}$ | 45$^{a}$ | 84$^{b}$ |
| | 10 | 5.18$^{b}$ | 36$^{ab}$ | 70$^{b}$ | 66$^{b}$ | 106$^{c}$ |
| | 20 | 5.07$^{b}$ | 40$^{ab}$ | 65$^{b}$ | 62$^{b}$ | 105$^{c}$ |
| Braidwood | | | | | | |
| Nil$^{+}$ | 0-20 | 3.18 | 53 | 4 | 6 | 57 |
| Lime$^{+}$ | 0-20 | 3.55 | 55 | 4 | 6 | 59 |
| Beechworth | | | | | | |
| Nill$^{+}$ | 0-20 | 3.08 | 37 | 18 | 33 | 55 |
| Lime$^{+}$ | 0-20 | 2.91 | 34 | 18 | 34 | 52 |

* Subterranean clover N as a proportion of total pasture N.

$^{+}$ There was no significant effect o phosphorus treatment at either Braidworth; data averaged.

The poor performance of pastures has been attributed to acid soil effects on $N_2$ fixation in mixed swards (Evans et al., 1980) and low P availability (Heylar and Anderson, 1970).

### *1.3.4. Lime by Phosphorus Interactions*

Liming is a common practice to raise soil pH and increase phosphorus bioavailability (Sanchez and Uehara, 1980). However, P sorption has been shown to increase, decrease or remain unchanged with increasing pH. Liming increased P sorption in three acid soils from southern Brazil up to pH 5.0 (Anjos and Rowell, 1987). Haynes

(1982) found that mineral surfaces became increasingly negative with increasing pH, resulting in more electrostatic repulsion and decreased P sorption. Reduced P sorption in a Cerrado Oxisol with an increase in pH was attributed to increased competition between hydroxyl and phosphate ions for specific adsorption on mineral surfaces (Smyth and Sanchez, 1980). Decreased P availability after liming was also attributed to the precipitation of insoluble calcium phosphates and / or increased P sorption on to newly formed hydroxyl Al surfaces formed following precipitation of exchangeable Al (Naidu et al., 1987; White and Taylor, 1977).

Lemare and Leon (1989) studied the effect of liming on the amounts of total and isotopically exchangeable phosphate adsorbed from solutions in five soils. Lime decreased the amount of phosphate sorbed at all concentrations in solution in an Oxisol and an inceptisol. In an Ultisol and an Inceptisol, lime increased the sorption of P at small concentrations and decreased it at large concentrations. In another context that contained spheroidal allophone and high organic matter, lime enhanced sorption at all concentrations of P. Phosphorus desorption exhibited the expected hysteresis between sorption and desorption at all three pH levels for each level of P loading (Sato and Comerford, 2005). Phosphorus sorption decreased up to 21 and 31% when pH increased from 4.7 to 5.9 and 7.0, respectively. P desorption increased with an increase in soil pH. Therefore, in this study, liming exhibited a dual trend of decreasing P sorption and increasing P desorption (Fig.1.3.4).

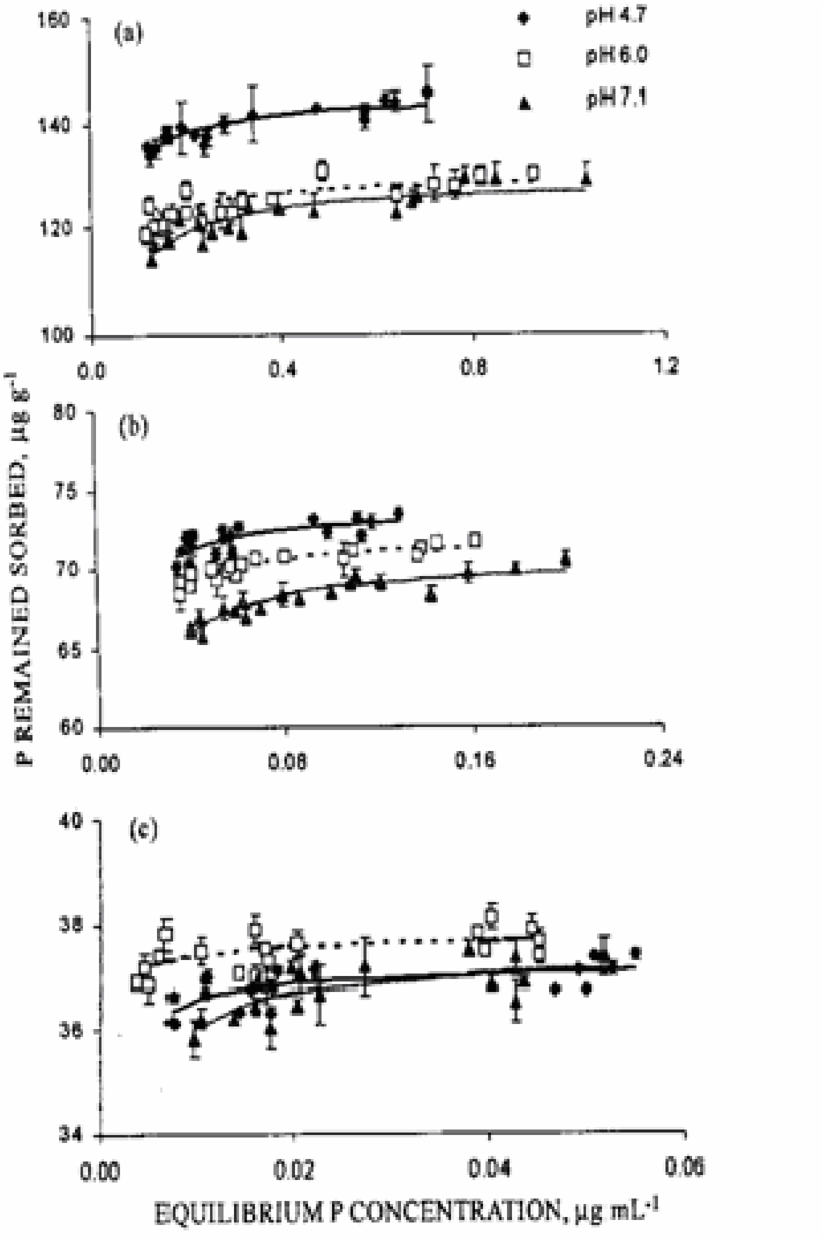

Figure1.3.4. Phosphorus desorption isotherms at three different soil pH levels with three different initial P addition levels (a) 180 µg $g^{-1}$ of P. (b) 80 µg $g^{-1}$. (c) 40 µg $g^{-1}$ of P (Sato and Comerford, 2005)

Both phosphorus and lime applications had nearly equivalent additive effects on dry matter production in white clover due to improvement in plant available P (Bailey and Laidlaw, 1999). Both liming and addition of P treatments seemed to increase the pool of plant available P in soil either by supplying P directly or liming which stimulates organic P mineralization (Bailey, 1991). The effect of P uptake on enhancement of dry matter yield in white clover is shown in Fig. 1.3.5.

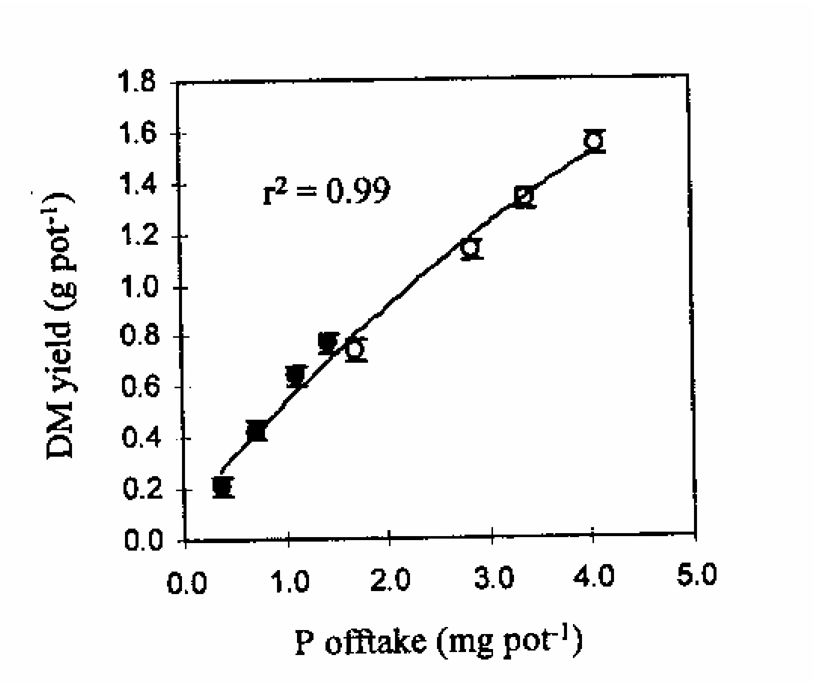

Fig. 1.3.5. Effect of P uptake on dry matter yield in white clover (Bailey and Laidlaw, 1999).

Fox et al. (1964) found that small additions of lime to acidic Hawaiin soils greatly increased the uptake of fertilizer P, but application of lime at pH 7.0 reduced P-uptake. Lime additions caused a marked decrease in soluble P concentration. Although concentrations of phosphate in saturation paste extracts increased considerably with increased P addition, they decreased significantly with increasing lime addition (Table 1.3.3).

Table 1.3.3. Effect of lime and P treatments on P, Al, Mn, Ca, Mg, K and Na concentrations in saturation paste extracts (Haynes and Ludecke, 1981).

| Treatment | Concentration (µM) | | | Concentration (mM) | | | |
|---|---|---|---|---|---|---|---|
| | P | Al | Mn | Ca | Mg | K | Na |
| $P_1$ $L_0$ | 1.9c | 296d | 41d | 1.38a | 0.78d | 0.83d | 1.59c |
| $L_1$ | 1.3bc | 82c | 17c | 5.63b | 0.50c | 0.57c | 1.42b |
| $L_2$ | 1.0b | 56b | 6b | 6.44c | 0.27b | 0.39b | 1.28ab |
| $L_3$ | 0.6a | 31a | 4a | 6.88d | 0.20a | 0.32a | 1.00a |
| $P_4$ $L_0$ | 81.6d | 131d | 35d | 4.81a | 0.53d | 0.67c | 1.44c |
| $L_1$ | 35.5c | 61c | 17c | 6.27b | 0.30c | 0.34b | 1.18b |
| $L_2$ | 17.4b | 52b | 6b | 7.53c | 0.24b | 0.31ab | 1.12b |
| $L_3$ | 11.9a | 30a | 4a | 7.89d | 0.17a | 0.28a | 0.92a |

With more added lime, phosphorus extracted by various methods (water soluble, resin extractable, Morgan extractable and Williams extractable) decreased (Table 1.3.4).

Table1.3.4. Effect of lime and P treatments on the amount of available P extracted by various methods. (Haynes and Ludecke, 1981).

| Treatment | P extracted by various methods ($\mu g\ g^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | Water soluble | Anion exchange resin | Morgan | Troug | Williams | Bray 1 |
| $P_1$ $L_0$ | 11.7c | 24.6d | 34.9d | 15.1a | 73.3d | 111a |
| $L_1$ | 11.6c | 20.1c | 26.1c | 14.9a | 60.8c | 118b |
| $L_2$ | 10.7b | 17.8b | 19.5b | 14.9a | 57.7b | 120bc |
| $L_3$ | 8.3a | 10.4a | 12.4a | 15.0a | 45.9a | 124c |
| $P_4$ $L_0$ | 96.8d | 178d | 145.0d | 122a | 463d | 413a |
| $L_1$ | 91.5c | 165c | 99.0c | 121a | 412c | 419b |
| $L_2$ | 77.9b | 115b | 89.1b | 124a | 355b | 437c |
| $L_3$ | 49.0a | 98a | 64.9a | 121a | 283a | 446d |

The immediate source of P for growing crops is inorganic P in the soil solution. Generally, agricultural crops require up to 0.3 μg P ml$^{-1}$ of soil solution (Russel, 1973). With increasing lime additions, available phosphate indices (i.e. water soluble, resin-, Morgan- and Williams-extractable) decreased significantly. Decrease was found in easily soluble P and 'Fe-bound' and to lesser extent 'Ca-bound' P fractions. The 'Reductant - soluble P' (occluded) was not affected by lime additions, whereas an increase was observed in the 'Al-bound' form (Haynes and Ludecke, 1981). These different forms of phosphate were categorized based on the type of extractant (i.e. water, resin, Morgan and William, Troug, and Bray 1) used (Table. 1.3.5).

Table 1.3.5. Effects of lime and P treatments on the various inorganic soil P fractions (Haynes and Ludecke, 1981).

| Treatment | P extractable (μg g$^{-1}$) | | | | |
|---|---|---|---|---|---|
| | Easily soluble | Al – bound | Fe- bound | Reductant soluble | Ca – bound |
| | | | (μg g$^{-1}$) | | |
| $P_1$ $L_0$ | 4.8 | 36 | 40 | 11 | 3.5 |
| $L_1$ | 2.9 | 38 | 36 | 11 | 3.3 |
| $L_2$ | 1.4 | 41 | 34 | 11 | 2.8 |
| $L_3$ | 0.6 | 44 | 34 | 10 | 2.8 |
| $P_4$ $L_0$ | 34.9 | 324 | 135 | 11 | 7.6 |
| $L_1$ | 15.3 | 356 | 126 | 11 | 7.3 |
| $L_2$ | 6.8 | 387 | 113 | 11 | 5.8 |
| $L_3$ | 3.0 | 399 | 108 | 11 | 5.7 |

Correlations between available P and plant uptake were positive and significant despite weak or non-significant correlations between phosphate indices in soil and yield of two species (Table 1.3.6). The legume yield and P uptake increased with increasing lime rates. The best correlations were seen with Troug and Bray P which were the only indices that did not decrease with increasing lime rates.

Table1.3.6. Simple correlation coefficients (r) between extractable soil P and total yield and P uptake of lotus and white clover (Haynes and Ludecke, 1981).

| Soil test | Lotus yield | Lotus P uptake | Clover yield | Clover P uptake |
|---|---|---|---|---|
| | $Mg\ ha^{-1}$ | % | $Mg\ ha^{-1}$ | % |
| Troug | 0.68** | 0.88*** | 0.62* | 0.86*** |
| Bray | 0.63** | 0.86*** | 0.58 | 0.84*** |
| Williams | 0.51 | 0.75*** | 0.47 | 0.70** |
| Water soluble | 0.44 | 0.69** | 0.39 | 0.63** |
| Resin extractable | 0.41 | 0.67** | 0.28 | 0.60* |
| Morgan | 0.25 | 0.51 | 0.08 | 0.61* |

Levels of significance shown: *$P \leq 0.05$; ** $P \leq 0.01$ and *** $P \leq 0.001$

Added lime increased the efficiency of P fertilization and also reduced the possibility of P pollution due to excessive P application. Increasing soil pH by liming reduced P concentration in soil solution ($P_{li}$) and increased anion resin exchangeable P ($P_{si}$). Added P increased $P_{si}$ linearly and produced a curvilinear decrease in $P_{li.}$ (Figure 1.3.6) (Chen and Barber, 1990).  In this study, as the pH increased, P was sorbed to exchangeable sites of newly formed surfaces and anion resin exchangeable P (Pi) increased. This would reduce P in soil solution, which would adversely affect P availability plants. So it is important to know the pH and determine the exact quantity of lime that causes P desorption sufficient to meet the P requirements of plants. These facts have to be considered when making fertilizer recommendations for acidic agricultural lands.

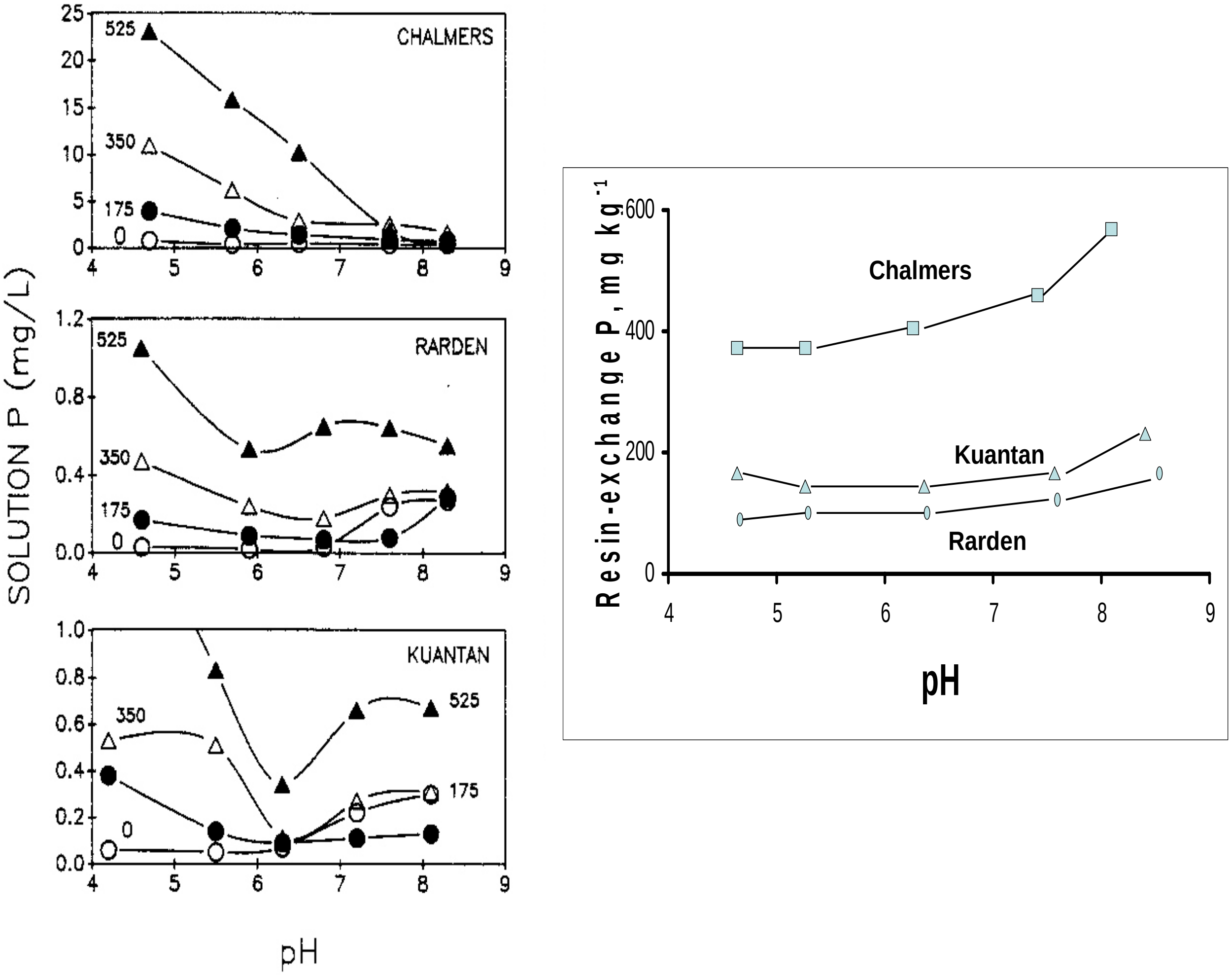

Fig. 1.3.6. Effect of soil pH and P rates on solution P and resin-exchange P (avg. of four rates of P) for three acid soils (Chen and Barber, 1990).

Liming had a P-sparing effect immediately after application, but thereafter may undergo complicated processes that negatively affect P bioavailability. There was an initial rapid release of P at different lime rates due to the P-sparing effect, but subsequently the P concentration in the equilibrating solutions decreased, which indicates some resorption of P until equilibrium was attained after 2-3 days (Curtin and Smillie, 1984) (Fig. 1.3.7).

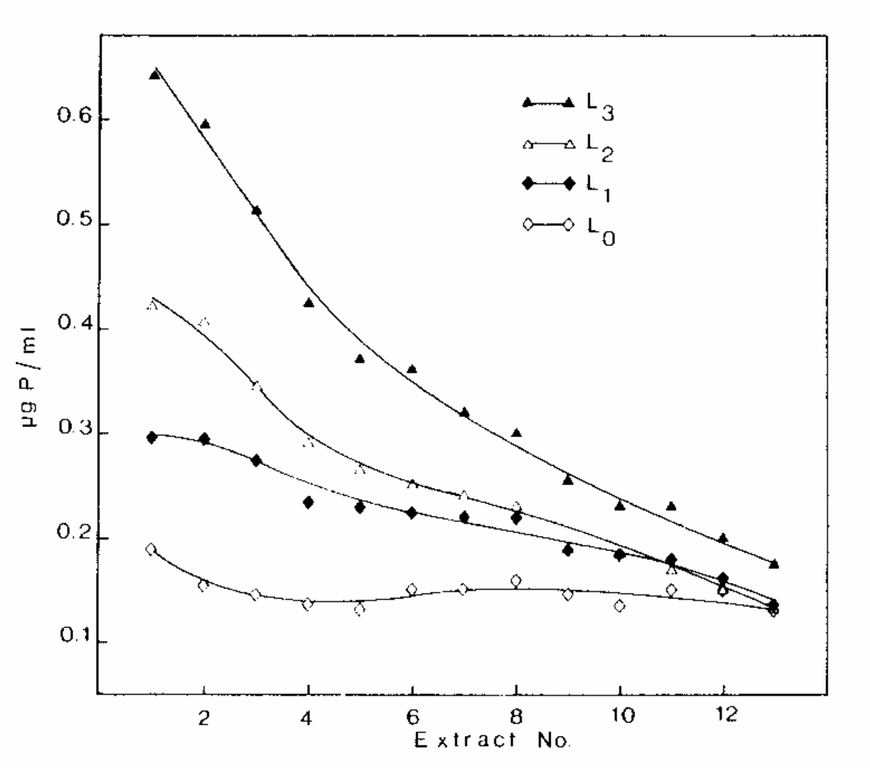

Fig. 1.3.7. Soil P desorption in an extraction sequence with 0.2 M NaCl at four lime levels (Curtin and Smillie, 1984).

As the pH of highly weathered soils increases, the concentration of phosphate in solution is generally observed to initially decrease, pass through a minimum for some time and then increase (Murrmann and Peech, 1969) (Fig. 1.3.8). This phenomenon is due to solubility of minimum phosphate in the pH range 5.5 to 6.5 and there is a close relationship between the effect of lime applications on the precipitation of exchangeable Al as amorphous hydroxides and the increased ability of soils to fix phosphate. If the soil pH increases above 6.5 to 7.0, the hydroxyl-Al species become soluble due to sequential deprotonation to form negatively charged aluminum complexes like $Al(OH)_4^-$, $Al(OH)_5^{2-}$ and $Al(OH)_6^{3-}$. These dissolved negatively charged hydroxyl-Al release previously sorbed phosphate. This process explains the phosphorus solubility curve in the figure 1.3.7 (Haynes, 1982).

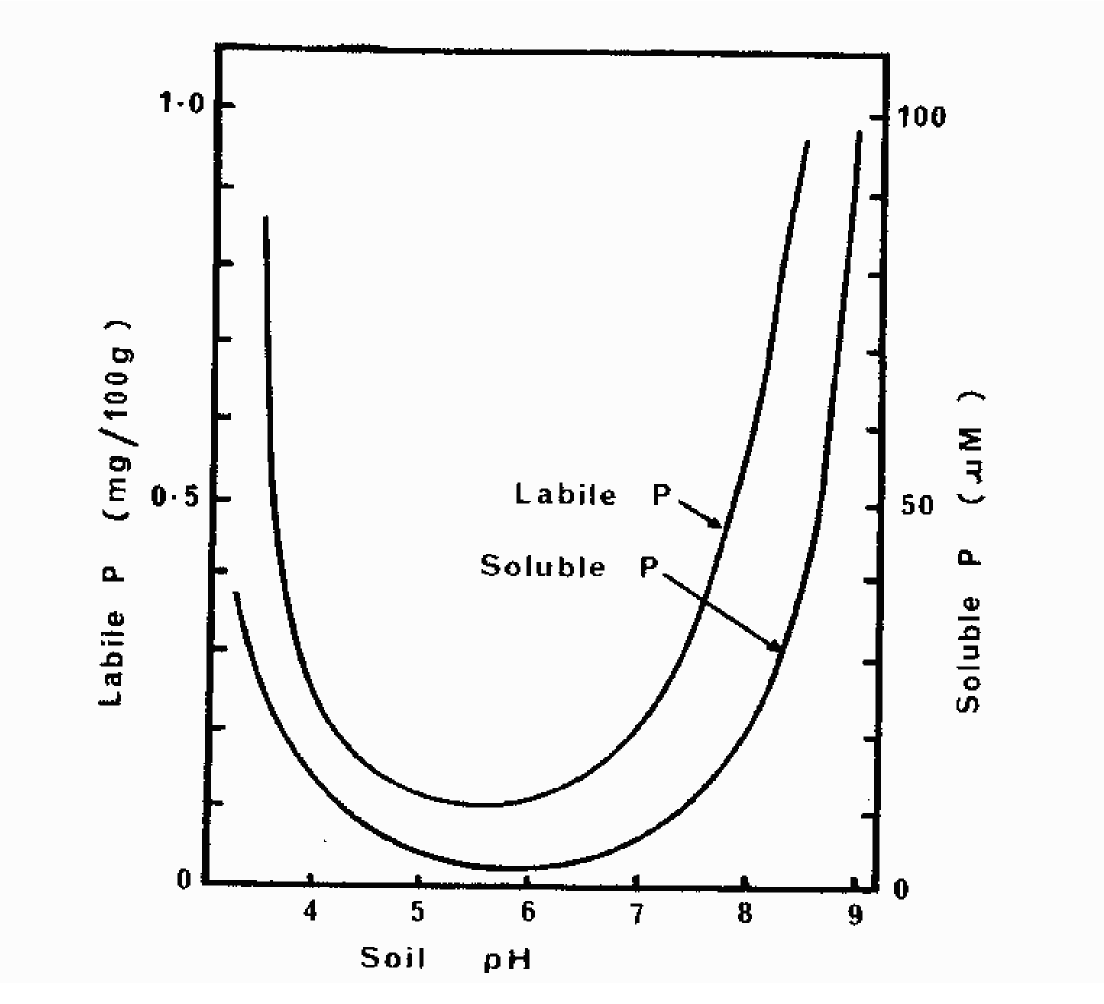

Fig. 1.3.8. Effect of soil pH on the P concentration in soil solution (Murrmann and Peech, 1969).

## 1.4. Soil Water

Topography has a significant effect on soil formation and water potential. For example, the thickness of the soil profile is often determined by the nature of its position on the landscape. With identical rainfall and comparable parent material the soil is more moist on gentle slopes than on steeply sloping land and still moist or wet in valleys and depressions (Brady and Weil, 1999). Soils on steep slopes are generally shallow, stony and have weakly-developed profiles with less distinguished horizons due to rain-wash and surface runoff. Steep slopes and accelerated erosion cause a slow downward movement of soil mass under the influence of gravity which is known as soil creep and produces thick colluvial soil at the slope toe. Variation in water potential due to toposequence also plays a critical role in solublization and transport of minerals in the soil and thus should be considered while designing management practices for pastures. Fertilizer use efficiency is a function of available water (Fiez et al., 1994; Gutierrez-Boem and Thomas, 1998). Thus, water potential has an influence on the movement and availability of nutrients from applied fertilizers and amendments.

### *1.4.1. Crop Response to Available Water*

The response of forage sorghum (*Sorghum bicolor L.*) to three irrigation treatments in semiarid environment was studied for two seasons in which the irrigation water at 8 mm day$^{-1}$ was delivered every 7 (light frequent), 10 (moderate less frequent) and 13 (heavy infrequent) days. Averaged over two seasons, maximum dry matter yields were 16.3, 11.8, and 10.5 tonnes ha$^{-1}$ for frequent, intermediate, and infrequent irrigation regimes respectively (Saeed and Nadi, 1998) (Fig.1.4.1)

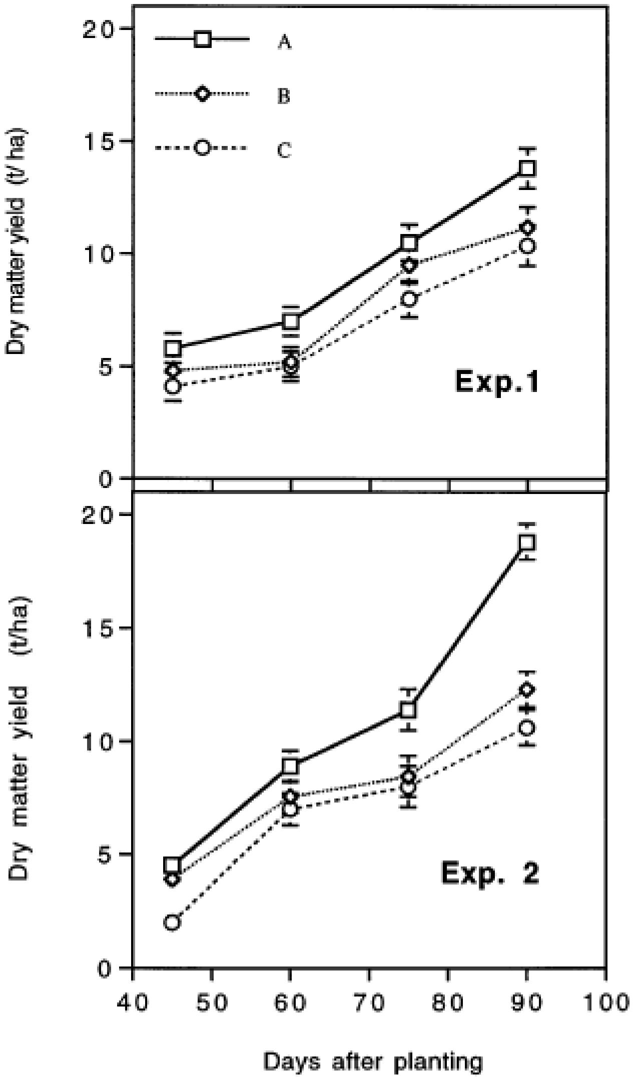

Fig.1.4.1. Average forage sorghum dry matter yield for four sampling occasions under the three water regimes (A (7 days), B (10 days), and C (13 days)) (Saeed and Nadi, 1998)

David (2004) found that dry matter yield of Kenaf (*Hibiscus cannabinus L.*) increased linearly with increases in available water and water use, with about 2000 kg ha$^{-1}$ DM yield produced with 274-mm water use, increasing to 6000 kg ha$^{-1}$ with 507 mm water use (Fig.1.4.2 ).

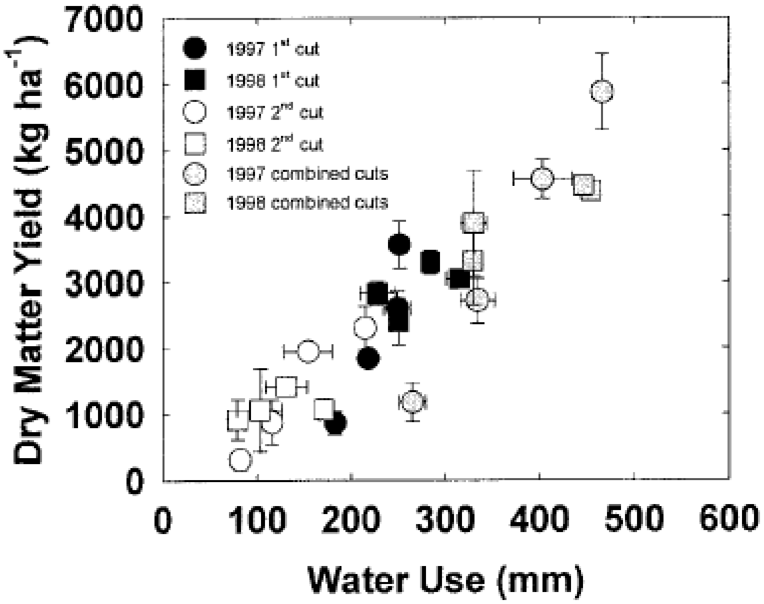

Fig.1.4.2. Dry matter yield vs water use for two cuttings of kenaf grown under an irrigation gradient at Akron, CO, in 1997 and 1998 (David, 2004)

### *1.4.2. Water by Lime by Nitrogen by Phosphorus Interactions*

The energy state of water in the soil is important in the process of nutrient absorption by plants. The water potential of a soil is responsible for the dissolution of applied fertilizers and affects nutrient availability through its effects on mass flow and diffusion processes. Thus, the water potential of soil is crucial in governing the physical, chemical and microbiological processes of nutrients taking place in the soil system. Soil microbial activity is also affected by soil water potential, and microorganisms perform many of the nutrient transformations in soil.

Robinson (1957) studied N-dynamics in soil in response to different moisture levels and found that the rates of processes such as ammonification were reduced to one half at wilting point. Miller and Johnson (1964) determined that the optimum matric suction in soil for N mineralization ranged from 0.15 to 0.5 bar. The rates of ammonification and nitrification were significantly influenced by soil moisture content at tensions between 0.2 and 15 bars (Reichman et al., 1966). These two processes are essential to make soil nitrogen available to plants. Hopmans et al. (1980) showed that N mineralization in forest soils under two different plantings (pine and eucalyptus) was strongly dependent upon soil moisture content (Table 1.4.1).

Table 1.4.1. Effect of moisture content on N-mineralization in forest soils (Hopmans et al., 1980)

| Incubation | Forest type | Nitrogen | Moisture content % | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | 5 | 10 | 15 | 20 | 25 | 30 | 35 |
| (days) | | ppm | | | | | | | |
| | Pine | $NH_4^+$ | 40 | 70 | 83 | 76 | 88 | 88 | 43 |
| | | $NO_3^-$ | 1 | 2 | 3 | 15 | 8 | 2 | 1 |
| | | Total | 41 | 72 | 86 | 91 | 96 | 84 | 44 |
| 90 | Eucalyptus | $NH_4^+$ | 99 | 91 | 105 | 135 | 126 | 99 | 100 |
| | | $NO_3^-$ | 1 | 4 | 3 | 2 | 5 | 11 | 1 |
| | | Total | 100 | 95 | 108 | 137 | 131 | 110 | 101 |

Nitrate concentration was reduced by 22% in lettuce when the water potential was reduced from -30 kPa to -100 kPa (Aggelides et al., 1999). The optimum soil water potential for gross N mineralization and nitrification, microbial and enzymatic activities was -10 kPa, compared with 0 kPa and -80 kPa (Zaman et al., 1999).

Pier and Doerge (1995) observed a pronounced positive water x N interactions in watermelon with maximum fruit yields occurred at rates of applied N between 200 and 270 K ha$^{-1}$ at mean soil water tension of 6 kPa (Fig. 1.4.3).

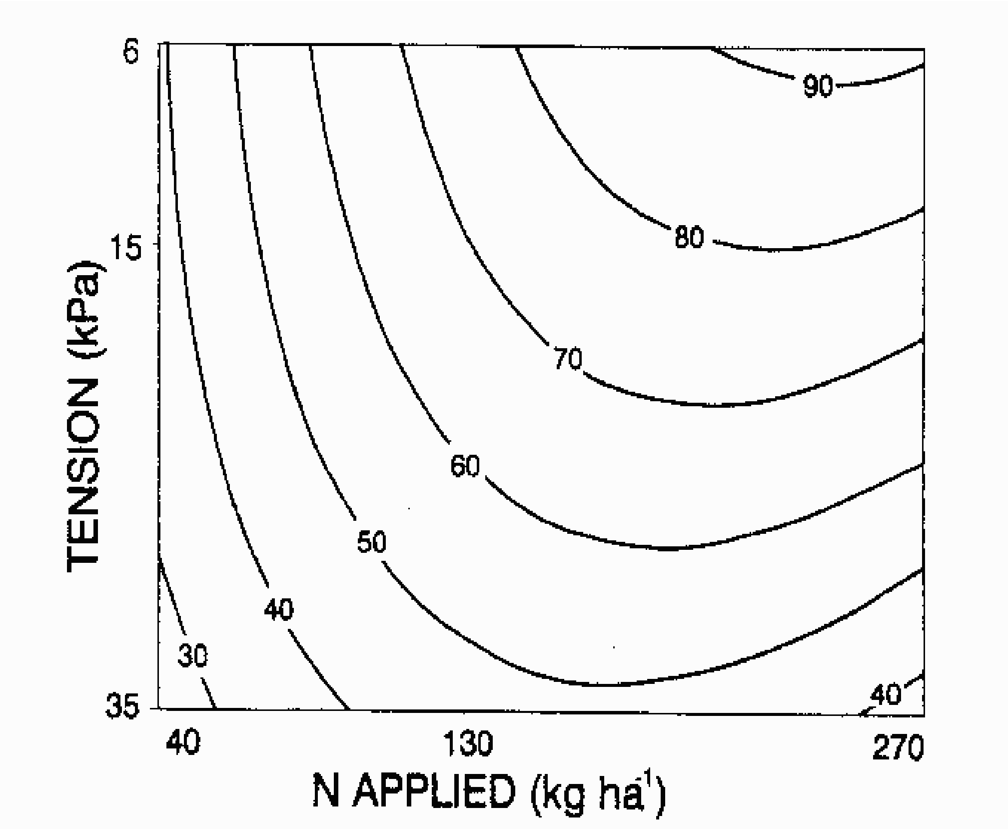

Fig. 1.4.3. Predicted marketable watermelon yield, Contour line units are Mg $ha^{-1}$. Response surface lack of fit: $P < 0.175$ (Pier and Doerge, 1995)

Soil moisture had a considerable effect on the mobility and uptake of phosphorus by corn (Mederski and Wilson, 1960). Olsen et al. (1965) observed that P uptake by corn seedling roots decreased by 50% as soil moisture decreased from that held at a water potential of -33 kPa to that at -300 kPa and lower moisture reduced P diffusion through the soil to the root surface. Dunham and Nye (1976) noted a significant reduction in P uptake by onion (*Allium cepa* L.) seedlings as soil moisture was reduced. An increase in water potential from -10 kPa to -0.1 kPa resulted in an increase of between 38% and 239% in the concentration of KCl-extractable inorganic P in the soil, depending on time and incubation temperature (Grierson et al., 1999). Mackay and Barber (1985) showed that as soil moisture was raised from 0.22 to 0.27 (volumetric basis), P-uptake by corn increased by 55 to 70% (Table 1.4.2).

Table 1.4.2. Influence of soil moisture content on P uptake by corn.

| | Moisture levels | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | M0 (0.22) | | | M1 (0.27) | | | M2 (0.32) | | |
| Soil types | S0 | S1 | S2 | S0 | S1 | S2 | S0 | S1 | S2 |
| Total plant wt g $Pot^{-1}$ | 1.76 | 3.39 | 7.75 | 2.52 | 4.86 | 8.74 | 2.44 | 4.35 | 7.28 |
| P uptake µ mol $Pot^{-1}$ | 150 | 229 | 477 | 271 | 381 | 741 | 226 | 352 | 611 |

Significance of F values from Analysis of variance

| Sources of variation | Plant uptake | P- uptake |
|---|---|---|
| Moisture (M) | ** | ** |
| Soil (S) | ** | ** |
| M X S | ** | ** |

** significant at 0.01 level

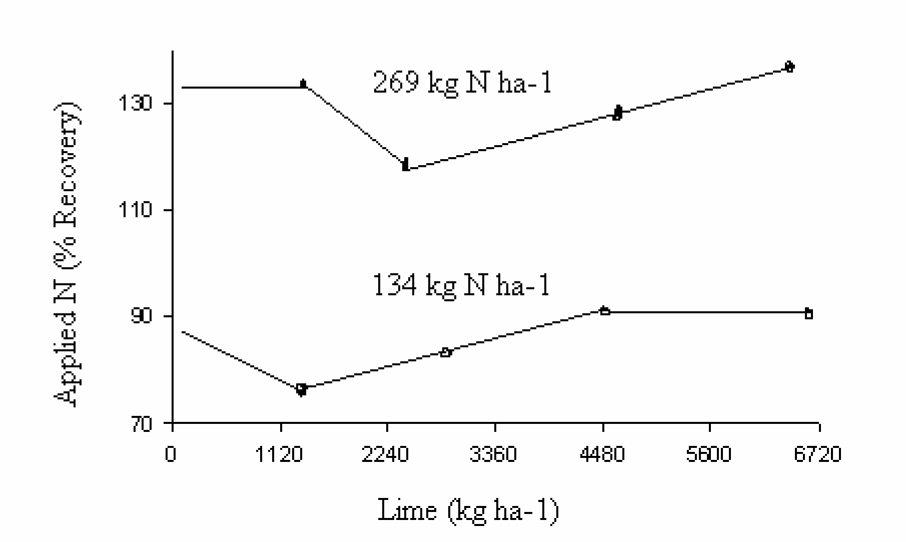

Fig. 1.4.4. Recovery of applied N on Kachemak silt loam (Winston et al., 1976)

Liming affects both chemical and microbial transformation of nitrogen in soils. The efficiency of nitrification inhibitors decreases with the addition of lime due to increase in activity of nitrifiers and general microbial activity resulting in rapid biodegradation of nitrification inhibitors (Slangen and Kerkhoff, 1984). Nyborg and Hoyt (1978) found a substantial increase in nitrogen availability by liming which may be due to microbial induced organic N mineralization. Timothy grass (*Phleum pretense* L.) showed increased recovery of N at both higher (269 kg/ha) and lower rates (134 kg/ha) in response to liming on Kachemak silt loam (Winston et al., 1976) (Fig.1.4.4). Lyngstad (1992) also observed that when soil pH was raised to 7.0 or above by application of lime, considerable organic N mineralization (mg $kg^{-1}$) occurred in soils (Table 1.4.3). Igue et al. (1970) noted a significant positive response of wheat grain yield to phosphorus and lime application. The P-sparing effect of liming resulted in an increase in concentration of P in plant tissue as well as an increase in dry matter production of perennial ryegrass (Helyar and Anderson, 1971; Bailey and Steven, 1989) (Fig. 1.4.5).

Table 1.4.3. Liming effect on N-mineralization in soils from six year pot experiment (Lyngstad, 1992)

| | CaO (t $ha^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | 0 | 1.8 | 3.7 | 5.5 | 11.7 | LSD |
| Year | Mineralized N (mg $kg^{-1}$) | | | | | |
| 1st | 53 | 59 | 67 | 75 | 99 | 9 |
| 2nd | 55 | 59 | 63 | 68 | 82 | 5 |
| 3rd | 62 | 64 | 68 | 70 | 78 | 5 |
| 4th | 65 | 69 | 68 | 68 | 70 | 4 |
| 5th | 61 | 66 | 63 | 62 | 66 | 5 |
| 6th | 67 | 70 | 69 | 68 | 67 | 5 |

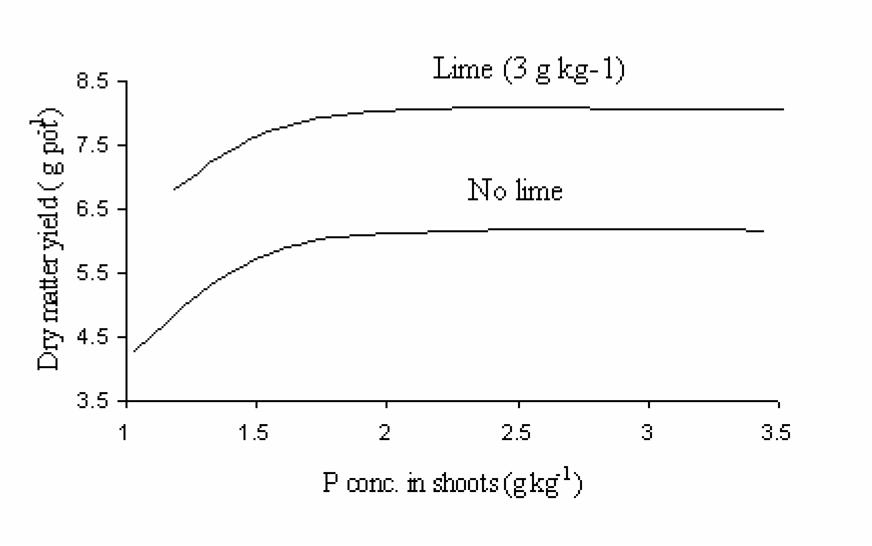

Fig.1.4.5. Effect of lime application on P-uptake by perennial ryegrass (Helyar and Anderson, 1971)

The mobilization of applied P was enhanced and more available to the crop with even a low lime dose (Bazegskii et al., 1976). Leaf analysis showed a pronounced increase in P concentration due to liming in soybean, sunflower and beans (Van Raij and Quaggio, 1990). Naidu et al. (1990) observed that the adsorption of phosphate reduced the soil positive charge at low pH and increased negative charges at high pH. The net number of surface charge per unit of phosphate adsorbed varied with pH and appeared to depend on the mineralogy of the soil (Fig. 1.4.6).

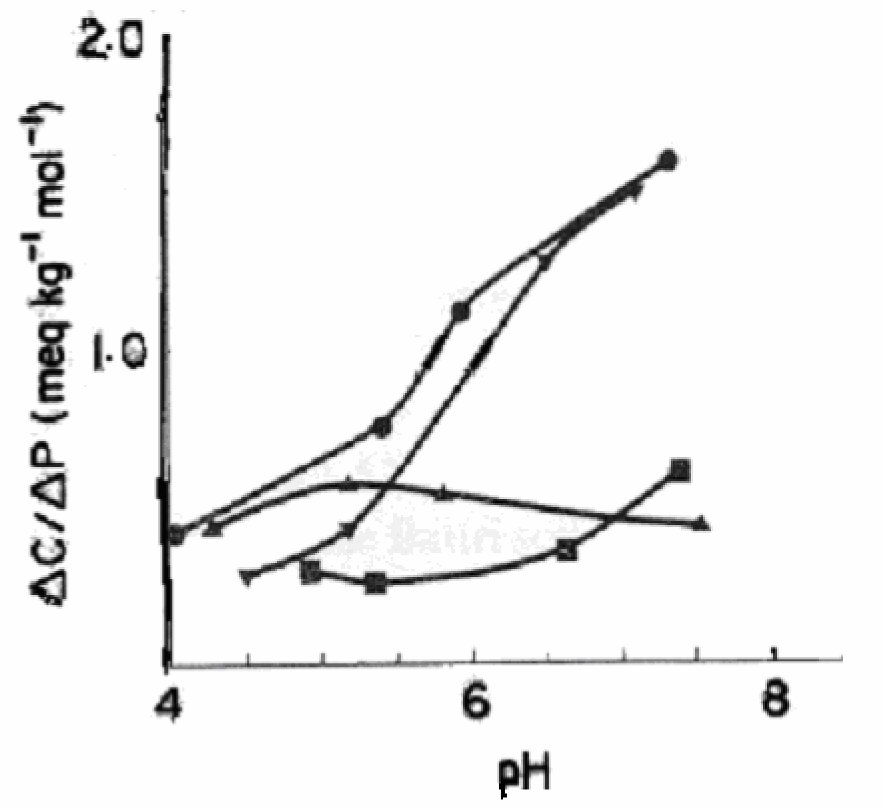

Fig.1.4.6. Net charge per mole of added P at different pH values in four different soils (Naidu et al., 1990)

Addition of phosphorus increased corn yield in all cropping seasons but the magnitude decreased as soil pH increased (Ernani et al., 2000). The availability and movement of phosphorus in the soil from added fertilizer is primarily influenced by moisture content of soil. The ability of plants to cope with mild water stress was enhanced by adequate P nutrition from fertilizers or manures and P uptake was affected by applied P, but not by water stress (Gutierrez-Boem et al., 1998) (Table 1.4.4).

Table 1.4.4. Influence of P application on water use efficiency (WUE) of plants under stressed conditions (Gutierrez-Boem et al., 1998).

| P treatment | Shoot dry weight | | Shoot P conc. | |
|---|---|---|---|---|
| | Well watered | Stressed | Well watered | Stressed |
| mg P $kg^{-1}$ soil | mg plant $g^{-1}$ | | mg P $g^{-1}$ | |
| P0 | 317 | 293 | 0.36 | 0.36 |
| P10 | 485 | 442 | 0.66 | 0.70 |
| P20 | 565 | 521 | 0.90 | 0.92 |
| Mean | 455 | 419 | 0.64 | 0.67 |
| Contrasts | | | | |
| P0 vs. P10 & P20 | | ** | | ** |
| P10 vs. P20 | | ** | | ** |

** Significant at the 0.01 probability level.

Application of 26.2 kg P $ha^{-1}$ to pea (*Pisum sativum L*) resulted in a marked improvement in yield, nutrient uptake and water use efficiency (Kasturikrishna and Alhlawat, 1999). The combination of N, P and organic fertilizer significantly improved winter wheat yield and its water use efficiency even at lower moisture regimes (Cao, 2000). Thus, the variation in water status along slope and its interactions with applied fertilizers and amendments should be considered when making recommendations for undulating pasture lands.

## 1.5. Summary

The success of a liming program is dependent on the accuracy of the lime recommendation, which in turn depends on the quality of the underlying correlations and calibrations. Expensive large-scale field calibration experiments are rarely conducted anymore. The relatively low economic returns from pastures, especially in West Virginia make it even more unlikely that a calibration experiment will be conducted. Therefore any improvements in lime recommendations of quick tests have to be made from lime correlations with reference method (lime incubation studies or direct calcium hydroxide solution). Moreover, it is unlikely that a single lime correlation can accurately identify appropriate lime rates for all soils. Hence, one of the objectives of this study was to improve the accuracy of lime predictions by quick tests by accounting for soil order and by developing equations based on lime correlations for acidic pasture soils of West Virginia. Following development of accurate lime recommendations using quick tests, it is necessary to understand how the applied lime interacts with soil physical and chemical characteristics such as water potential, N and P levels to ultimately affect the productivity of grasslands.

Any pasture system needs appropriate agronomic practices to maximize productivity. Management of acidic pasture soils of Appalachian region will benefit from accurate and rapid methods of characterizing soil and nutrient factors that influence production. Among these factors, water potential, pH, N and P levels were recognized as most critical to successfully maximize grassland productivity. So, following development of an accurate quick tests to determine lime requirement in the first experiment, the second objective of this research was to determine the optimal pH, N and P needs as a function of water potential for bluegrass alone and a bluegrass - white clover mixture.

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# CHAPTER II

## Grouping Soils by Taxonomic Order to Improve Lime Recommendations

### 2.1. ABSTRACT

The success of a liming program is dependent upon the accuracy of the lime recommendation, which in turn depends on the quality of the underlying correlations and calibrations. Due to the expense, large-scale field calibration experiments are rarely conducted. The relatively low economic returns from pastures make it even more unlikely that a calibration experiment will be conducted, especially in West Virginia. Therefore any improvements in lime recommendations have to be made from lime correlations. Moreover, it is unlikely that a single lime correlation can accurately identify appropriate lime rates for all soils. Hence, the objectives of this study were to improve the accuracy of lime requirement using quick tests by accounting for soil order and to develop lime correlations for acidic pasture soils of West Virginia. Twenty five surface soil samples (0 – 7.5 cm) from the three major soil orders in the state (Alfisols, Inceptisols, Ultisols) were collected, most in cooperation with state soil scientists. Standard procedures for the determination of lime requirements by the Mehlich single Buffer, Adams-Evans Buffer and Shoemaker-McLean-Pratt Single Buffer methods were used. Statistically significant improvements in lime recommendations for target pH 6.5 and 5.5 were achieved by accounting for soil order. Mehlich single buffer recommendations were better for Alfisols and Ultisols than for Entisols to achieve pH 6.5. Lime correlations were developed for all three chemical buffers by multiple

regression where the independent variables were target pH and soil-buffer pH. The Adam -Evans buffer predicted lime rates better for target pH 5.5.

## 2.2. INTRODUCTION

The dominant soil orders for grasslands in West Virginia are Alfisols, Ultisols and Inceptisols. These soils tend to be acidic due to high precipitation and undulating topography. As a result of these factors, removal rate of base cations exceeds the rate of their liberation from non-exchangeable forms (DeWalle et al., 1985) resulting in soils dominated by variable charge minerals (Ritchey and Snuffer, 2002). Although lime is an inexpensive soil amendment, because economic returns to pasture are relatively low and lime applications can be difficult on the steep soils of the region, it is important that lime application accurately reflect to correct soil acidity.

Pasture soil samples for lime requirement determination are typically collected from the upper most portion of the A-horizon, typically less than 7.5 cm. The properties used to distinguish between soil orders occur in subsurface horizons (e.g. base saturation at 125 cm below the top of argillic horizon to distinguish Alfisols from Ultisols), and so soil order would not be expected to influence epipedon lime requirement (Buol et al., 2003). However, in West Virginia, Aflisols are found over basic parent material and Ultisols over acid (felsic) crystalline rock and acidic sediments. Therefore, we are hypothesizing that accounting for soil order may improve lime recommendation correlations.

Various quick tests to estimate lime requirement based on the pH change of a buffer solution have been proposed. The choice of a buffer method depends on the physico-chemical properties of the soils to be tested and so tend to be common to a region of the country. Single-buffer methods were found to be as accurate as the more complicated double buffer methods to determine lime requirements after appropriate calibration (Tran and VanLierop, 1981). The most common chemical buffers used are Shoemaker, McLean, and Pratt single buffer (SMPB), Adams-Evans buffer (AEB), and Mehlich single buffer (MB). The SMPB method was designed to determine lime requirements for soils with high amounts of extractable aluminium and high buffer capacity (Shoemaker et al., 1961). The AEB was developed for soils (Ultisols) with low cation exchange capacity (Adams and Evans, 1962). Both SMPB (McLean et al., 1978) and AEB (Fox, 1980) were observed to underestimate LR of low buffer capacity soils and to overestimate the LR in soils with intermediate to high buffer capacity. The Mehlich buffer was designed to predict the amount of lime needed to neutralize extractable acidity (Tran and VanLierop, 1982). Average lime doses determined by the Mehlich buffer method were 59% of lime predictions by incubations (Mehlich, 1976). West Virginia is the only state in the northeast region (NEC-67, 1995) and one of only two states in the Appalachian region (Sims, 1996) to use the Mehlich buffer method for lime requirement determinations (North Carolina is the other state).

Comparative studies of different methods for determining lime requirement have been carried out all over the world to determine the most appropriate buffer method. Nevertheless, disagreements still exist about the most accurate assessment of the lime requirement for a specific soil-plant system. Soil test lime correlations are strictly valid only for the soils used in making the determination. There are approximately 177 soil series mapped in West Virginia belonging to six orders (59 Alfisols, 50 Ultisols, 41

Inceptisols, 19 Entisols, six Mollisols and two Spodosols) in four Major Land Resource Areas (MLRAs). Given this range of soils, a single correlation is unlikely to identify the appropriate lime rate for each soil. Possibly, lime recommendations by quick tests can be improved by developing correlations with reference methods such as lime incubations and direct $Ca(OH)_2$ titrations.

## 2.3. OBJECTIVES

1. To test the suitability of Shoemaker-McLean-Pratt buffer (SMPB) and Adams-Evans buffer (AEB) for making lime recommendations in West Virginia
2. Test the hypothesis that accounting for soil order will improve lime recommendations, and
3. Determine lime correlations for the Adams-Evans, Shoemaker-McLean-Pratt and Mehlich buffer methods.

## 2.4. MATERIALS AND METHODS

Samples from 25 soil series were collected in West Virginia, most in cooperation with State soil scientists. Samples were collected from the upper 7.5 cm of soil, air dried, sieved to pass a 2 mm sieve and stored in plastic containers until use. When necessary, soils were incubated with $Al_2(SO_4)_3$ to reduce initial pH to a common starting point of approximately 5.0. Many of these samples, collected as part of ongoing soil survey work in the state, were point samples from control pedons.

Standard methods were used to determine the chemical and physical properties known to influence lime requirement of each soil sample. Texture was determined by the pipette method (Gee and Bauder, 1986); organic matter content by dry combustion using a LECO CNS 2000 (Nelson and Sommers, 1996); secondary nutrients (Ca, Mg, K and P) by Mehlich I extraction (NEC-67), micronutrients by DTPA extraction (NEC-67); exchangeable Al and exchangeable acidity by 1 M KCl extraction (Sims, 1996); cation exchange capacity (Chapman, 1965), and non-crystalline oxides by ammonium oxalate extraction in the dark (Jackson et al., 1986). All elemental concentrations were determined by ICP-AES (Perkin Elmer P400, Norwalk, CT).

The ‘true’ value of the lime requirement was assumed to be equal to that determined by $Ca(OH)_2$ titration (Dun, 1943). This approach has been used in many other lime requirement determination studies (e.g. Follet and Follet, 1980; McConnell et al., 1990). Soil buffer pH was determined by the Mehlich single Buffer (MB), Adams-Evans Buffer (AEB) and Shoemaker-McLean-Pratt Single Buffer (SMPB) methods (Sims, 1996). All determinations were performed in triplicate. ‘Estimated’ lime requirements were obtained using measured buffer pH and the appropriate calibration table (Van Lierop, 1990; Adams and Evans, 1962).

Lime correlations were determined by multiple regression where the independent variables were target pH and soil-buffer pH. Estimated LR values were compared to true LR values using Dunnett’s t-test ($\infty = 0.05$), before and after grouping by order.

## 2.5. RESULTS AND DISCUSSION

As collected, the mean pH of soil samples varied from 4.78 to 5.04, clay content from 22.7 to 25%, organic matter content from 4.68 to 5.53%, and CEC (cmol$_c$ kg$^{-1}$) from 13.33 to 15.6 (Table 2.5.1).

Table 2.5.1. Mean, range and standard deviation of soil pH, silt, clay and organic matter contents and cation exchange capacity (CEC) grouped by soil order.

| | | | Soil Order | |
|---|---|---|---|---|
| Parameter | Statistic | Alfisol | Ultisol | Inceptisol |
| pH | mean | 4.92 | 4.78 | 5.04 |
| | range | 4.8 – 5.17 | 4.44 – 5.08 | 4.8 – 5.17 |
| | st. dev | 0.17 | 0.30 | 0.13 |
| Silt (%) | mean | 39.14 | 45.41 | 42.9 |
| | range | 9.36 – 61.16 | 21.74 – 55.63 | 30.4 – 51.3 |
| | st. dev | 17.82 | 13.6 | 7.09 |
| Clay (%) | mean | 23.57 | 22.7 | 25 |
| | range | 17.9 – 31.9 | 18.1 – 27.3 | 17 – 38.2 |
| | st. dev | 3.82 | 3.49 | 6.85 |
| OM (%) | mean | 5.53 | 4.68 | 5.01 |
| | range | 3.8 – 9.2 | 3.5 – 7.9 | 2.9 – 7.5 |
| | st. dev | 1.72 | 1.84 | 1.67 |
| CEC (cmol$_c$ kg) | mean | 14.7 | 13.3 | 15.6 |
| | range | 8.2 – 24.7 | 8.5 – 16.1 | 8.3 – 22.8 |
| | st. dev | 5.16 | 3.47 | 6.43 |

### *2.5.1. Determination of lime requirement with chemical buffers*

The ‘true’ LR increased as target pH increased, as expected (Table. 2.5.2). The rate of increase was approximately 1.2 Mg ha$^{-1}$ per unit increase in target pH. SMPB ‘estimated’ LRs were consistently higher than either AEB or MB for all target pH levels. The mean over-prediction was greater for SMPB and AEB than for MB.

Table 2.5.2. Mean LR values for different target pH levels

| | | Lime Requirement | | |
|---|---|---|---|---|
| | | Target pH | | |
| Order | Method | 5.5 | 6.0 | 6.5 |
| | | ---------------------------- | Mg $ha^{-1}$ | ---------------------------- |
| Alfisols | SMPB | 6.11 | 7.83 | 9.24 |
| | AEB | 2.76 | 5.23 | 8.15 |
| | MB | 3.23 | 5.73 | 6.05 |
| | Titration | 1.53 | 2.89 | 4.25 |
| Ultisols | SMPB | 5.60 | 7.51 | 8.68 |
| | AEB | 3.04 | 5.51 | 8.28 |
| | MB | 3.51 | 6.15 | 6.52 |
| | Titration | 1.54 | 2.54 | 3.71 |
| Inceptisols | SMPB | 4.74 | 6.46 | 7.41 |
| | AEB | 1.73 | 4.20 | 7.4 |
| | MB | 3.8 | 5.53 | 5.82 |
| | Titration | 0.97 | 2.02 | 3.10 |

Except for AEB and a target pH of 5.5, all buffer methods over-estimated LR at all target pH (Table. 2.5.3) compared to true LR values by direct calcium hydroxide titration method. The over-prediction for SMPB was consistently larger than for the other two methods. Shoemaker et al. (1961) found that predicted lime values using SMPB were significantly higher than the amount required by $CaCO_3$ incubation to attain pH 6.5.

Table 2.5.3. Comparison of buffer methods with direct calcium hydroxide titration method for different target pH levels before grouping by soil order

| Target pH | Method | Mean Difference* | Mean square error | Dunnett's t value | Dunnett's t critical value |
|---|---|---|---|---|---|
| 6.5 | SMPB | 5.20 | | 7.74* | |
| | MB | 1.98 | 1.60 | 2.94* | 2.38 |
| | AEB | 3.61 | | 5.37* | |
| 6.0 | SMPB | 4.76 | | 7.94* | |
| | MB | 3.19 | 4.48 | 5.32* | 2.38 |
| | AEB | 2.42 | | 4.04* | |
| 5.5 | SMPB | 4.25 | | 7.79* | |
| | MB | 1.87 | 3.71 | 3.42* | 2.38 |
| | AEB | 1.15 | | 2.10 | |

* Mean difference between Buffer method predicted LR and $Ca(OH)_2$ titration estimated LR

The 'estimated' LR by chemical buffers were plotted against the true LR by direct $Ca(OH)_2$ titration to target pH 6.5 (Fig. 2.5.1). The SMPB lime requirement for target pH 6.5 ranged from 1.2 to 18.8 Mg ha$^{-1}$. SMPB exhibited greater change in buffer pH, ranging from 4.92 to 7.07. The buffering capacity of the SMPB solution seemed to be lowest. Vanlierop (1983) also oberved that SMPB has a greater sensitivity to change in pH for a given soil lime requirement. The higher sensitivity of SMPB resulted in a significant correlation ($R^2 = 0.89$) with actual values determined by direct $Ca(OH)_2$ titration. The mean difference between AEB and true LR values significantly different (3.63 Mg ha$^{-1}$) for target pH 6.5 (Table 2.5.3). AEB overestimated the lime requirement despite a significant correlation ($R^2 = 0.81$) with titration method (Fig. 2.5.1). The AEB solution showed relatively high resistance to change in buffer pH (6.96 - 7.68) for a given soil. The Mehlich single buffer under-predicted lime requirements for soils with low buffer capacity and over-predicted it for highly buffered soils. Lime requirements were significantly correlated ($R^2 = 0.88$) with 1:1 line of true values (a plot of LR values determined by direct calcium hydroxide titration method). The mean of estimated LR values of Mehlich buffer was significantly higher (1.98 Mg $ha^{-1}$) than values of direct $Ca(OH)_2$ titration at target pH 6.5. The change in buffer pH of Mehlich buffer with soils ranged from 5.30 to 6.56 which indicated a relatively better sensitivity in predicting lime requirements than AEB. In this study, few lime values of highly buffered soils had enough influence on the regression line of Mehlich single buffer to deviate significantly from 1:1 line of true LR values.

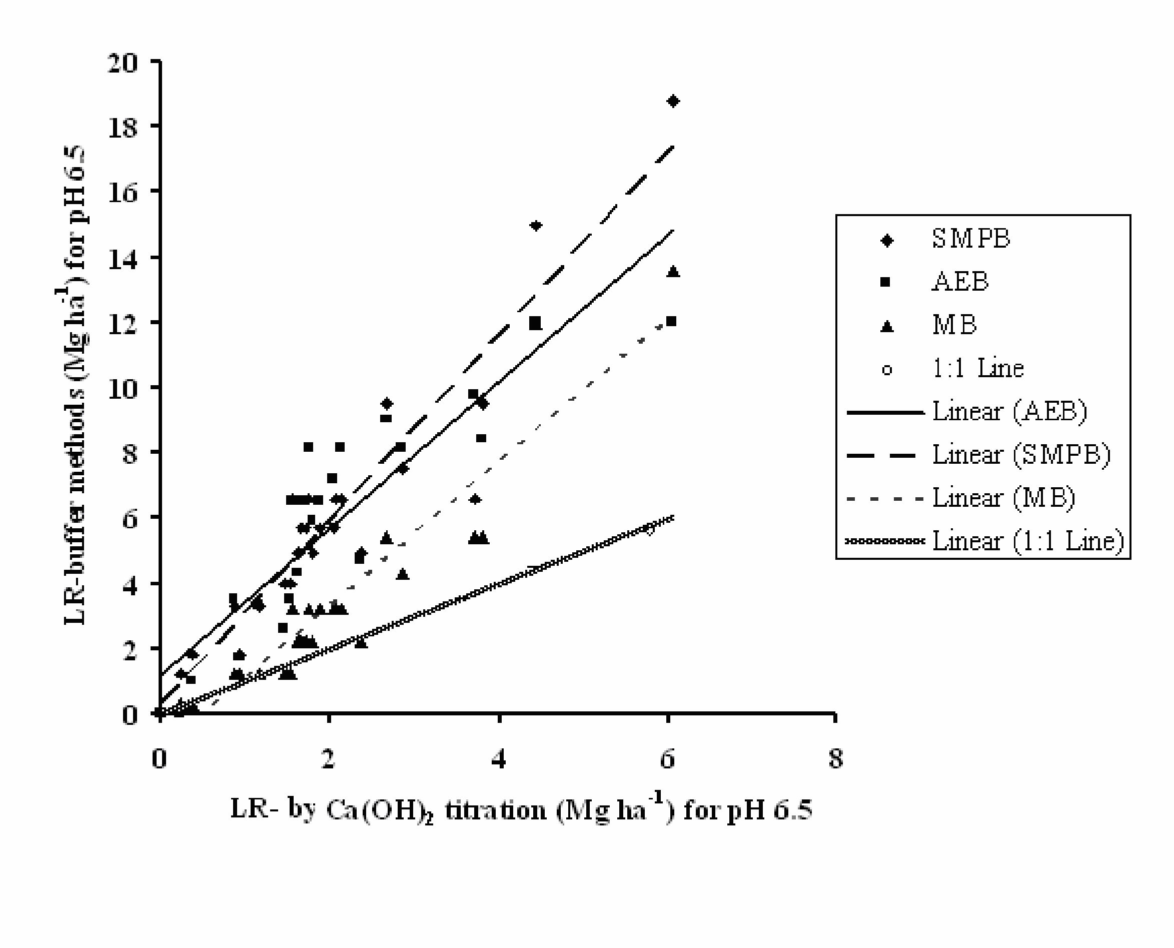

Figure 2.5.1. Lime requirement of 25 pasture soils as measured by three buffer methods vs $Ca(OH)_2$ titration.

### *2.5.2. Effect soil order on chemical buffer lime requirement predictions*

The SMPB method predictions did not improve after grouping by soil order at any target pH. For a target pH of 5.5, grouping improved predictions for Alfisols and Ultisols with AEB and MB (Table 2.5.4). For a target pH 6.0, grouping improved predictions for Ultisols with AEB and MB. For target pH 6.5, grouping improved predictions for Alfisols and Ultisols with MB (Figures 2.5.2a – 2.5.2c).

Table 2.5.4. Soil grouping effect on lime requirement by quick tests for different target pH levels.

| Order | Target pH | Method | Mean Difference | Mean square error | Dunnett's t value | Dunnett's t critical value |
|---|---|---|---|---|---|---|
| Alfisols | 5.5 | SMPB | 4.50 | | 5.07* | |
| | | AEB | 1.16 | 5.12 | 1.30 | 2.42 |
| | | MB | 1.63 | | 1.83 | |
| | 6.0 | SMPB | 5.03 | | 5.18* | |
| | | AEB | 2.44 | 6.11 | 2.51* | 2.42 |
| | | MB | 2.94 | | 3.03* | |
| | 6.5 | SMPB | 4.62 | | 4.49* | |
| | | AEB | 2.80 | 6.86 | 2.72* | 2.42 |
| | | MB | 1.14 | | 1.10 | |
| Inceptisols | 5.5 | SMPB | 3.81 | | 7.16* | |
| | | AEB | 0.79 | 0.99 | 1.48 | 2.50 |
| | | MB | 2.15 | | 4.04* | |
| | 6.0 | SMPB | 4.17 | | 6.61* | |
| | | AEB | 2.22 | 1.39 | 3.52* | 2.50 |
| | | MB | 3.55 | | 5.63* | |
| | 6.5 | SMPB | 5.28 | | 8.56* | |
| | | AEB | 3.78 | 1.33 | 6.13* | 2.50 |
| | | MB | 2.94 | | 4.76* | |
| Ultisols | 5.5 | SMPB | 4.05 | | 3.14* | |
| | | AEB | 1.49 | 4.14 | 1.15 | 2.59 |
| | | MB | 1.97 | | 1.53 | |
| | 6.0 | SMPB | 4.97 | | 3.38* | |
| | | AEB | 2.97 | 5.39 | 2.02 | 2.59 |
| | | MB | 3.60 | | 2.45 | |
| | 6.5 | SMPB | 5.43 | | 3.55* | |
| | | AEB | 4.38 | 5.84 | 2.86* | 2.59 |
| | | MB | 2.92 | | 1.91 | |

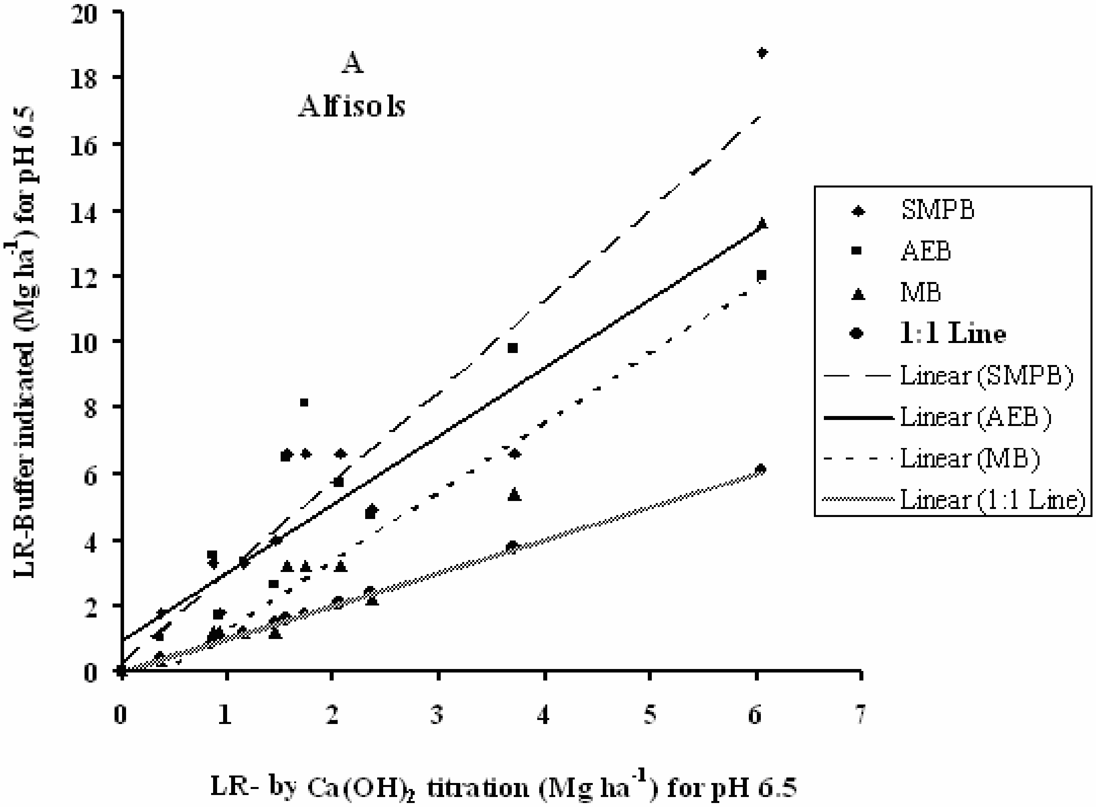

Figure 2.5.2a. Lime requirement of Alfisols as measured by three buffer methods vs. Ca(OH)$_2$ titration.

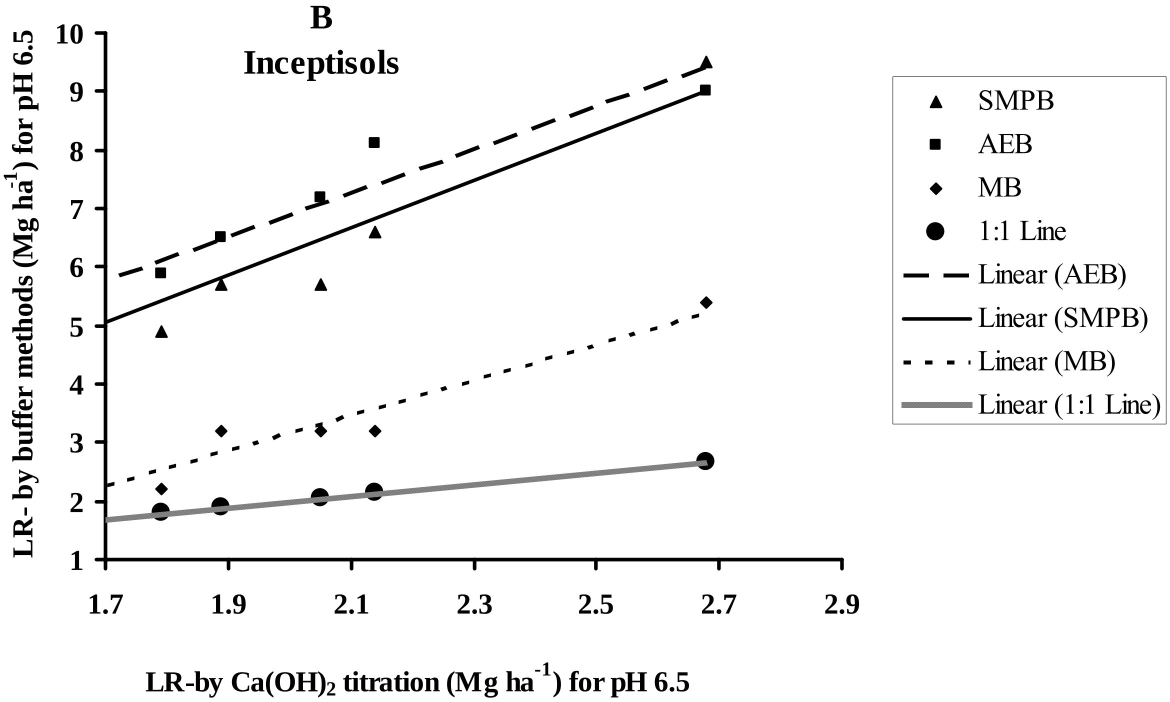

Figure 2.5.2b. Lime requirement of Inceptisols as measured by three buffer methods vs. $Ca(OH)_2$ titration.

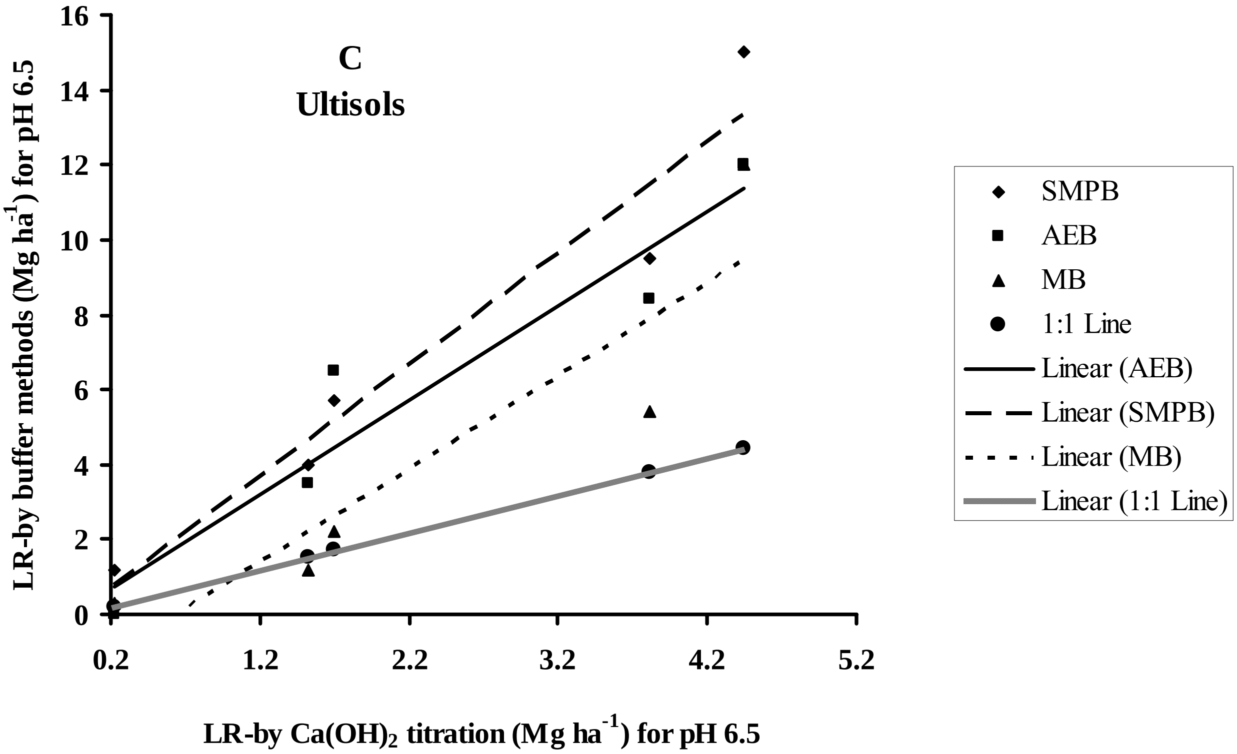

Figure 2.5.2c. Lime requirement of Ultisols as measured by three buffer methods vs. $Ca(OH)_2$ titration.

### *2.5.3. Improved lime recommendation correlations*

There are two reasons why the buffer method LR predictions may differ from the true LR as determined by $Ca(OH)_2$ titration. First, the titration results may not represent the results obtained by $CaCO_3$ incubation. Second, the underlying lime correlation equation may be in error. Because $Ca(OH)_2$ titration has been shown to accurately predict $CaCO_3$ incubation results (Alabi, 1986), and accounting for soil order significantly improved predictions for Alfisols and Ultisols for AEB and MB, we assumed that the error was with the lime correlation. The new correlation equations, some of which were not linear are given in Tables 2.5.5 – 2.5.7. Additional data will be needed to test the validity of these new correlation equations.

Table 2.5.5. Regression equations to predict lime requirements for target pH 5.5

| Buffer | Type | Order | Equations for LR (Mg $ha^{-1}$) to target pH 5.5 |
|---|---|---|---|
| MB | | | |
| | Linear | Alfisols | $LR = 15.0 - 2.28*BpH$ |
| | Quadratic | Inceptisols | $LR = 10.96 - 1.70*BpH + 4.80*(BpH - 5.94)^2$ |
| | | Ultisols | $LR = 23.15 - 3.62*BpH - 5.84*(BpH - 5.86)^2$ |
| AEB | | | |
| | Quadratic | Alfisols | $LR = 10.96 - 1.31*BpH + 0.67*(BpH - 7.18)^2$ |
| | | Inceptisol | $LR = 4.21 - 0.46*BpH + 6.81* (BpH - 7.25)^2$ |
| | | Ultisols | $LR = 22.79 - 2.94*BpH - 3.29* (BpH - 7.18)^2$ |
| SMPB | | | |
| | Quadratic | Alfisols | $LR = 6.89 - 0.91*BpH + 0.50*(BpH - 5.85)^2$ |
| | | Inceptisols | $LR = 5.73 - 0.80*BpH + 3.62* (BpH - 6.0)^2$ |
| | | Ultisols | $LR = 14.03 - 2.10*BpH - 1.87*(BpH - 5.84)^2$ |

Table 2.5.6. Regression equations to predict lime requirements for target pH 6.0

| Buffer | Type | Order | Equations for LR (Mg $ha^{-1}$) to target pH 6.0 |
|---|---|---|---|
| MB | | | |
| | Quadratic | Alfisols | $LR = 37.06 - 5.77*BpH - 4.12*(BpH - 5.90)^2$ |
| | | Inceptisols | $LR = 32.90 - 5.20*BpH - 12.55*(BpH - 5.91)^2$ |
| | | Ultisols | $LR = 26.64 - 4.04*BpH - 6.42* (BpH - 5.86)^2$ |
| AEB | | | |
| | Linear | Alfisols | $LR = 22.91 - 2.80*BpH$ |
| | Quadratic | Inceptisol | $LR = 5.20 - 0.51*BpH + 17.28*(BpH - 7.25)^2$ |
| | | Ultisols | $LR = 24.09 - 2.98*BpH - 3.25*(BpH - 7.18)^2$ |
| SMPB | | | |
| | Linear | Alfisols | $LR = 17.09 - 2.44*BpH$ |
| | Quadratic | Inceptisols | $LR = 51.19 - 8.1*BpH - 20.06*(BpH - 6.02)^2$ |
| | | Ultisols | $LR = 16.00 - 2.27*BpH - 1.84*(BpH - 5.84)^2$ |

Table 2.5.7. Regression equations to predict lime requirements for target pH 6.5

| Buffer | Type | Order | Equations for LR (Mg $ha^{-1}$) to target pH 6.5 |
|---|---|---|---|
| MB | | | |
| | Quadratic | Alfisols | $LR= 52.45 - 8.02*BpH - 4.28*(BpH - 5.90)^2$ |
| | | Inceptisols | $LR = 19.82 - 2.87* BpH + 6.28*(BpH - 5.91)^2$ |
| | | Ultisols | $LR = 14.03 - 2.10* BpH - 1.87*(BpH - 5.84)^2$ |
| AEB | | | |
| | Linear | Alfisols | $LR = 34.98 - 4.18*BpH$ |
| | Quadratic | Inceptisol | $LR = 4.84- 0.32*BpH + 13.75* (BpH - 7.25)^2$ |
| | Linear | Ultisols | $LR = 26.17 - 3.14*BpH$ |
| SMPB | | | |
| | Linear | Alfisols | $LR = 25.43 - 3.50*BpH$ |
| | Quadratic | Inceptisols | $LR = 13.84 - 1.83*BpH + 3.25*(BpH - 6.01)^2$ |
| | | Ultisols | $LR = 18.38 - 2.50*BpH - 1.41*(BpH - 5.84)^2$ |

In conclusion, in this study it was hypothesized that the accuracy of lime requirement could be improved by accounting for soil order. However, an improvement in accuracy was only seen in case of Mehlich and Adams-Evans buffer predictions and new lime correlation equations were developed. There appears to be an opportunity to improve lime predictions by accounting for soil order. However, these findings should be confirmed by extensive testing with larger number of samples.

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# CHAPTER III

## Available Water Effect On Optimum pH, Nitrogen and Phosphorus Requirements

## I. Kentucky Bluegrass

### 3.1. ABSTRACT

The productivity of grasslands depends on soil factors such as water potential, pH, N and P levels. There is a need to understand the interactive effects of these factors on yields of grasslands. Response surface methodology was applied to optimize yield of bluegrass for an acidic pasture soil. The effects of two levels of water potential (WP) and five levels each of pH, N, and P fertilizer additions were evaluated to optimize bluegrass herbage mass. Water potential, pH, and N were significant main effects, as were the interactions WP x pH, WP x N, and pH x N. The yield response function was derived from these four factors. The order of importance for these model parameters was WP > N > pH ≈ WP x pH >WP x N > N x N > pH x N. The optimum levels of these four factors were predicted by the RSREG procedure. These results have implications for how to divide pastures into management zones for optimal bluegrass production.

### 3.2. INTRODUCTION

Remediation of soil acidity is crucial for improving pasture soil quality and increasing herbage accumulation. Application of liming materials and fertilizers are needed to stimulate plant growth by reducing acid related constraints and increasing the availability of Ca, N, P and Mo (Adams, 1984). Liming results in changes in soil chemical and physical properties which improve conditions for plant growth (Menzies et al., 1994).

Liming has been shown to reduce sodium acetate extractable Al, Fe and H ions (Ryan and Smillie, 1975), while increasing the soil cation exchange capacity (Hockman et al., 1992) and crop yields (Holford and Crocker, 1994). Another important reason for liming is to increase phosphate availability (Sanchez and Uehara, 1980). However, liming soils can either increase or decrease extractable P (Mendoza et al., 1995). Application of fertilizers to lime amended soils is an important management practice to restore the balance among cations and anion concentrations in soil solution and so promote plant growth.

Crop growth will be improved by liming when sufficient levels of plant essential nutrients are available. Therefore, optimum plant growth requires well balanced nutrient applications in addition to liming. Nitrogen fertilization is the main agronomic practice influencing grassland productivity and quality (Wilkinson and Langdale, 1974), and has been studied for many years. Johnson et al. (2001) studied the effects of nitrogen fertilization on yield of three tropical grasses in a study where five rates of nitrogen (0, 39, 78, 118, and 157 kg N ha$^{-1}$) were applied. The forage mass increased by 129% at 78 kg N ha$^{-1}$ compared with no N fertilization. Additional N did not cause a further increase in forage mass. A similar increase in dry matter yield due to N fertilization in warm-season grasses was observed (Harvey et al., 1996; Caraballo et al., 1997). Malhi et al. (2004) studied the effect of N, P and K levels on productivity of timothy (*Phleum pretense L.*). They found that application of N markedly increased dry matter yield but P and K had moderate effects. The supply of N and P in fertilizers has been proven to significantly influence dry matter yield of grasslands.

Liming and application of fertilizers also have an impact on uptake of nutrients by plants. The uptake of P, K, Ca, Mg, and Na, utilization of N and P, and nutrient ratios were all positively correlated with dry matter yield and crude fiber concentration of meadow fescue grown from 1965 to 1974 (Wermke,1975).

Pasture fertilization increases nutrient availability in soil, interacts with other elements present in the soil, and increases forage growth (Clark and Harris, 1996). Liming along with application of fertilizers enhanced the concentration of N, P, Ca, and Mg in the soil as well as doubled the uptake by meadow plants without any negative effect on their soil concentrations (Kasperczyk et al., 2005). Staputis (2000) observed that soil pH, liming and fertilization affected the yield and nutrient accumulation in a spring barley-red clover-spring wheat rotation. He also found that the optimal pH for nutrient uptake by plants was 4.6-5.0 in loamy sand and 5.0 in light and medium loam soil, despite the higher N assimilated at pH 6.5 in medium loam soil.

Uptake of nutrients by plants is influenced by other elements present in the soil (Clark and Harris, 1996). Mayfield et al. (2002) observed maximum uptake of N, Ca, K, and P by *Nandina domestica* grown in soil-less media in treatments that received lime compared to the un-limed controls. Fageria et al. (1995) found that increasing levels of applied P (0. 50 and 175 mg $kg^{-1}$) significantly increased nutrient uptake by upland rice (*Oryza sativa L.*), wheat (*Triticum aestivum L.*), common bean (*Phaseolus vulgaris L.*) and Corn (*Zea mays L.*) grown on an Oxisol. But, increasing levels of lime (0, 2, and 4 g $kg^{-1}$) tended to decrease uptake of P, Zn, K, Cu, Mn, and Fe and increased the uptake of

Ca and Mg in all crops. Foloni et al. (2006) observed that the application of ammonium sulfate along with lime was most effective in the enhancement of Ca and Mg uptake by cotton plants grown for 60 days in PVC columns filled with a sandy loam Oxisol. It was concluded that nitrogen fertilization added anions that increased the solubility of basic cations in the soil due to the formation of ionic pairs.

In contrast, liming agents and rates did not enhance the degree of absorption of macronutrients by sugarcane under field conditions (Prado et al., 2002). Different rates of lime application had no influence on K uptake by rice and lettuce grown on acid sulfate soils (Ramesh and Chonkar, 2001). Liming decreased the uptake of Mg, Mn, and Zn by maize plants grown on two acid Ultisols. Maize grown in an Ultisol expressed severe Mn deficiency due to liming soil to neutralilty even though a moderate amount of Mn was applied (Juo and Uzu, 1977). Increased application of CaO or MgO reduced the uptake of N and Fe in rice plants, but K uptake was unaffected (Houng et al., 1967). Application of CaO was observed to increase Mg uptake, whereas Mg application reduced Ca uptake. Moreover, application of Mg without Ca caused severe stunting in rice.

The important and often neglected factor affecting nutrient availability in the field is soil water content, which has a significant effect on nutrient release from applied fertilizers as well as on mineralization reactions (Koerselman et al., 1993). Fertilizer use efficiency is a function of available water (Fiez et al., 1994; Gutierrez-Boem and Thomas, 1998). Superphosphate requires minimal moisture to dissolve P from the granule (Lawton and Vomocil, 1954). For grasslands on undulating terrain, the variation in toposequence influences water potential which can play a critical role in solubilization and transport of minerals in the soil and thus should be considered while designing management practices for pastures.

Available literature on forage response to water potential and fertilization is fragmented and not always integrated into a continuum of information relating to optimization of forage production on acidic pasture soils. A greater research effort is needed to develop comprehensive input recommendations to modify these low production and low income systems. In order to transform these low productivity systems to higher producing pasture systems, we need a better understanding of the interactions between fertilizers, water potential and other elements present in the soil.

The objectives of this study were to quantify the effects of water potential (WP), soil pH, N and P on Kentucky bluegrass yield and nutrient uptake.

## 3.3. MATERIALS AND METHODS

An acidic soil was collected near Morgantown, WV from the Culleoka – Westmoreland map unit, air-dried, crushed and passed through a 2mm sieve. Soil pH was determined by glass membrane electrode; texture by the pipette method (Sternberg and Creager, 1961); organic matter content by loss on ignition (Oliver et al., 2001); and CEC by the ammonium acetate method (Chapman, 1965). A lime response curve was determined by direct $Ca(OH)_2$ titration (Alabi et al., 1986). The soil moisture characteristic curve was determined using a dew-point potentiometer (Decagon Model WP4-T) and gravimetry. All determinations were done in triplicate.

To produce soils with different pH levels, sufficient $Ca(OH)_2$ was added, based on the lime response curve, to separate sub-samples to establish a range of final soil pH from 4.5 to 6.5 in approximately 0.5 increments. Limed soils were incubated at field capacity for one week, or until equilibrium pH was reached. Soils were again air-dried and stored until use. Soil was placed in pots (30.5 cm x 30.5 cm x 5 cm) and four rates of nitrogen were established by incorporating nitrogen ($NH_4NO_3$) or phosphorus (as $KH_2PO_4$). Nitrogen was added at 0, 10, 25, 50 and 100 mg N $kg^{-1}$ soil. Phosphorus was added at 0, 10, 20, 40 and 80 mg P $kg^{-1}$ soil. Two water potentials, near field capacity (pF 2.7) and just above the permanent wilting point (pF 3.9), as determined from the soil-water characteristic curve, were imposed and maintained using a sensor-based irrigation system (NETAFIM Flori 1). Water content was measured regularly by potentiometer (Decagon Model WP4-T). To reduce the number of experimental units a centrally composite rotatable design (Myers and Montgomery, 1995) with three replications was used (Appendix (Table A5)). Pots were directly seeded with Kentucky bluegrass (*Poa pratensis L.*) at the rate of 4 gm $pot^{-1}$. Every three weeks a sample of the soil solution before watering was drawn with a soil solution sampler (Rhizon SMS) and analyzed for pH (microelectrode) and $Ca^{2+}$, $PO_4^{3-}$, $NH_4^+$ and $NO_3^-$ by ion chromatography (DX-300, Dionex Corp). At the end of the experiment (60 days after sowing) herbage accumulation was measured by clipping at ground level and drying the herbage at 105 $^0$C for 48 hours. The nutrient concentration in plants was determined by analyzing the above ground portion. Herbage was digested with concentrated $HNO_3$ using microwave (MARS 5, CEM) ) (Rechcigal and Payne 1990). The extracts from this wet digestion were used to determine nutrient concentrations by ICP-OES (Perkin Elmer P400, Norwalk, CT). Nutrient concentrations were expressed on a tissue dry mass basis.

Herbage accumulation data were analyzed using a response surface methodology and the PROC RSREG procedure with Ridge max option in SAS (ver 9.1, SAS Institute, Cary, NC, USA). Herbage accumulation was the response variable and water potential, pH, N, and P rates were added to construct model main effects. The linear, quadratic, and cross product terms of these factors were also determined. A step-wise regression procedure was used to determine the best model. Adjusted $R^2$ and Cp statistics were used to select model parameters. The effect of factors as linear, quadratic, and interaction (cross product) coefficients on the response variable (herbage accumulation) was tested for adequacy and fitness by analysis of variance. Concentrations of nutrients in herbage were analyzed to study the effect of water potential, pH, N, and P levels.

## 3.4. RESULTS AND DISCUSSION

The soil texture was a silt clay loam (34.3 % clay; 44.0 % silt), with an initial pH of 4.8, organic matter content – 9.2%, Ca – 42.5 ppm, Mg – 9.8 ppm, K- 40.8 ppm, P – 4.06 ppm, and a CEC of 15.84 $\text{cmol}_c\ \text{kg}^{-1}$. The lime response curve was linear from pH 5.2 to 6.5 (Appendix (Fig. A1)). On average, water potential (pF) was 2.7 in the field capacity treatment and 3.91 in the near wilting point treatment which were gravimetrically equal to 16% and 30% respectively (Appendix (Fig. A2-A3)).

### 3.4.1. *Yield model*

Analysis of variance showed that the model significantly predicted herbage accumulation (response variable) despite the presence of a significant lack-of-fit (Table 3.4.1). A residual plot indicated no pattern in the residuals (Fig. 3.4.1), but a large variability. The lack of fit term was not significant when mean values were used (Fig. 3.4.2). These results suggest that a factor affecting yield was not captured by the treatments selected.

Table 3.4.1. Analysis of variance for model of response surface function

| Source | df | Sum of Squares | Mean Square | F Ratio | Pr > F |
|---|---|---|---|---|---|
| Model | 13 | 121.5 | 9.34 | 92.29 | < 0.0001 |
| Error | 82 | 8.30 | 0.10 | | |
| Lack Of Fit | 16 | 3.96 | 0.24 | 3.77 | <0.0001 |
| Pure Error | 66 | 4.33 | 0.06 | | |
| C. Total | 95 | 129.8 | | | |

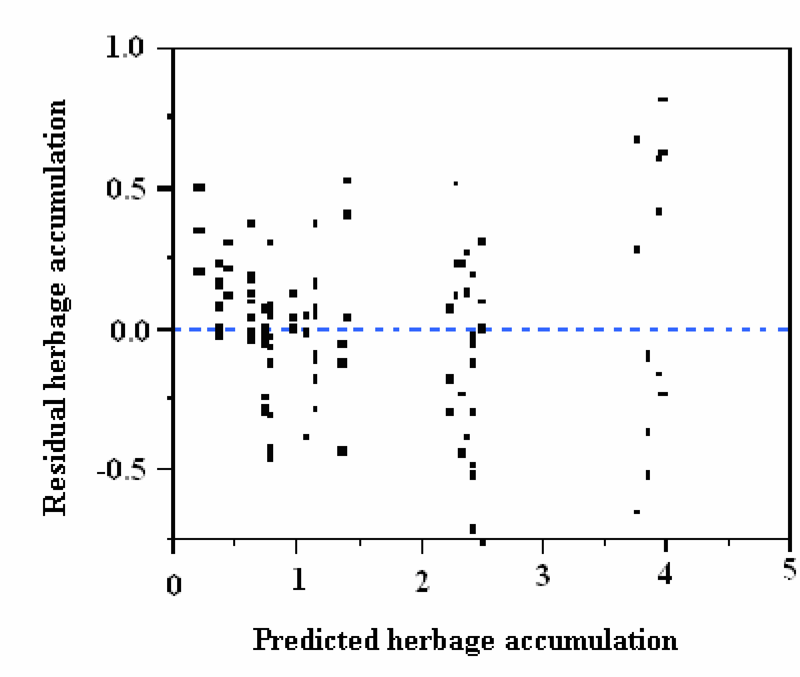

Figure. 3.4.1. Residuals plot for herbage accumulation

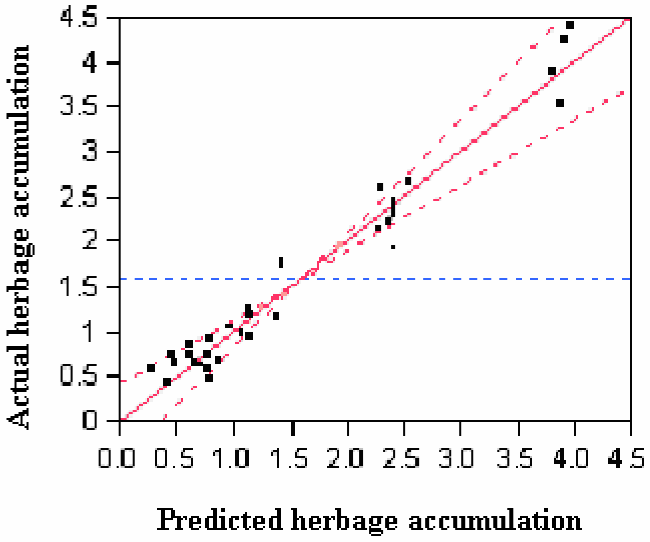

Figure 3.4.2. Actual vs. predicted herbage accumulation. Dashed lines indicate 95% confidence interval

Water potential, pH and N levels were the only main effects that influenced herbage accumulation ($p<0.05$) (Table 3.4.2). The cross product terms of water potential, pH and N as well as quadratic term of N were also significant. Phosphorus level was not significant as a main effect or as an interaction.

Water potential had the largest influence on bluegrass herbage accumulation, as indicated by sum of squares followed by N level (Table 3.4.2), The main effect of pH and the water potential by pH interaction were of similar importance, followed by the water potential by N interaction and the N quadratic effect. These terms were used to determine the response surface function,

$$Y = 2.12 - (1.5*WP) + (0.7*pH) + (0.02*N) -$$

$$1.09* (WP-3.305)*(pH-5.5) - 0.017*(WP-3.305)*(N- 30.625)$$

$$+ 0.01*(pH-5.5)*(N-30.625) - 0.00023*(N-30.625)*(N-30.625) \qquad [3.4.1]$$

where Y is herbage accumulation (Mg $ha^{-1}$), WP is water potential (pF), pH is in standard units, N is nitrogen rate (mg $kg^{-1}$), and P is phosphorus rate (mg $kg^{-1}$). Although the pH by N interaction was statistically significant, it was not included in the response surface model because it accounted for so little of the sum of squares (Table 3.4.2).

Table 3.4.2. Analysis of variance for the overall and interaction effects of the four factors on bluegrass yield

| **Source** | **df** | **Estimates** | **Sum of squares** | **F-ratio** | **Pr >F** |
|---|---|---|---|---|---|
| WP (pF) | 1 | -1.477792 | 76.737720 | 757.7211 | <.0001 |
| N | 1 | 0.0229643 | 14.474719 | 142.9258 | <.0001 |
| pH | 1 | 0.6761241 | 10.009114 | 98.8317 | <.0001 |
| P | 1 | 0.0036056 | 0.209323 | 2.0669 | 0.1543 |
| WP *pH | 1 | -1.093205 | 10.498455 | 103.6635 | <.0001 |
| WP*N | 1 | -0.017119 | 5.877817 | 58.0385 | <.0001 |
| N*N | 1 | -0.00023 | 2.702855 | 26.6884 | <.0001 |
| pH*N | 1 | 0.0111268 | 0.611855 | 6.0416 | 0.0161 |
| P*P | 1 | -0.000114 | 0.256907 | 2.5367 | 0.1151 |
| pH*P | 1 | -0.008014 | 0.182767 | 1.8047 | 0.1829 |
| N*P | 1 | -0.000071 | 0.022681 | 0.2240 | 0.6373 |
| pH*pH | 1 | 0.0473971 | 0.016209 | 0.1601 | 0.6901 |
| WP*P | 1 | -0.000719 | 0.006345 | 0.0627 | 0.8030 |

Based on parameter estimates, as the value of water potential increased (therefore drier) herbage accumulation was decreased (Table 3.4.2). The positive sign on parameter estimates of N and pH indicate that increasing soil pH and nitrogen fertilization increased herbage accumulation (Table 3.4.2)

The water potential by soil pH interaction showed that in addition to increasing herbage accumulation as pF decreased (increase in water potential), the rate of the increase per unit increase in soil pH increased as pF decreased (Fig. 3.4.3). Increasing soil pH did not increase herbage accumulation at the lowest water potential (pF 3.90).

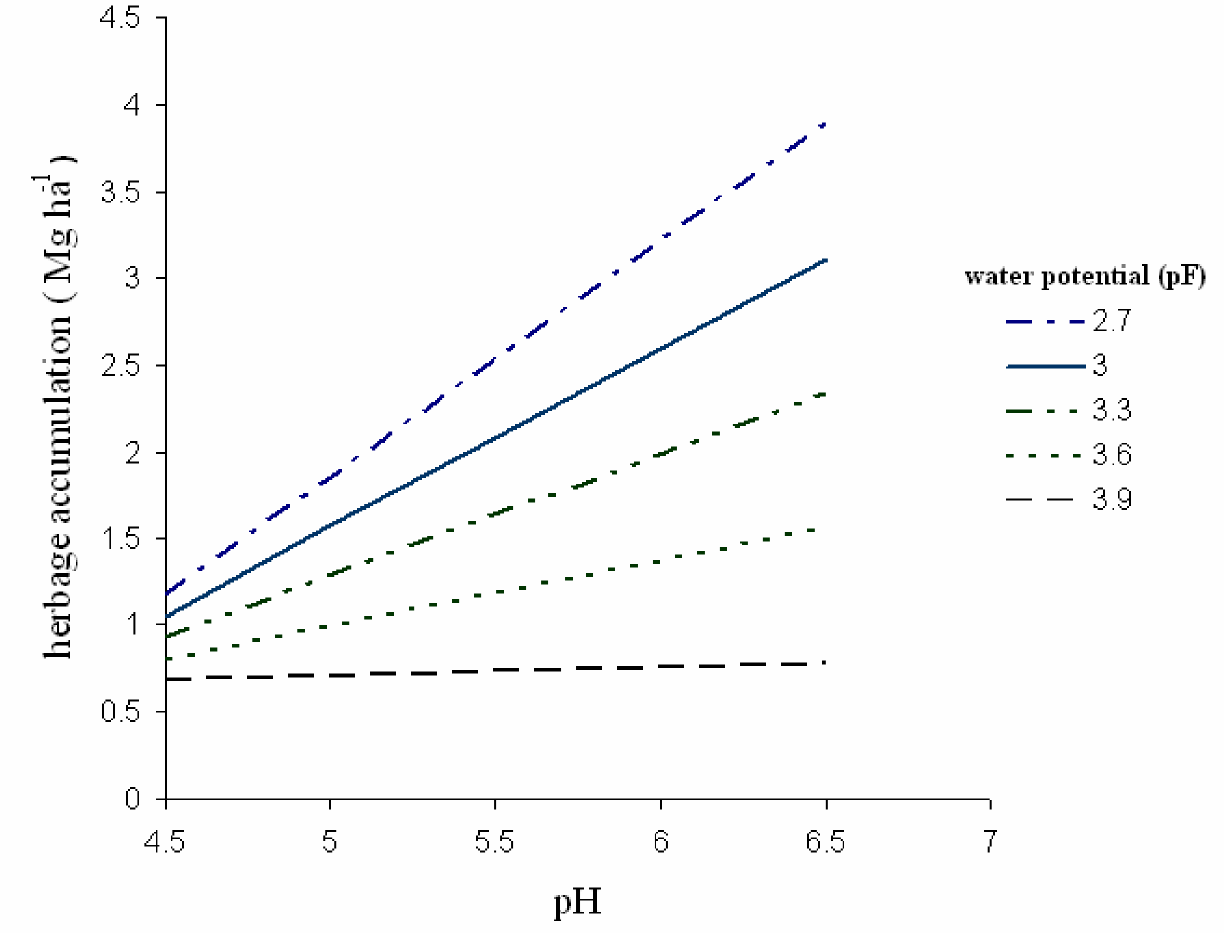

Fig. 3.4.3. Effect of water potential and pH level on Kentucky bluegrass herbage accumulation

Saeed and El- Nadi (1998) observed a response in dry matter yield of forage sorghum (*Sorghum bicolor L.*) to irrigation over two seasons. In their study, the dry matter yields were 16.3, 11.8, and 10.5 Mg ha$^{-1}$ for frequent (8 mm day$^{-1}$ every 7 days), intermediate (8 mm day$^{-1}$ every 10 days) and infrequent (8 mm day$^{-1}$ every 13 days) irrigation regimes respectively. Paula et al. (1989) studied the effect of liming on yields of wheat. They observed maximum dry matter yields of 15.86, 15.88 and 12.53 g/pot for higher quantities of calcium to reach target pH 6.0. There have not been studies on the effects of both water potential and pH on dry matter yield as has been done in this study.

The yield response to added N increased as soil moisture increased (Figure 3.4.4). At the lowest water potential (high pF), N additions had minimal effect on herbage accumulation and actually reduced yields at the higher N rates. The highest dry matter yields were observed at the highest water potential (low pF) with at least 100 mg kg$^{-1}$ N. The N rate that produced maximum yield generally decreased as water potential decreased, and was between 60-80 mg kg$^{-1}$ for all but the wettest and driest soils. The reduction in herbage accumulation particularly at low water potential (pF > 2.7) with higher N levels ( > 80 mg kg$^{-1}$ ) may be due to salinity effect /osmotic effect on plants where there is not enough moisture to mobilize the applied nutrients. Pier and Doerge (1995) also observed pronounced positive interactions in watermelon with maximum fruit yields occurred at rates of applied N between 200-270 kg ha$^{-1}$ at a mean soil water tension of 6 kPa. Fertilizer use efficiency is a function of available soil water (Fiez et al., 1994) because of the effect water potential has on nutrient availability through processes such as movement, dissolution and hydrolysis.

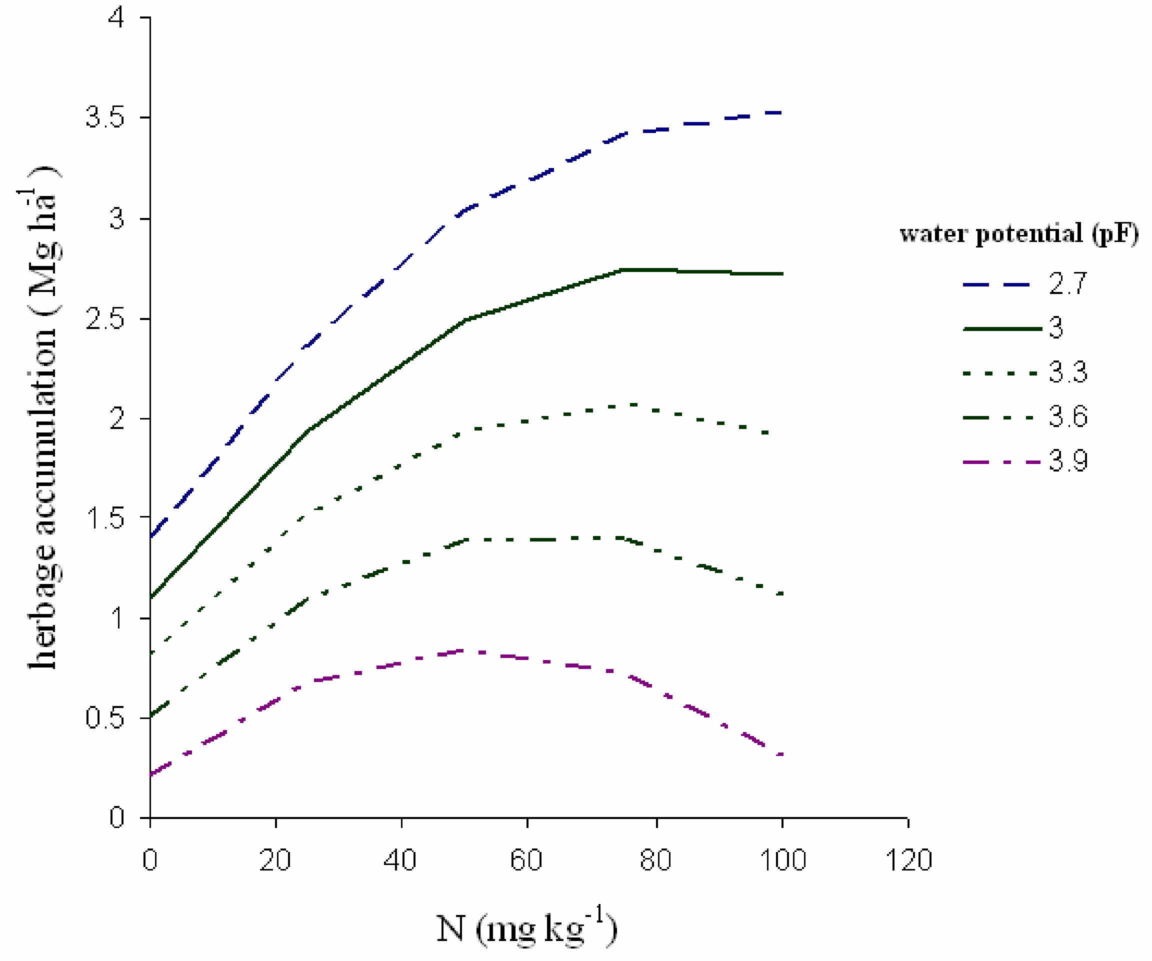

Fig. 3.4.4. Effect of water potential and N levels on Kentucky bluegrass herbage accumulation.

The herbage accumulation of bluegrass was also influenced significantly by the interaction between pH and N level (Fig. 3.4.5). Increasing pH increased herbage accumulation at all N levels, especially at higher rates of N. The N rate that produced maximum yield increased as pH increased up to pH 6.5. Decreases in yield were observed as N rate exceeded 50 – 80 mg kg$^{-1}$ when soil pH was less than 5.5. This may again be a salinity effect. Winston et al. (1976) observed an increase in recovery of N as well as yield in Timothy grass (*Phleum pretense L.*) in response to liming on Kachemak silt loam.

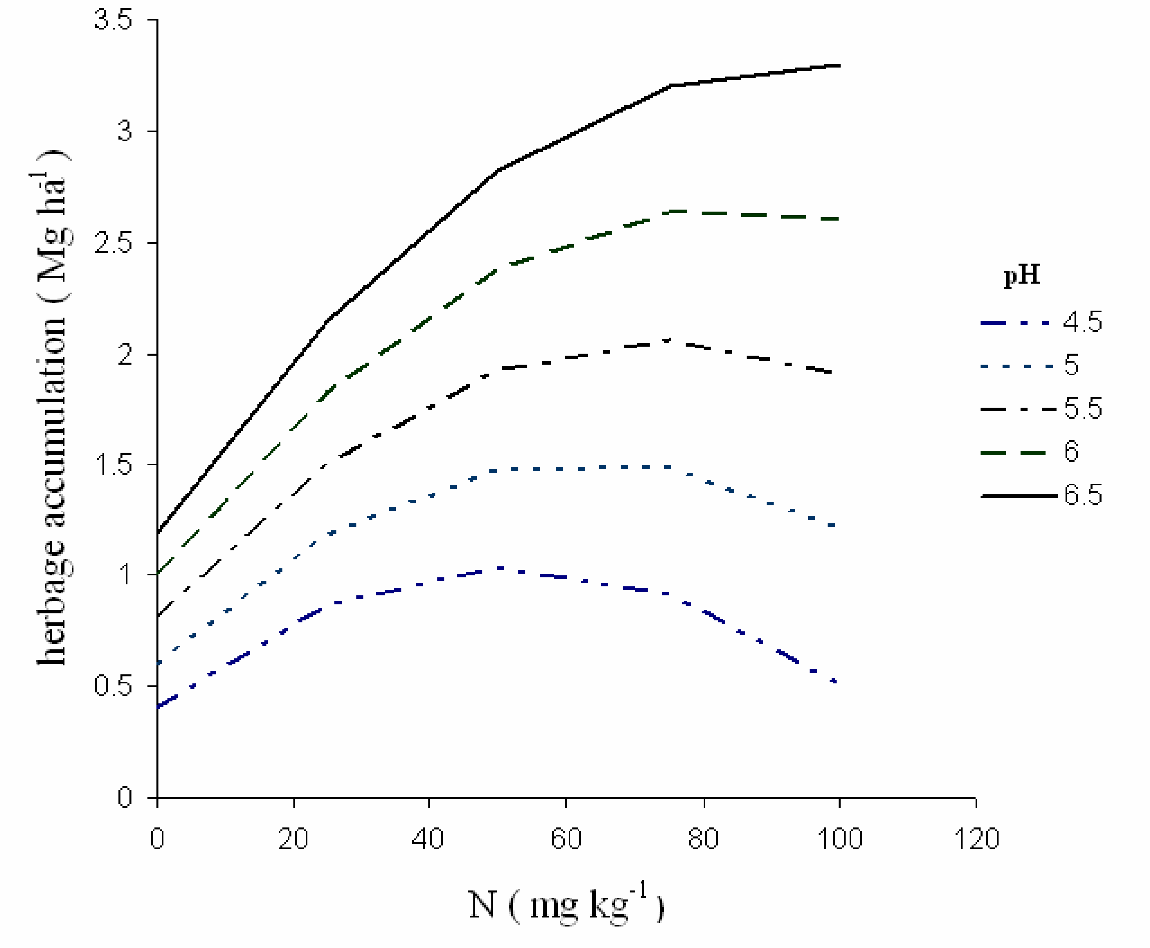

Fig. 3.4.5. Effect of pH and N levels on Kentucky bluegrass herbage accumulation

The RSREG using ridge max option in proc step of SAS program provided the optimum levels of these four factors to obtain maximum herbage accumulation (response) in bluegrass (Table 3.4.3). The higher herbage accumulation was observed when water potential (pF) ranges about 2.88 to 3.30, pH ranges 5.5- 6.1, and N levels ranges around 50-70 mg $kg^{-1}$. These are the optimum conditions to be maintained to get higher herbage accumulation in bluegrass. Small variations of P levels found from 40.0 to 36.0 mg $kg^{-1}$ in agreement with the observations regarding the ineffectiveness of the P doses to the herbage accumulation in bluegrass. The water potential, pH and N levels showed a significant positive influence on the herbage accumulation.

Table 3.4.3. Predicted herbage accumulation at optimum conditions

| Optimum conditions | | | | |
|---|---|---|---|---|
| Water potential (pF) | pH | N (mg $kg^{-1}$) | P (mg $kg^{-1}$) | Predicted herbage accumulation (Mg $ha^{-1}$) |
| 3.30 | 5.5 | 50.0 | 40.0 | 2.11 |
| 3.26 | 5.5 | 52.2 | 39.9 | 2.26 |
| 3.21 | 5.6 | 54.3 | 39.7 | 2.42 |
| 3.17 | 5.6 | 56.3 | 39.5 | 2.59 |
| 3.13 | 5.7 | 58.2 | 39.1 | 2.77 |
| 3.08 | 5.7 | 60.0 | 38.8 | 2.96 |
| 3.04 | 5.8 | 61.1 | 38.4 | 3.16 |
| 3.00 | 5.9 | 63.7 | 37.9 | 3.37 |
| 2.96 | 5.9 | 65.6 | 37.4 | 3.59 |
| 2.92 | 6.0 | 67.3 | 36.9 | 3.82 |
| 2.88 | 6.1 | 69.0 | 36.3 | 4.06 |

Optimum conditions were obtained from ridge analysis

### *3.4.2. Nutrient concentration in herbage*

The effect of factors individually and their interactions on nutrient concentration in bluegrass herbage was also studied in this experiment (Table 3.4.4).

Table 3.4.4. Model significance of nutrient concentration in Kentucky bluegrass

| **Source** | **N%** | **P%** | **K%** | **Ca%** | **Mg%** |
|---|---|---|---|---|---|
| | **---------------------------- Pr > F** | | | **-----------------------------** | |
| WP (pF) | <.0001 | 0.0182 | <.0001 | <.0001 | <.0001 |
| pH | <.0001 | <.0001 | <.0001 | <.0001 | <.0001 |
| N | <.0001 | 0.0196 | 0.6586 | 0.1367 | 0.1074 |
| P | 0.0518 | <.0001 | 0.1043 | 0.7683 | 0.5434 |
| WP*pH | 0.2124 | 0.7635 | 0.0153 | 0.0096 | 0.0195 |
| pH*pH | 0.2138 | 0.1248 | 0.1171 | 0.2569 | 0.0114 |
| WP*N | 0.0240 | 0.3834 | 0.9607 | 0.3680 | 0.4285 |
| pH*N | 0.9009 | 0.4034 | 0.3666 | 0.7763 | 0.5032 |
| N*N | 0.0793 | 0.7187 | 0.8787 | 0.9479 | 0.1389 |
| WP*P | 0.3305 | 0.0815 | 0.9564 | 0.8015 | 0.5793 |
| pH*P | 0.2789 | 0.1192 | 0.8094 | 0.7802 | 0.6108 |
| N*P | 0.0860 | 0.3842 | 0.5833 | 0.9043 | 0.8255 |
| P*P | 0.7786 | 0.0117 | 0.6061 | 0.8434 | 0.5638 |

The nitrogen concentration was significantly influenced by water potential, pH, N level, and a water potential by pH interaction (Table 3.4.4). Higher nitrogen uptake was seen at higher water potential (pF 2.7) with nitrogen level between 80 and 100 mg kg$^{-1}$ (Fig. 3.4.6). The higher nitrogen concentration may be due to water potential being in the optimum range for transport associated processes. An impact of water potential and pH on nitrogen uptake was also found by Aggelides et al. (1999), who found that nitrate concentrations in lettuce were reduced when water potential was reduced from -30 kPa to -100 kPa. The decrease in N uptake by *Dalbergia sissoo* seedlings was observed as irrigation rate decreased from 20 mm to 8 mm (Singh and Singh, 2006). Liming along with application of fertilizers enhanced the uptake of nitrogen by meadow plants (Kasperczyk et al., 2005).

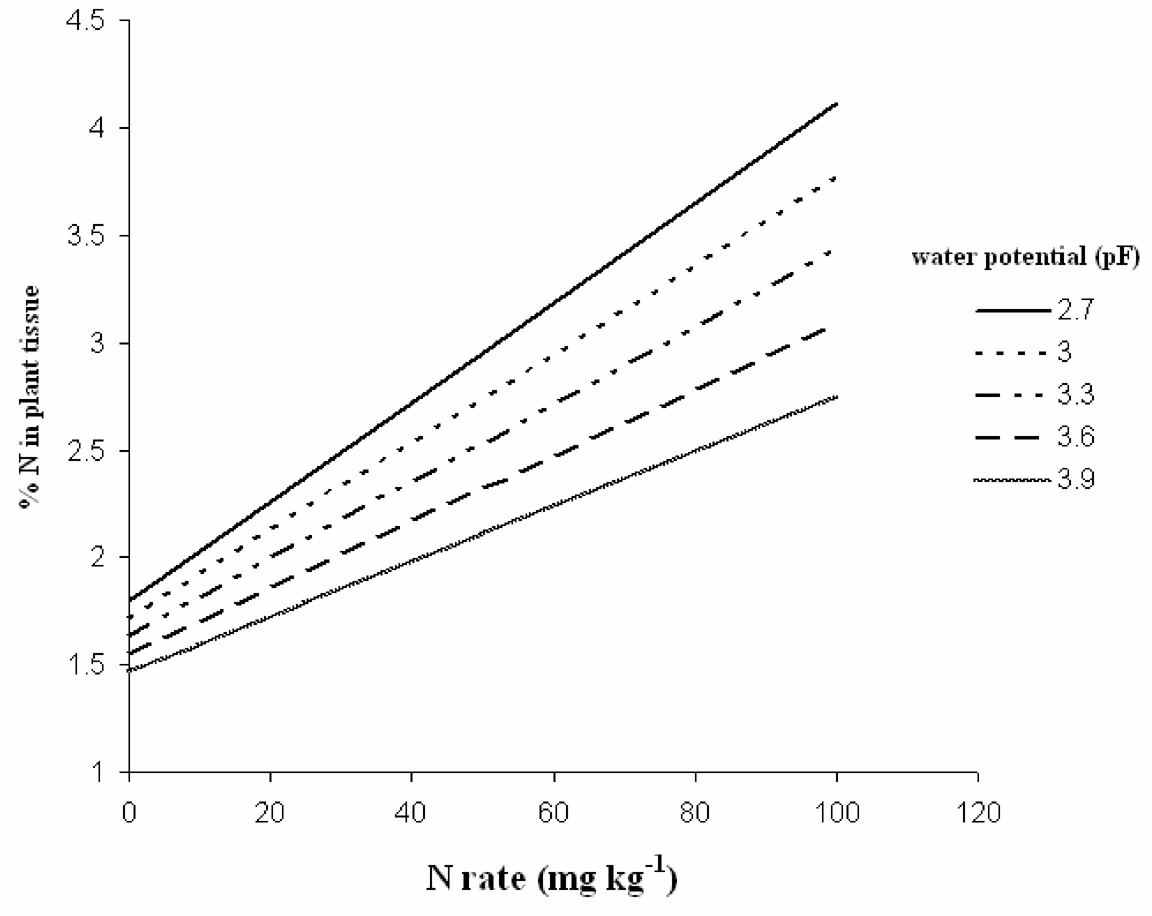

Fig. 3.4.6. Effect of water potential and N levels on N concentration in tissue

Phosphorus concentration was affected by water potential, pH, N and P levels, but interactions were not significant (Table. 3.4.4). As water potential increased (low pF) the phosphorus concentration was also increased. This increase may be due to enhancement in diffusion, the principal mechanism for P movement through the soil to root surface. Similar phenomenon was observed by several researchers (Mederski and Wilson, 1960). Increase in pH also had a significant effect on P uptake. Mayfield et al. (2002) also observed higher uptake of P by *Nandina domestica* grown in soil-less media in treatments that received lime compared to un-limed controls. The amount of applied N increased P uptake in this experiment which was contrast to previous literature. George et al. (1999) observed that a high supply of N reduced the uptake of P in young spruce plants (*Picea abies* L.) due to lower root:shoot ratio. Increased amounts of applied P enhanced the uptake of P in this study. Fageria et al. (1995) also found that higher levels of applied P (0, 50 and 175 mg $kg^{-1}$) significantly increased nutrient uptake by upland rice (*Oryza sativa L.*), wheat (*Triticum aestivum L.*), common bean (*Phaseolus vulgaris L.*) and corn (*Zea mays L.*) grown on an oxisol.

The concentrations of K, Ca, and Mg in shoots were significantly affected by the levels of water potential and pH of soil (Fig. 3.4.7-3.4.9). The concentration of Ca, Mg and K was significantly higher at higher levels of pH and water potential (low pF values). This enhancement in cation concentration at higher water potentials may be due to optimum soil moisture conditions making these cations available to plants. Similar results were observed for uptake of Ca by perennial ryegrass (Newbould et al., 1971) and for K by corn (Mackay and Barber, 1985) which they attributed to enhancement in transport processes such as mass flow and diffusion. The increase in pH also enhanced the concentration of cations (Ca, Mg, and K) in this experiment. Kasperczyk et al. (2005) also observed an increase in concentrations of calcium and magnesium in meadow plants with the application of lime. The concentration of potassium in herbage was not affected by incidental supply of K in applied P ($KH_2PO_4$) in this study, but it was affected by levels of water potential and pH.

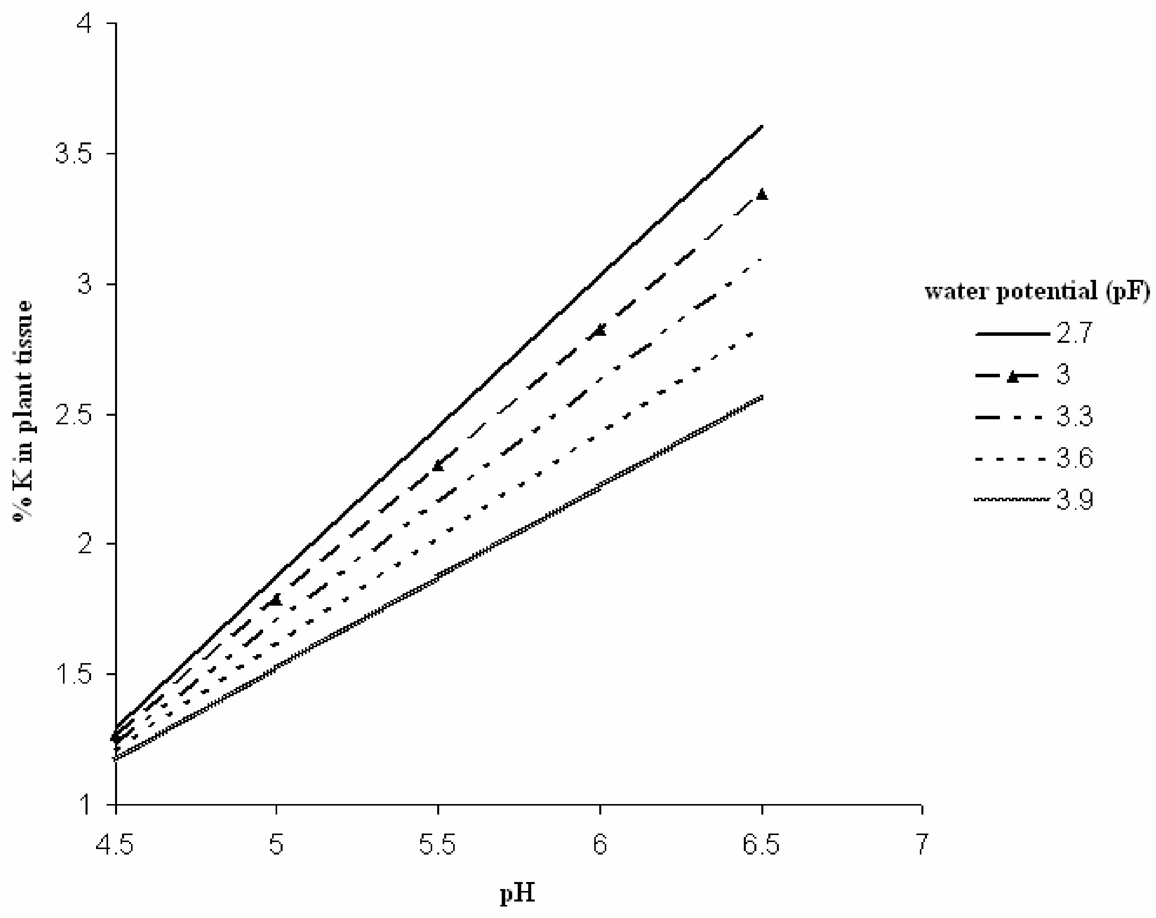

Fig. 3.4.7. Effect of water potential and pH on K concentration in tissue

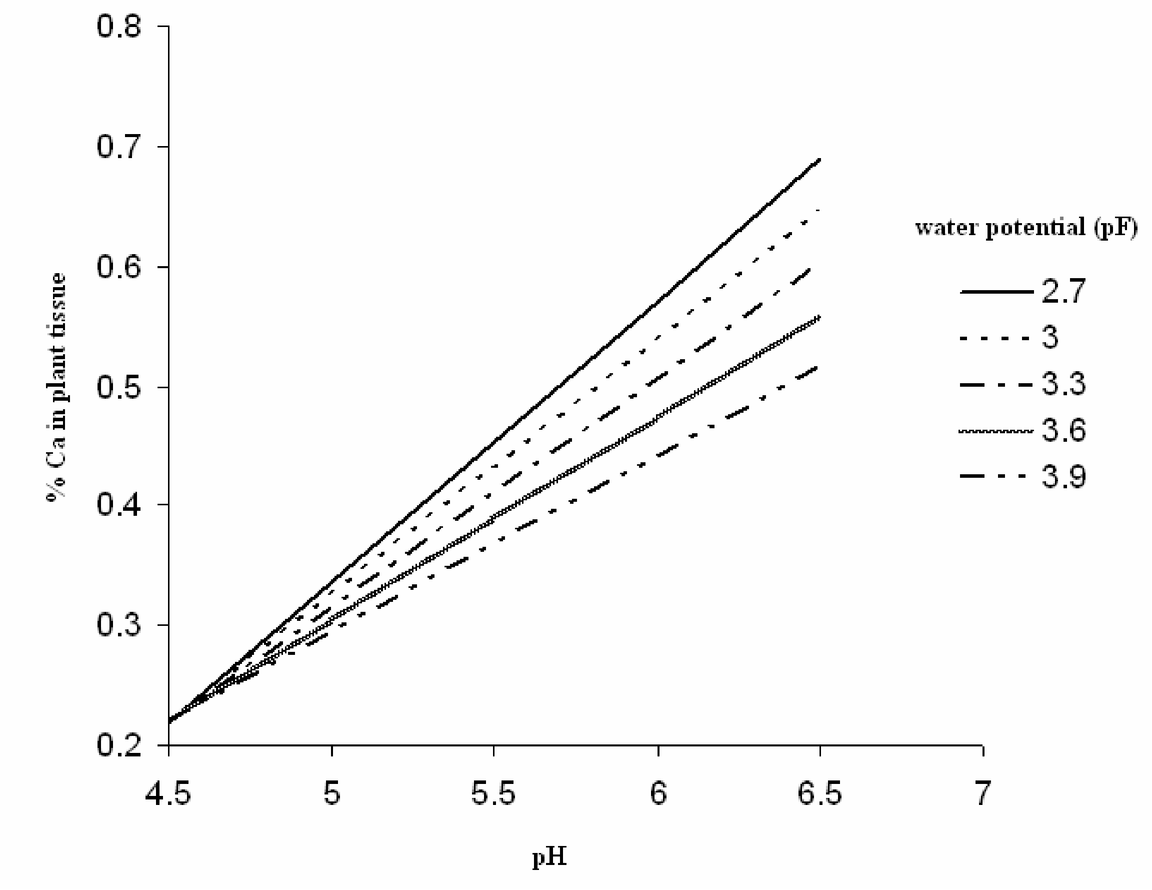

Fig. 3.4.8. Effect of water potential and pH on Ca concentration in tissue

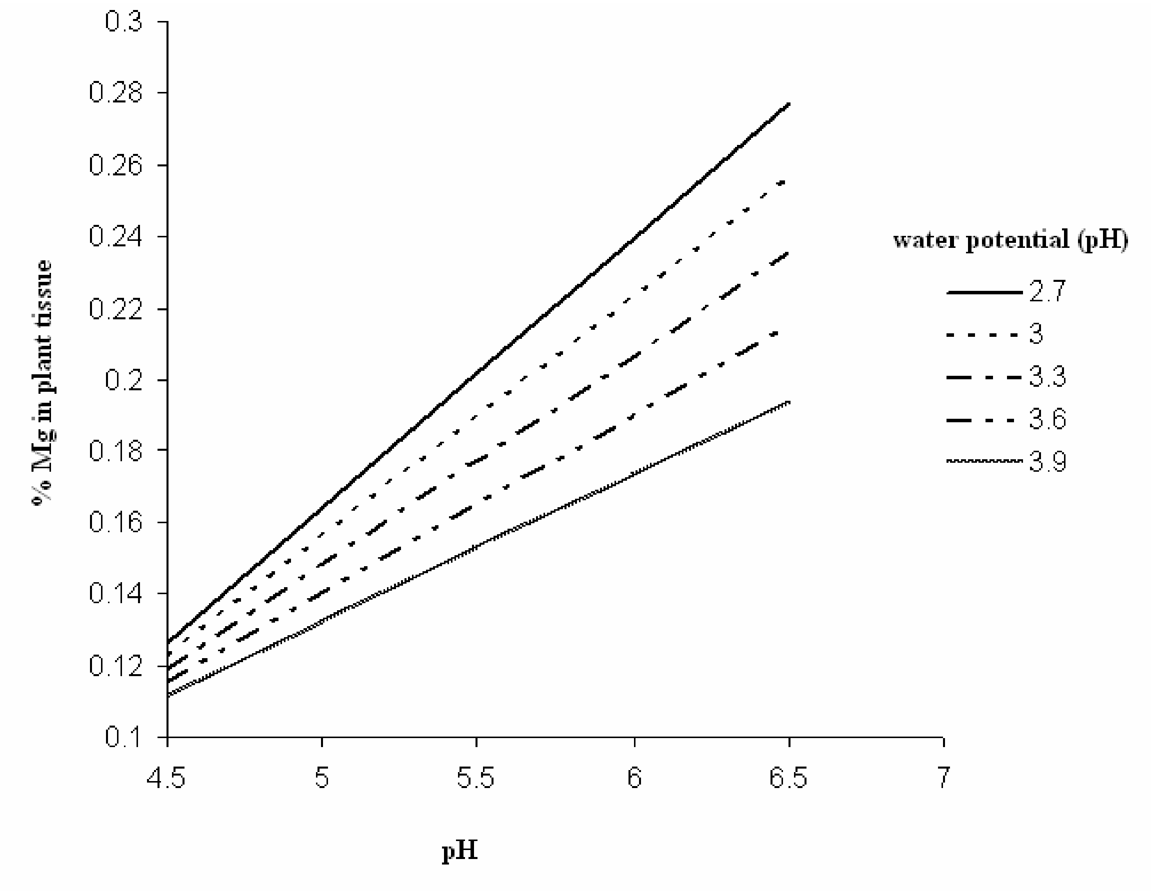

Fig. 3.4.9. Effect of water potential and pH on Mg concentration in tissue

Response surface methodology used in this study has provided a response function for Kentucky bluegrass herbage accumulation in an acidic pasture soil of the Appalachian region. The function also allows for prediction yield response, indicating that an improvement of forage production can be achieved. Optimal levels of growth determining factors were also derived to maximize the production of bluegrass. Nutrient concentrations in bluegrass herbage were affected by water potential, pH, N and P levels in a similar way. It was concluded that water potential and pH had significant impacts on uptake of N, P, Ca, Mg, and K. Significant interaction effects of WP x N and WP x pH were observed on concentration of N and cations respectively.

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# CHAPTER IV

## Available Water Effect On Optimum pH, Nitrogen and Phosphorus Requirements

## II. Kentucky Bluegrass – White Clover

### 4.1. ABSTRACT

The productivity of grasslands depends on soil factors such as water potential, pH, N and P levels. There is a need to understand the interactive effects of these factors on yield of grasslands. Response surface methodology was applied to optimize herbage accumulation of a bluegrass-white clover mixture for an acidic pasture soil. The effects of two levels of water potential (WP) and five levels each of pH, N, and P fertilizer additions were evaluated. Water potential, pH, N and P were significant main effects, as were the interactions WP x pH, WP x N, pH x pH, P x P, pH x N, and N x P. The order of influence of factors on herbage accumulation was WP > N > pH >WP x N > pH x pH > P > WP x pH > N x P > pH x N > P x P. Optimum levels of these four factors to maximize herbage accumulation were determined by using the RSREG procedure. These results have implications for how to divide pastures into management zones for optimal bluegrass-white clover production.

## 4.2. INTRODUCTION

Legumes are an important component of grasslands and have been shown to increase herbage dry matter yield and quality (Malhi et al., 2002; Rhodes and Ortega, 1997). White clover (*Trifolium repens L.*) is one of the important legume crops in temperate pastures and can provide acceptably high levels of production under low-input systems (Rochon et al., 2004). White clover is commonly sown in grasslands of temperate zones around the world in order to improve fodder quality and to fix atmospheric nitrogen (Ledgard, 2001).

Remediation of soil acidity is crucial for improving pasture soil quality and increasing forage yield. Liming to remediate acidic soils has a longer history than any other forms of fertility amendments (Gardner and Garner, 1953). Liming results in changes in chemical and physical properties of soil which improve conditions for plant growth (Menzies et al., 1994). Red clover and lime increased the productivity and nutrient uptake by all other plants in a crop rotation, which also led to imbalance in N and K in the soil that could be corrected by fertilization (Shempel and Kukresh, 1975). Therefore, it is essential to include legumes in reclaimed acidic pasture lands to maximize productivity of these low-input systems.

There is a need to study the interactions of liming and nutrient levels of soil to derive better management practices for grasslands. Several long-term experiments demonstrated the importance of basic slag and P-rich fertilizers in raising the productivity of relatively infertile permanent pasture by promoting growth of white clover (Elliott and Thomas, 1934; Arnold et al., 1976). The important role of P fertilizers along with lime, K, and N in improving pasture quality and output was observed in the Welsh uplands

(Milton and Davies, 1947; Jones, 1967). Cockayne (1956) observed that the topdressing with super phosphate was a major factor for increasing pasture production and livestock output. Ozgur and Sebahattin (2006) found that phosphorus treatments significantly affected dry matter yield and crude protein yield in white clover cultivars. Nitrogen fixing plants have a greater need for P than nitrate-supplied plants (Israel, 1987). N inputs were recognized as equally important to increase herbage production and provide potential to absorb other essential elements from soil such as potassium (Reith et al., 1961).

Soil water content is an essential growth factor which can influence the success of any application of amendments and fertilizers. It had significant effect on nutrient release from applied fertilizers as well as mineralization reactions (Koerselman et al., 1993). Fertilizer use efficiency is a function of available water (Fiez et al., 1994; Gutierrez-Boem and Thomas, 1998).

Forage can be produced on acidic soils with appropriate agronomic practices. These practices will be affected by available soil water. Given the undulating topography of many Appalachian pastures and the resulting variability in soil water content, there is a need to understand the interactions between soil water, pH, N and P application rates. This study was designed to derive yield response model for legume based pastures, and to quantify the interactions of water potential, pH, N and P levels.

## 4.3. MATERIALS AND METHODS

An acidic soil (pH <5.5) was collected near Morgantown, WV from a Culleoka - Westmoreland map unit, air-dried and passed through a 2 mm sieve. Soil pH was determined using a glass membrane electrode; texture by the pipette method (Sternberg and Creager, 1961); organic matter content by loss on ignition (Oliver et al., 2001); and CEC by the ammonium acetate method (Chapman, 1965). Lime response curve for the collected soil was developed by direct $Ca(OH)_2$ titration method (Alabi et al., 1986). The soil moisture characteristic curve was determined using a dew-point potentiometer (Decagon Model WP4-T) and gravimetry. All determinations were done in triplicate.

Sufficient $Ca(OH)_2$ was added to separate sub-samples produce different pH levels based on the lime response curve to establish a range of final soil pH from 4.5 to 6.5 in approximately 0.5 increments. Limed soils were incubated at field capacity for one week, or until equilibrium pH was reached. Soils were again air-dried and stored until use. The experiment was a centrally composite rotatable design with three replications in order to reduce the number of experimental units (Myers and Montgomery, 1995) (Appendix. (Table A5)). Soil was placed in pots (30.5 cm x 30.5 cm x 20 cm) and five fertilizer rates were established by incorporating nitrogen as ($NH_4NO_3$) or phosphorus (as $KH_2PO_4$) to the soil. Nitrogen was added at 0, 10, 25, 50 and 100 mg N $kg^{-1}$ soil. Phosphorus was added to give final phosphorus concentrations of 0, 10, 20, 40 and 80 mg P $kg^{-1}$ soil. Two water contents, near field capacity (pF 2.7) and just above the permanent wilting point (pF 3.9), as determined from the soil-water characteristic curve were imposed and maintained using a sensor-based irrigation system (NETAFIM Flori I). Water content was measured regularly by potentiometer (Decogon Model WP4 -T).

Pots were seeded with bluegrass (*Poa pratensis L.*), white clover (*Trifolium repens L.*), or a 75% bluegrass - 25% white clover mixture (weight basis). White clover seeds were inoculated with *Rhizobium trifoli* just before seeding. Every three weeks a sample of the soil solution before watering was drawn with a soil solution sampler (Rhizon SMS) and analyzed for $Ca^{2+}$, $PO_4^{3-}$, $NH_4^+$ and $NO_3^-$ by ion chromatography (DX-300, Dionex Corp). At the end of the experiment (60 days after sowing) herbage accumulation was measured by clipping at ground level and drying the herbage at 105 $^0$C for 48 hours. Nutrient concentration was determined in herbage by wet digestion with concentrated $HNO_3$ using microwave (MARS 5, CEM) (Rechcigal and Payne 1990). The extracts from this wet digestion were used to determine nutrient concentrations by ICP-OES (Perkin Elmer P400, Norwalk, CT). Nutrient concentrations were expressed on a tissue dry matter basis.

Herbage accumulation data were analyzed using a response surface methodology and the PROC RSREG procedure with Ridge max option in SAS (ver 9.1, SAS Institute, Cary, NC, USA). Herbage accumulation was the response variable and water potential, pH, N, and P rates were added to construct model main effects. The linear, quadratic, and cross product terms of these factors were also determined. A step-wise regression procedure was used to determine the best model. Adjusted $R^2$ and Cp statistics were used to select model parameters. The effect of factors as linear, quadratic, and interaction (cross product) coefficients on response variable (dry matter yield) was tested for adequacy and fitness by analysis of variance. Nutrient concentrations in herbage were analyzed to study the effect of water potential, pH, N and P levels.

## 4.4. RESULTS AND DISCUSSION

The soil texture of the pot medium was a silt clay loam (34.3 % clay; 44.0 % silt), with an initial pH of 4.8, 9.2% organic matter, 42.5 ppm Ca, 9.8 ppm Mg, 40.8 ppm K, 4.06 ppm P, and a CEC of 15.84 $\text{cmol}_c\ \text{kg}^{-1}$. The lime response curve was linear from pH 5.2 to 6.5 (Appendix (Fig. A1)). On average water potential (pF) was 2.70 in the field capacity treatment and 3.91 in the near wilting point treatment of both were maintained during the entire period of the experiment which were gravimetrically equal to 16% and 30%, respectively (Appendix (Fig. A2-A3)).

### *4.4.1. Yield model*

Analysis of variance showed that the model significantly predicted herbage accumulation (response variable) despite the presence of a significant lack of fit (Table 4.4.1). A residual plot indicated no pattern in the residuals (Fig. 4.4.1), but a large variance. High variance in residual data from stratum may be due to a larger effect of treatments. The lack of fit term was not significant when mean values were used (Fig. 4.4.2). These results suggest that a factor affecting yield was not captured by the treatments selected.

Table 4.4.1. Analysis of Variance for the response model

| Source | df | Sum of Squares | Mean Square | F Ratio | Prob > F |
|---|---|---|---|---|---|
| Model | 13 | 143.27 | 11.02 | 122.26 | < .0001 |
| Error | 82 | 7.39 | 0.09 | | |
| Lack Of Fit | 16 | 5.72 | 0.35 | 14.17 | <.0001 |
| Pure Error | 66 | 1.66 | 0.02 | | |
| C. Total | 95 | 150.66 | | | |

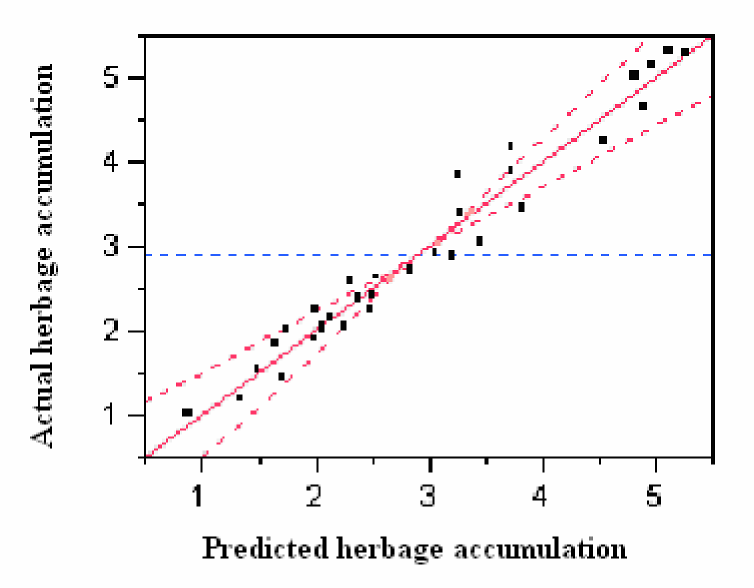

Fig. 4.4.1. Actual vs. predicted herbage accumulation using the model. Dashed lines indicate the 95% confidence interval.

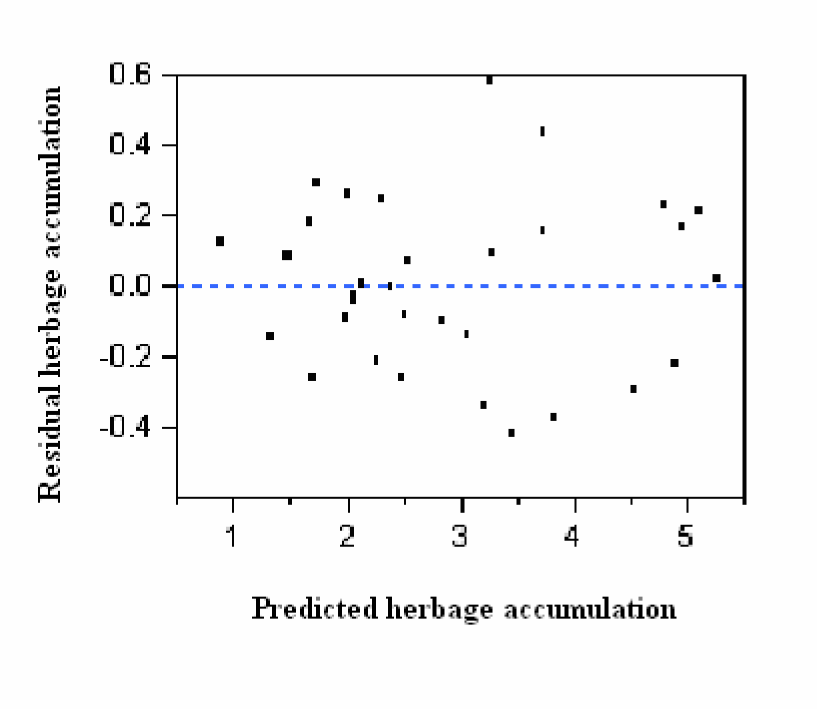

Fig. 4.4.2. Residual vs. Predicted values of herbage accumulation using the model

Water potential, pH, N and P were the main effects that influenced herbage accumulation ($P<0.05$) (Table. 4.4.2). The cross product terms of water potential x N, water potential x pH, N x P, pH x N as well as quadratic terms of pH and P also showed significant effects on herbage accumulation.

Water potential had the largest influence on bluegrass-white clover herbage accumulation, as indicated by sum of squares followed by N, pH and P levels. The order of influence of interaction terms on herbage accumulation was WP x N > pH x pH > WP x pH > N x P > pH x N > P x P. These terms were used to determine the response surface function.

$$Y = -(1.24*WP) + (0.79*pH) + (0.02*N) + (0.01*P) - 0.40*(WP - 3.305)*(pH - 5.5) - 0.01*(WP - 3.305)*(N-30.625) - 0.67*(pH - 5.5)*(pH - 5.5) + 0.01*(pH - 5.5)*(N-30.625) + 0.0005*(N - 30.305)*(P - 25) + 0.0001*(P-25)*(P-25) \qquad [4.4.1]$$

where Y is herbage accumulation of the bluegrass-white clover mixture in Mg $\mathrm{ha}^{-1}$, WP is water potential (pF), N and P are levels of nitrogen and phosphorus (mg $\mathrm{kg}^{-1}$) respectively.

Table 4.4.2. ANOVA for effect of factors and their interactions on herbage accumulation of bluegrass and white clover mixture

| **Source** | **df** | **Estimates** | **Sum of Squares** | **F Ratio** | **Pr > F** |
|---|---|---|---|---|---|
| WP (pF) | 1 | -1.239285 | 53.966483. | 383.9171. | <.0001 |
| N | 1 | 0.026478 | 19.2438650 | 136.9007 | <.0001 |
| pH | 1 | 0.790049 | 13.666329 | 97.22210 | <.0001 |
| P | 1 | 0.010981 | 1.9416700 | 13.81300 | 0.0004 |
| WP*N | 1 | -0.014851 | 4.423316 | 31.4674 | <.0001 |
| pH*pH | 1 | -0.674432 | 3.281965 | 23.3479 | <.0001 |
| WP*pH | 1 | -0.402648 | 1.42070 | 10.1318 | 0.0021 |
| N*P | 1 | 0.000530 | 1.267860 | 9.0196 | 0.0036 |
| pH*N | 1 | 0.015327 | 1.161047 | 8.2597 | 0.0052 |
| P*P | 1 | 0.000197 | 0.774595 | 5.5105 | 0.0213 |
| pH*P | 1 | -0.013973 | 0.555554 | 3.9522 | 0.0502 |
| WP*P | 1 | -0.005952 | 0.435184 | 3.0959 | 0.0823 |
| N*N | 1 | 6.586e-5 | 0.222140 | 1.5803 | 0.2123 |

Based on parameter estimates, as water potential increased (drier soil conditions), herbage accumulation decreased (Table 4.4.2). The positive sign on parameter estimates of N, pH and P indicate that increasing soil pH, N and P fertilization increased herbage accumulation (Table 4.4.2).

The water potential by N interaction showed that in addition to increasing herbage accumulation as pF decreased (increase in water potential), the rate of increase per unit increase in N rate increased as pF decreased (Fig. 4.4.3). Pier and Doerge (1995) also observed pronounced positive interactions in watermelon with maximum fruit yields occuring at rates of applied N between 200-270 kg $ha^{-1}$ at a mean soil water tension of 6 kPa. Fertilizer use efficiency is a function of available soil water (Fiez et al., 1994) because of the effect water potential has on nutrient availability through processes such as movement, dissolution and hydrolysis.

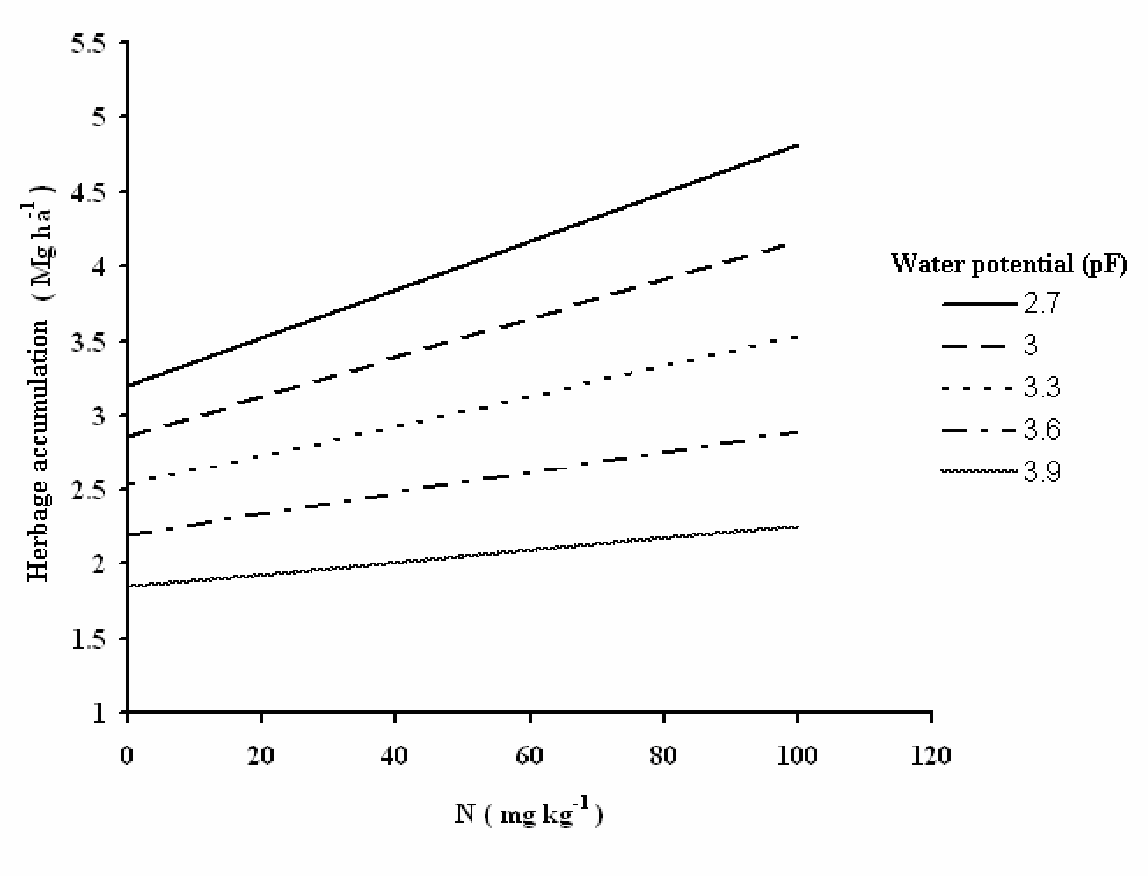

Fig. 4.4.3. Effect of water potential and N level on herbage accumulation of bluegrass and white clover mixture.

The increase of water potential and pH had significant effects on herbage accumulation (Fig. 4.4.4). Saeed and El-Nadi (1998) also observed a response in dry matter yield of forage sorghum (*Sorghum bicolor L.*) to irrigation over two seasons. In their study, the dry matter yields were 16.3, 11.8, and 10.5 Mg ha$^{-1}$ for frequent (8 mm day$^{-1}$ every 7 days), intermediate (8 mm day$^{-1}$ every 10 days) and infrequent (8 mm day$^{-1}$ every 13 days) irrigation regimes respectively. Paula et al. (1987) studied the effect of liming on yields of wheat. They observed maximum dry matter yields of 15.86, 15.88 and 12.53 g/pot for higher quantities of calcium to reach target pH 6.0. There have not been studies on the effects of both water potential and pH on dry matter yield as has been done in this study.

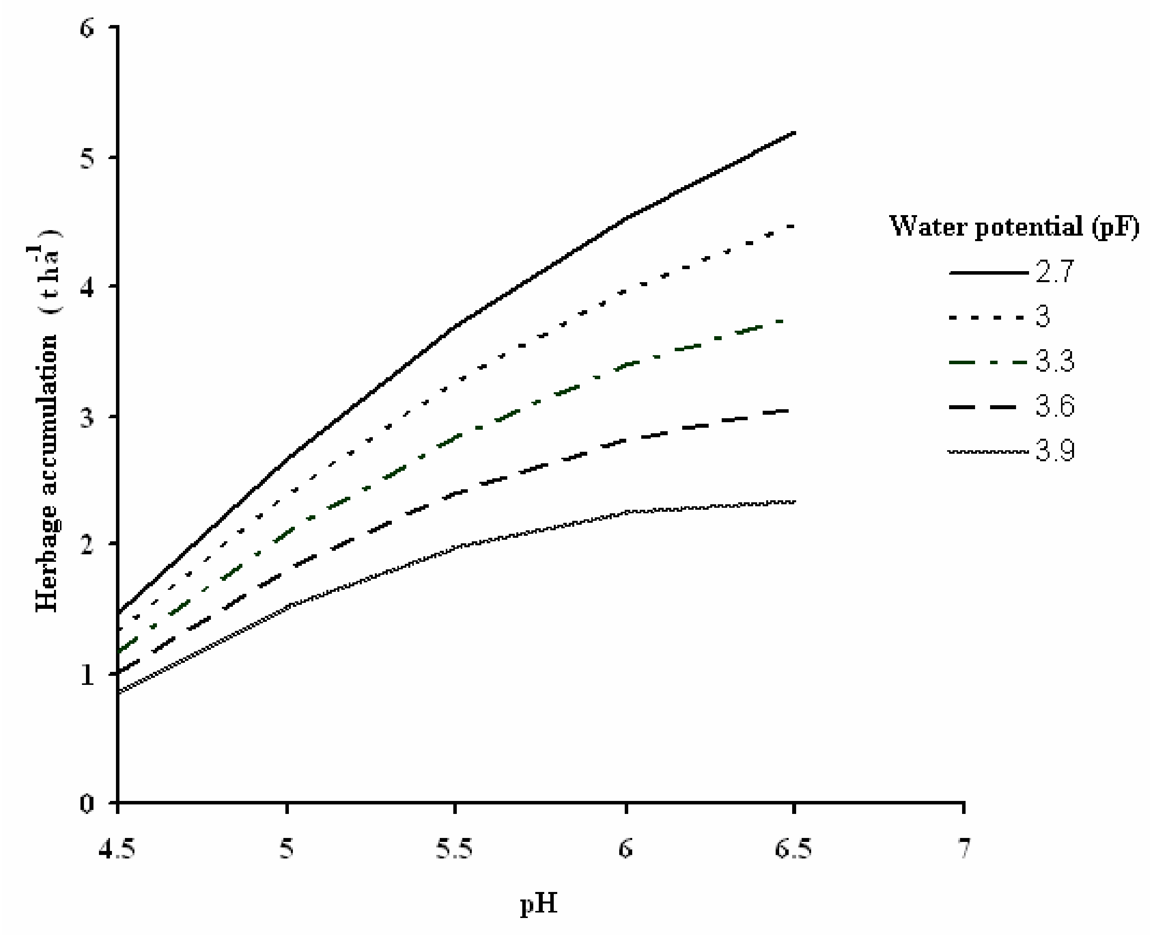

Fig. 4.4.4. Effect of water potential and pH level on herbage accumulation of bluegrass and white clover mixture.

The interaction between N and P levels also showed a statistically significant effect on herbage accumulation (Fig. 4.4.5). As the rate of P increased (0 to 80 mg kg$^{-1}$), the increase in N rate (0 to 100 mg kg$^{-1}$) had a significant effect on herbage accumulation. Nuttall et al. (1991) also observed an increase in herbage accumulation of a bromegrass-alfalfa mixture as rates of N and P increased from 0 to 90 kg N $ha^{-1}$ and 0 to 20 kg P $ha^{-1}$ respectively. The increase in dry matter production of Galega-Bromus mixture as the rates of N fertilizer increased from 30 to 150 kg $ha^{-1}$ along with P and K fertilizers (60 kg $ha^{-1}$ P and 90 kg $ha^{-1}$ K) (kshnikatkina et al. 2002).

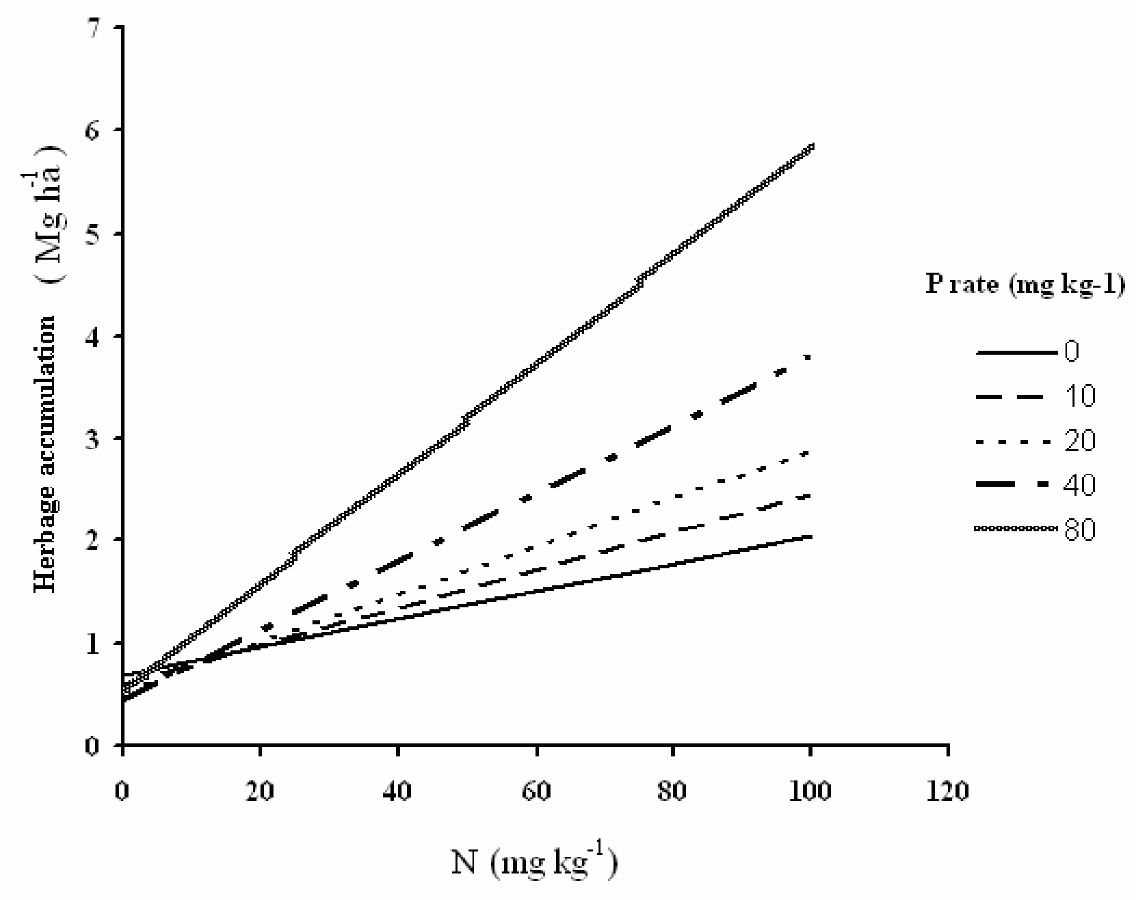

Fig. 4.4.5. Effect of N and P level on herbage accumulation of bluegrass and white clover mixture.

Herbage accumulation also responded significantly to the rate of nitrogen along with liming (Fig. 4.4.6). As the pH increased from 5.5 to 6.5 with the increase in N rate, herbage accumulation also increased. But there was a decrease in response of herbage accumulation to N additions at pH above 5.5. Timothy (*Phleum pretense*) exhibited a high response to N fertilization with liming on Kachemak silt loam in terms of yield as well as N-uptake by plants (Winston et al., 1976).

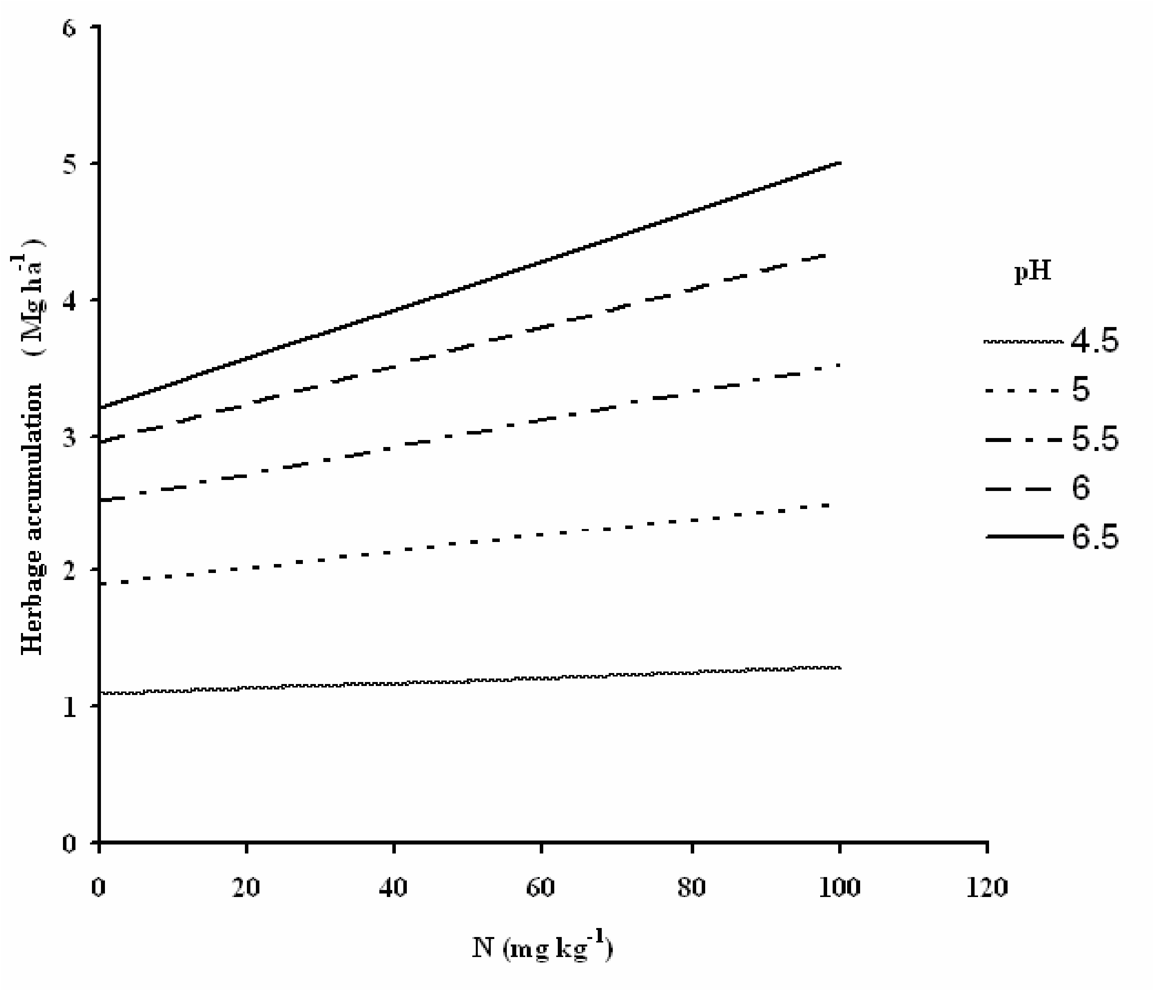

Fig. 4.4.6. Effect of nitrogen and pH level on herbage accumulation of bluegrass and white clover mixture.

In this study, the optimum levels of these four factors were determined to maximize herbage accumulation using ridge max option in proc step of the SAS program (Table 4.4.3). Higher herbage accumulation was observed when water potential (pF) ranged from 2.87 to 3.30, pH from 5.50 to 6.00, N from 50 to 70 mg kg$^{-1}$ and P from 35 to 40 mg kg$^{-1}$. These are the optimum conditions to be maintained to get highest herbage accumulation in bluegrass-white clover. Water potential, pH, N and P showed a significant positive influence on herbage accumulation.

Table 4.4.3. Predicted response for different levels of four factors

| Optimum conditions | | | | |
|---|---|---|---|---|
| Water potential (pF) | pH | N (mg kg$^{-1}$) | P (mg kg$^{-1}$) | Predicted herbage accumulation (Mg ha$^{-1}$) |
| 3.30 | 5.50 | 50.0 | 40.0 | 3.30 |
| 3.26 | 5.57 | 50.6 | 40.4 | 3.47 |
| 3.22 | 5.63 | 51.5 | 40.6 | 3.63 |
| 3.17 | 5.70 | 52.7 | 40.6 | 3.80 |
| 3.13 | 5.76 | 54.3 | 40.5 | 3.97 |
| 3.08 | 5.82 | 56.2 | 40.3 | 4.14 |
| 3.04 | 5.87 | 58.3 | 39.4 | 4.32 |
| 2.99 | 5.92 | 60.8 | 38.5 | 4.50 |
| 2.95 | 5.97 | 63.5 | 37.5 | 4.70 |
| 2.91 | 6.02 | 66.4 | 36.2 | 4.89 |
| 2.87 | 6.07 | 69.5 | 34.8 | 5.10 |

*Optimum conditions were obtained from ridge analysis

### *4.4.2. Nutrient concentration in bluegrass - white clover herbage*

The impact of all four factors and interactions on nutrient concentration is given in Table 4.4.4 Water potential and pH had significant effects on uptake of all nutrients.

Table 4.4.4. Model significance for effects of factors and their interactions on nutrient concentrations in Kentucky bluegrass-white clover mixture

| **Source** | **N %** | **P %** | **K %** | **Ca %** | **Mg %** |
|---|---|---|---|---|---|
| | ------------------ | ------------ | **Pr > F** | ------------ | ------------------ |
| WP (pF) | <.0001 | <.0001 | 0.0001 | <.0001 | <.0001 |
| pH | <.0001 | <.0001 | <.0001 | <.0001 | <.0001 |
| N | <.0001 | 0.9071 | 0.9021 | 0.2432 | 0.7878 |
| P | 0.5486 | <.0001 | 0.6819 | 0.8861 | 0.8885 |
| WP*pH | 0.9631 | 0.1092 | 0.2996 | 0.7508 | <.0001 |
| pH*pH | 0.0138 | 0.0055 | 0.1178 | 0.0344 | 0.0812 |
| WP*N | 0.8178 | 0.9845 | 0.4382 | 0.7250 | 0.3352 |
| pH*N | 0.0337 | 0.5353 | 0.3819 | 0.3918 | 0.9376 |
| N*N | 0.0579 | 0.9320 | 0.6692 | 0.6248 | 0.5038 |
| WP*P | 0.9476 | 0.0311 | 0.8553 | 0.4527 | 0.9769 |
| pH*P | 0.4528 | 0.0211 | 0.3002 | 0.8731 | 0.8282 |
| N*P | 0.9194 | 0.6091 | 0.6178 | 0.6639 | 0.8553 |
| P*P | 0.6610 | 0.2511 | 0.3640 | 0.7628 | 0.7671 |

Nitrogen concentration was significantly affected by water potential, pH, N level, and pH by N interaction (Table 4.4.4). Maximum N concentration was observed at higher water potential (low pF value) with pH 6.5 and nitrogen levels between 80 and 100 mg kg$^{-1}$ (Fig. 4.4.7). But the rate of increase in N concentration was less above pH 5.5 and was low between pH 6.0 and 6.5. Aggelides et al. (1999) observed that nitrate concentration in lettuce leaves was reduced when water potential decreased from -30 kPa to -100 kPa. Singh and Singh (2006) found that N uptake by *Dalbergia sissoo* decreased as irrigation level decreased from 20 mm to 8 mm. Application of N along with lime increased the uptake of nitrogen by meadow plants (Kasperczyk et al., 2005). Concentration of N in bromegrass (*Bromus inermis*) and alfalfa (*Medicago media*) was positively correlated with applied N rates (Nuttall, 1980).

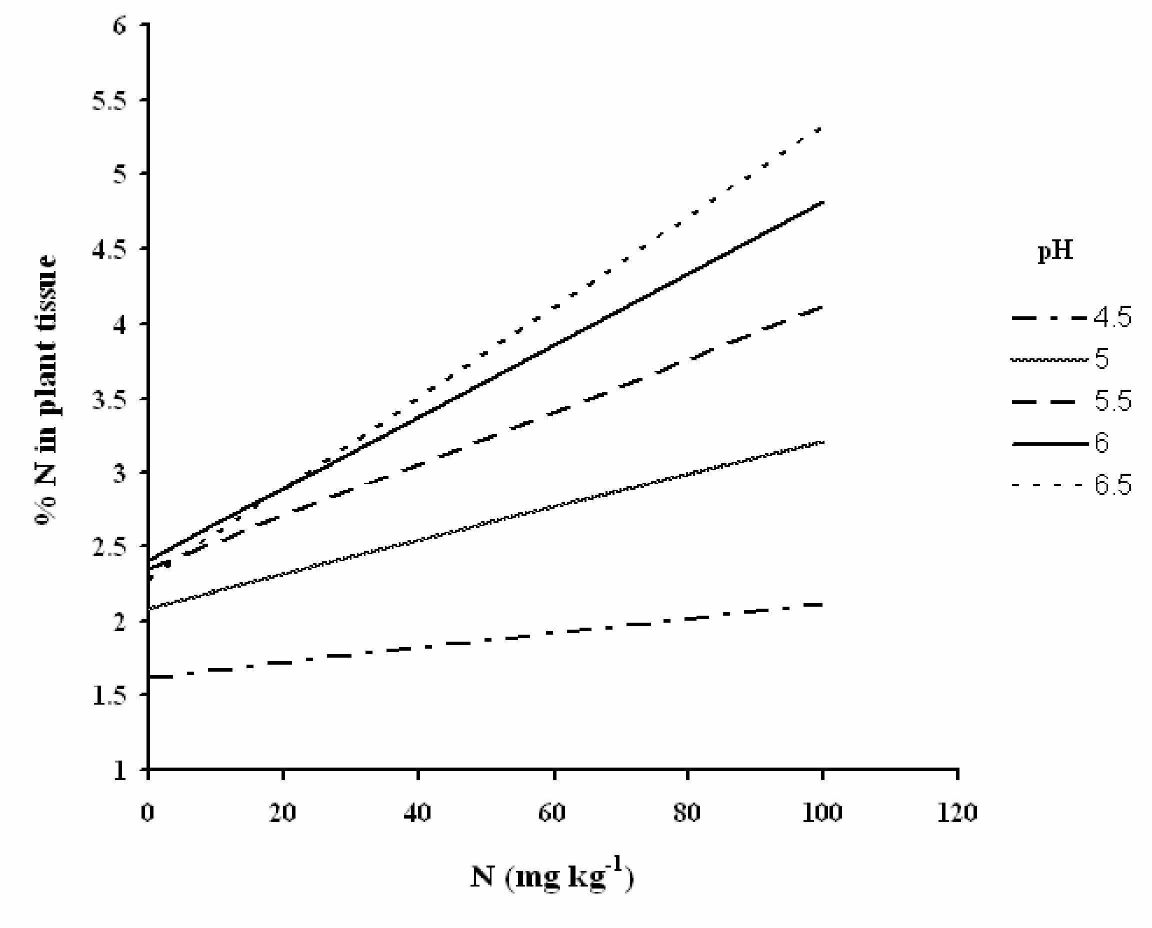

Fig. 4.4.7. Effect of pH and N level on N concentration of tissue

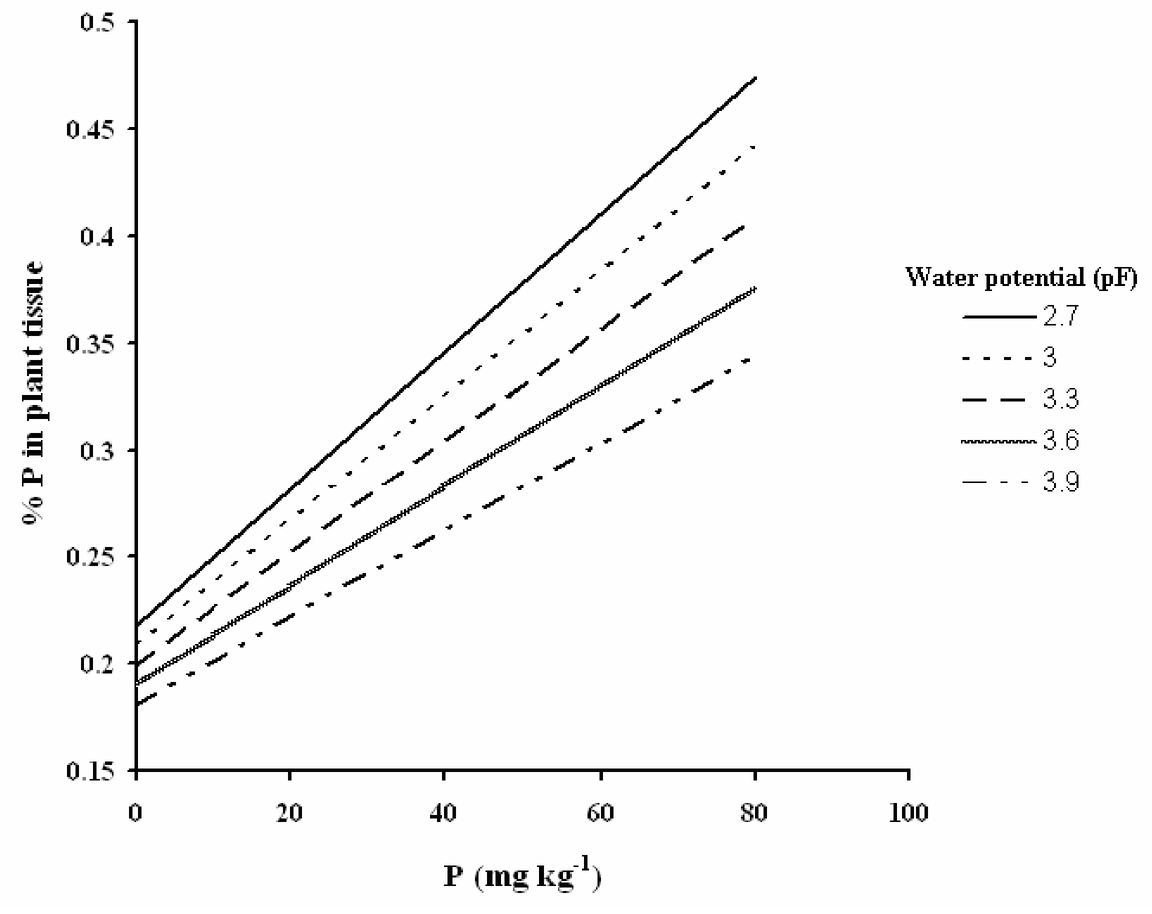

Fig. 4.4.8. Effect of water potential and P level on P concentration in tissue

Phosphorus concentration was significantly affected by water potential, pH, and P level (Table 4.4.4). The interaction of P level with water potential and pH also had significant influence on P concentration. The increased P concentration in plant tissue at the higher water potential may be due to enhancement in the diffusion process, which was observed previously by several researchers (Mederski and Wilson, 1960) (Fig. 4.4.8). Increase in pH up to 6.0 due to liming also had a significant effect on P concentration (Fig. 4.4.9). But P concentration was not affected by the increase of pH above 6.0.

Mayfield et al. (2002) also observed maximum uptake of P by *Nandina domestica* grown in soil-less media in treatments that received lime compared to the un-limed controls. Concentration of P in pasture herbage was significantly increased by application of P fertilizer (20 kg ha$^{-1}$), from 0.16 to 0.30% in alfalfa (*Medicago media*) and 0.16 to 0.31% in bromegrass (*Bromus inermis*) (Nuttall, 1980).

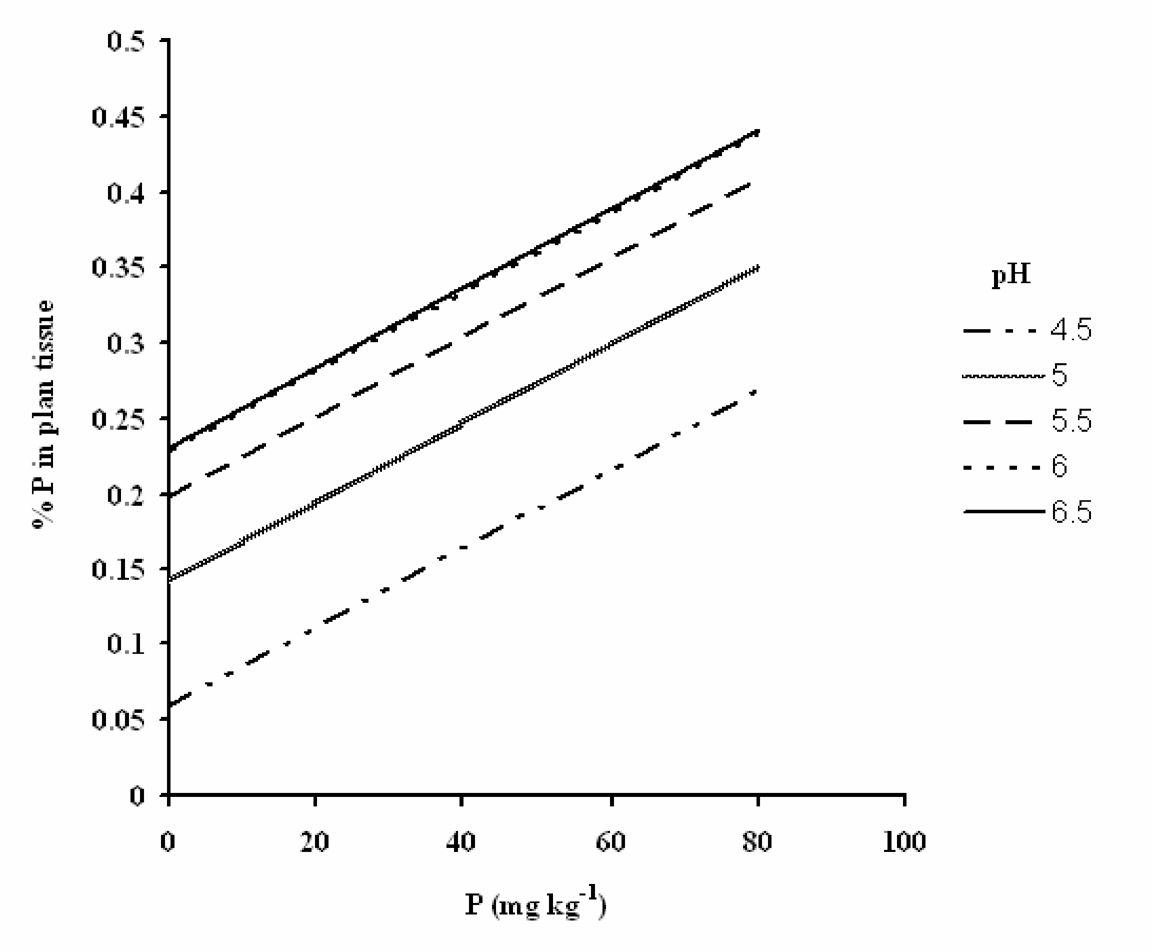

Fig. 4.4.9. Effect of pH and P level on P concentration in tissue

Concentration of K, Ca, and Mg in shoots was significantly affected by water potential and pH of soil (Table. 4.4.4). A significant effect of water potential and pH was observed in the case of Mg uptake (Fig. 4.4.10). The increased concentrations of K, Ca, and Mg were observed at higher water potentials which may be due to an increase in the magnitude of processes such as mass flow and diffusion (Mackay and Barber, 1985). The increase in pH also enhanced the concentration of cations (K, Ca, and Mg) in this study. Kasperczyk et al. (2005) also observed an increase in concentration of calcium and magnesium in meadow plants due to application of lime. The concentration of potassium was not affected by K applied with P ($KH_2PO_4$) in this study, but was affected by levels of water potential and pH.

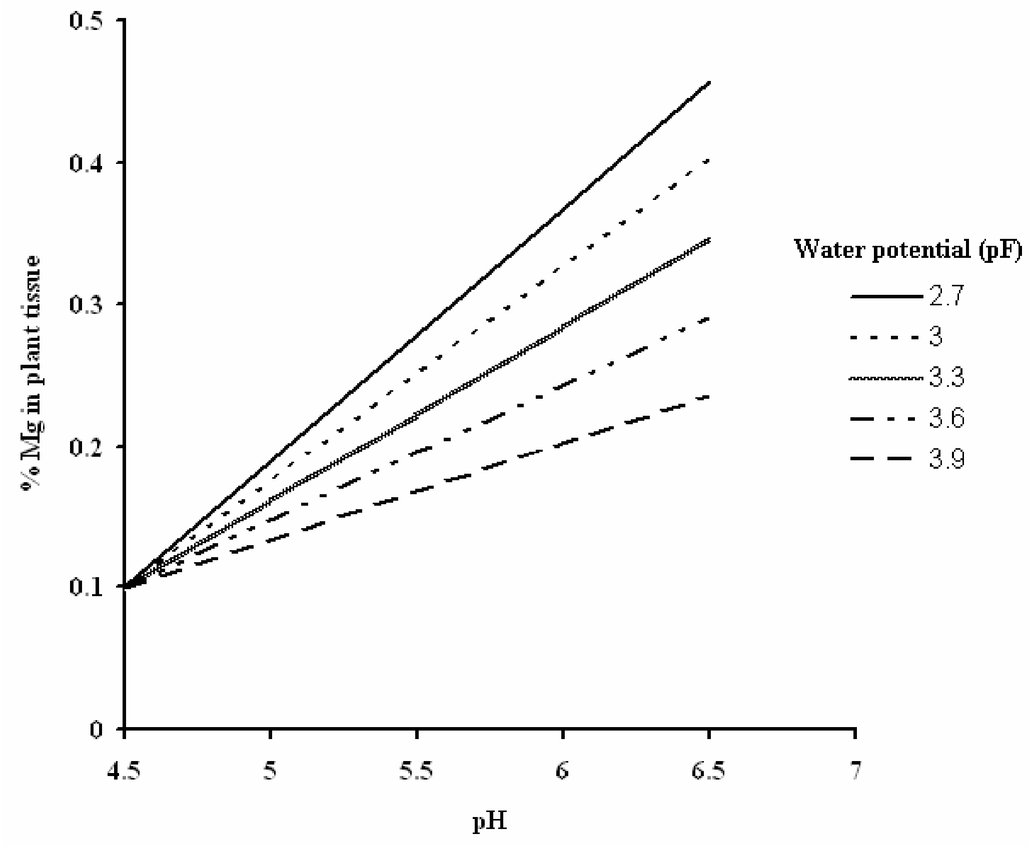

Fig. 4.4.10. Effect of water potential and pH on Mg concentration in tissue

This study showed that soil water potential, pH, and N and P levels need emphasis when designing management practices for low-input production systems using acidic pasture lands in West Virginia. The response yield function determined in this study might be practically useful for grassland farmers in Appalachian region. There is still a need to explore these four factors to reduce common environmental problems of managed pasture lands, such as leaching of applied nitrogen and phosphorus fertilizers which may contaminate ground water and adjacent bodies of surface water.

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# APPENDIX

Table A1. Mean lime requirement (Mg ha$^{-1}$) values by direct calcium hydroxide titration method

| | | Lime requirement (Mg ha$^{-1}$) by direct calcium hydroxide titration | | | |
|---|---|---|---|---|---|
| | | Target pH | | | |
| **Soil** | **Order** | 5.5 | 6.0 | 6.2 | 6.5 |
| 2 | Alfisol | 0.50 | 1.22 | 1.56 | 2.13 |
| 8 | Alfisol | 1.25 | 2.22 | 2.63 | 3.27 |
| 9 | Alfisol | 1.80 | 2.88 | 3.32 | 4.04 |
| 11 | Alfisol | 2.98 | 4.61 | 5.27 | 6.26 |
| 12 | Alfisol | 1.56 | 2.82 | 3.33 | 4.08 |
| 14 | Alfisol | 1.29 | 3.01 | 3.72 | 4.89 |
| 16 | Alfisol | 2.18 | 3.41 | 3.85 | 4.40 |
| 17 | Alfisol | 0.73 | 1.30 | 1.54 | 1.90 |
| 19 | Alfisol | 2.00 | 4.48 | 5.57 | 7.36 |
| 22 | Alfisol | 1.20 | 2.28 | 2.74 | 3.47 |
| 24 | Alfisol | 2.01 | 4.20 | 5.12 | 6.55 |
| 25 | Alfisol | 1.10 | 2.39 | 2.94 | 3.84 |
| 26 | Alfisol | 1.34 | 2.77 | 3.39 | 4.44 |
| 1 | Inceptisol | 1.07 | 1.91 | 2.21 | 2.69 |
| 3 | Inceptisol | 0.96 | 1.92 | 2.30 | 2.88 |
| 4 | Inceptisol | 0.78 | 1.69 | 2.05 | 2.57 |
| 6 | Inceptisol | 1.07 | 2.86 | 3.62 | 4.80 |
| 7 | Inceptisol | 0.69 | 1.53 | 1.89 | 2.52 |
| 10 | Inceptisol | 1.48 | 2.58 | 3.03 | 3.72 |
| 18 | Inceptisol | 0.76 | 1.67 | 2.03 | 2.62 |
| 13 | Ultisol | 0.89 | 1.99 | 2.47 | 3.28 |
| 15 | Ultisol | 1.70 | 2.81 | 3.21 | 3.78 |
| 20 | Ultisol | 0.84 | 1.67 | 1.98 | 2.44 |
| 21 | Ultisol | 2.31 | 3.41 | 3.90 | 4.69 |
| 23 | Ultisol | 1.99 | 2.81 | 3.16 | 3.75 |

Table A2. Mean lime requirement (Mg ha$^{-1}$) values by Shoemaker McLean Pratt buffer (SMP) method

| | **Lime requirement (Mg ha$^{-1}$) by SMP buffer method** | | | |
|---|---|---|---|---|
| | Target pH | | | |
| soil | order | 5.5 | 6.0 | 6.5 |
| 2 | Alfisol | 4.87 | 6.58 | 8.29 |
| 8 | Alfisol | 5.72 | 7.44 | 9.15 |
| 9 | Alfisol | 4.01 | 5.73 | 7.44 |
| 11 | Alfisol | 13.17 | 14.88 | 16.59 |
| 12 | Alfisol | 6.58 | 8.29 | 10 |
| 14 | Alfisol | 4.87 | 6.58 | 8.29 |
| 16 | Alfisol | 3.16 | 4.87 | 6.58 |
| 17 | Alfisol | 2.3 | 4.02 | 5.73 |
| 19 | Alfisol | 10.86 | 12.57 | 14.28 |
| 22 | Alfisol | 2.3 | 4.02 | 5.73 |
| 24 | Alfisol | 11.71 | 13.42 | 15.14 |
| 25 | Alfisol | 4.27 | 5.98 | 7.69 |
| 26 | Alfisol | 5.72 | 7.44 | 9.15 |
| 1 | Inceptisol | 4.01 | 5.73 | 7.44 |
| 3 | Inceptisol | 4.01 | 5.73 | 7.44 |
| 4 | Inceptisol | 4.01 | 5.73 | 7.44 |
| 6 | Inceptisol | 4.87 | 6.58 | 8.29 |
| 7 | Inceptisol | 4.87 | 6.58 | 8.29 |
| 10 | Inceptisol | 7.44 | 9.15 | 10.86 |
| 18 | Inceptisol | 4.01 | 5.73 | 7.44 |
| 13 | Ultisol | 3.16 | 4.87 | 6.58 |
| 15 | Ultisol | 6.41 | 9.12 | 9.83 |
| 20 | Ultisol | 4.01 | 5.73 | 7.44 |
| 21 | Ultisol | 10.43 | 12.14 | 13.85 |
| 23 | Ultisol | 4.01 | 5.73 | 7.44 |

Table A3. Mean lime requirement (Mg ha$^{-1}$) values by Adam Evans buffer (AEB) method

| | **Lime requirement (Mg ha$^{-1}$) by AE buffer method** | | | |
|---|---|---|---|---|
| | | Target pH | | |
| soil | order | 5.5 | 6.0 | 6.5 |
| 2 | Alfisol | 2.3 | 4.77 | 7.24 |
| 8 | Alfisol | 4.31 | 6.78 | 9.24 |
| 9 | Alfisol | 1.95 | 4.42 | 6.88 |
| 11 | Alfisol | 8.97 | 11.44 | 13.9 |
| 12 | Alfisol | 2.88 | 5.35 | 7.82 |
| 14 | Alfisol | 1.93 | 4.4 | 6.87 |
| 16 | Alfisol | 1.37 | 3.83 | 6.3 |
| 17 | Alfisol | 0.4 | 2.87 | 5.34 |
| 19 | Alfisol | 3.51 | 5.98 | 8.45 |
| 22 | Alfisol | 0.22 | 2.68 | 5.15 |
| 24 | Alfisol | 3.76 | 6.22 | 8.69 |
| 25 | Alfisol | 3.37 | 5.84 | 8.31 |
| 26 | Alfisol | 1 | 3.47 | 5.93 |
| 1 | Inceptisol | 1.03 | 3.5 | 5.96 |
| 3 | Inceptisol | 1.18 | 3.65 | 6.12 |
| 4 | Inceptisol | 0.87 | 3.34 | 5.81 |
| 6 | Inceptisol | 1.99 | 4.46 | 6.93 |
| 7 | Inceptisol | 2.05 | 4.52 | 6.99 |
| 10 | Inceptisol | 4.4 | 6.87 | 9.34 |
| 18 | Inceptisol | 0.6 | 3.07 | 5.54 |
| 13 | Ultisol | 0.87 | 3.34 | 5.81 |
| 15 | Ultisol | 3.3 | 5.77 | 8.24 |
| 20 | Ultisol | 2.21 | 4.68 | 7.14 |
| 21 | Ultisol | 6.17 | 8.64 | 11.11 |
| 23 | Ultisol | 2.65 | 5.12 | 7.59 |

Table A4. Mean lime requirement (Mg ha$^{-1}$) values by Mehlich single buffer (MB) method

| | **Lime requirement (Mg ha$^{-1}$) by Mehlich buffer method** | | | |
|---|---|---|---|---|
| | | | Target pH | |
| soil | order | 5.5 | 6.0 | 6.5 |
| 2 | Alfisol | 2.53 | 4.68 | 4.85 |
| 8 | Alfisol | 3.16 | 5.66 | 5.97 |
| 9 | Alfisol | 2.53 | 4.68 | 4.85 |
| 11 | Alfisol | 7.61 | 12.21 | 13.37 |
| 12 | Alfisol | 3.16 | 5.66 | 5.97 |
| 14 | Alfisol | 2.53 | 4.68 | 4.85 |
| 16 | Alfisol | 1.94 | 3.73 | 3.77 |
| 17 | Alfisol | 4.51 | 2.82 | 2.71 |
| 19 | Alfisol | 2.53 | 7.71 | 8.31 |
| 22 | Alfisol | 1.37 | 4.68 | 4.85 |
| 24 | Alfisol | 4.51 | 7.71 | 8.31 |
| 25 | Alfisol | 3.16 | 5.66 | 5.97 |
| 26 | Alfisol | 2.53 | 4.68 | 4.85 |
| 1 | Inceptisol | 2.53 | 4.68 | 4.85 |
| 3 | Inceptisol | 3.16 | 5.66 | 5.97 |
| 4 | Inceptisol | 2.53 | 4.68 | 4.85 |
| 6 | Inceptisol | 3.82 | 6.67 | 7.12 |
| 7 | Inceptisol | 2.53 | 4.68 | 4.85 |
| 10 | Inceptisol | 4.51 | 7.71 | 8.31 |
| 18 | Inceptisol | 2.53 | 4.68 | 4.85 |
| 13 | Ultisol | 2.53 | 4.68 | 4.85 |
| 15 | Ultisol | 3.16 | 5.66 | 5.97 |
| 20 | Ultisol | 1.94 | 3.73 | 3.77 |
| 21 | Ultisol | 6.79 | 11.04 | 12.05 |
| 23 | Ultisol | 3.16 | 5.66 | 5.97 |

Table.A5. Experimental design used for bluegrass (alone) and bluegrass and white clover mixed cropping system

| **Treatment No.** | **Water potential (pF)** | **pH** | **N (mg kg$^{-1}$)** | **P (mg kg$^{-1}$)** |
|---|---|---|---|---|
| 1 | 3.91 | 5 | 10 | 10 |
| 2 | 3.91 | 6 | 10 | 10 |
| 3 | 3.91 | 5.5 | 100 | 20 |
| 4 | 3.91 | 4.5 | 25 | 20 |
| 5 | 3.91 | 5.5 | 25 | 80 |
| 6 | 3.91 | 5 | 50 | 10 |
| 7 | 3.91 | 6 | 10 | 40 |
| 8 | 3.91 | 5.5 | 25 | 20 |
| 9 | 3.91 | 5 | 10 | 40 |
| 10 | 3.91 | 6.5 | 25 | 20 |
| 11 | 3.91 | 5.5 | 25 | 20 |
| 12 | 3.91 | 5 | 50 | 40 |
| 13 | 3.91 | 5.5 | 25 | 0 |
| 14 | 3.91 | 6 | 50 | 10 |
| 15 | 3.91 | 5.5 | 0 | 20 |
| 16 | 3.91 | 6 | 50 | 40 |
| 17 | 2.7 | 5 | 10 | 10 |
| 18 | 2.7 | 6 | 10 | 10 |
| 19 | 2.7 | 5.5 | 100 | 20 |
| 20 | 2.7 | 4.5 | 25 | 20 |
| 21 | 2.7 | 5.5 | 25 | 80 |
| 22 | 2.7 | 5 | 50 | 10 |
| 23 | 2.7 | 6 | 10 | 40 |
| 24 | 2.7 | 5.5 | 25 | 20 |
| 25 | 2.7 | 5 | 10 | 40 |
| 26 | 2.7 | 6.5 | 25 | 20 |
| 27 | 2.7 | 5.5 | 25 | 20 |
| 28 | 2.7 | 5 | 50 | 40 |
| 29 | 2.7 | 5.5 | 25 | 0 |
| 30 | 2.7 | 6 | 50 | 10 |
| 31 | 2.7 | 5.5 | 0 | 20 |
| 32 | 2.7 | 6 | 50 | 40 |

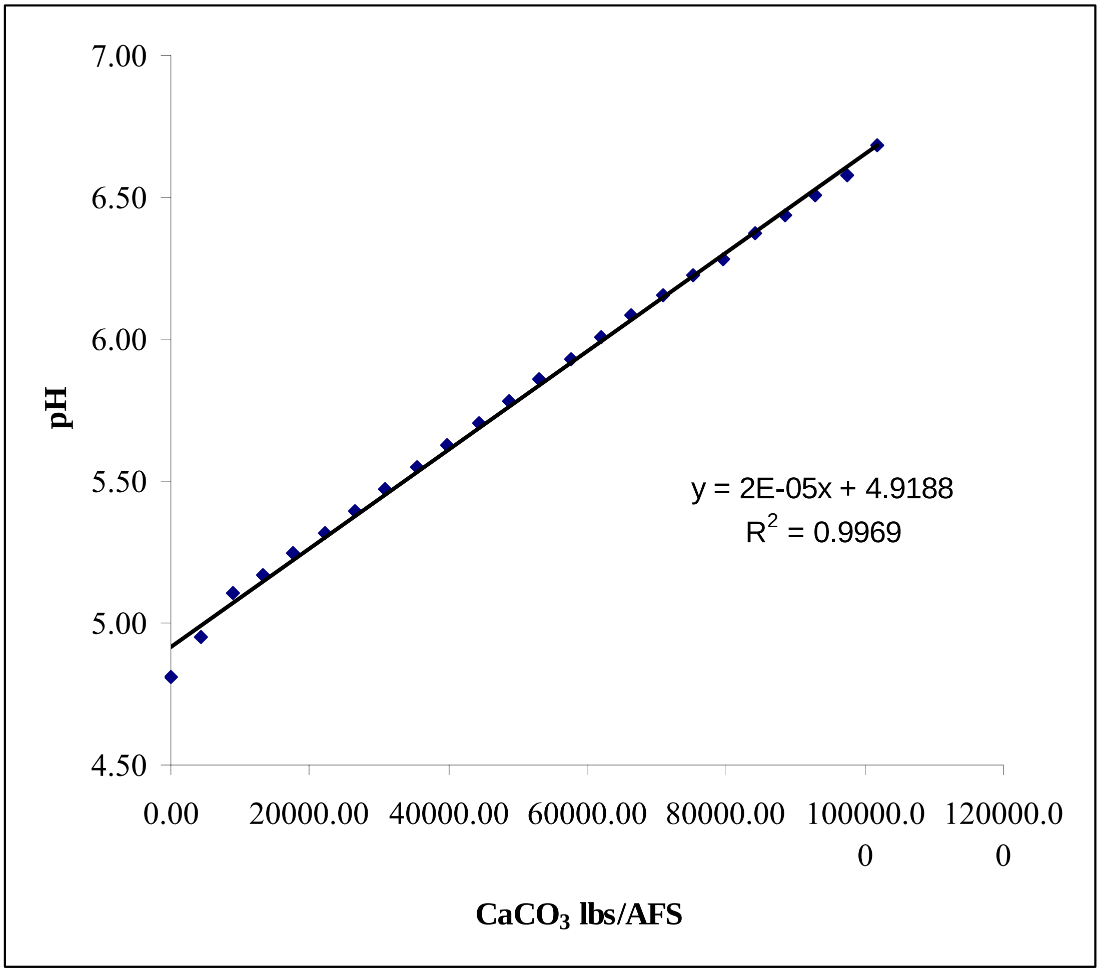

Fig A1. Lime response curve of green house soil

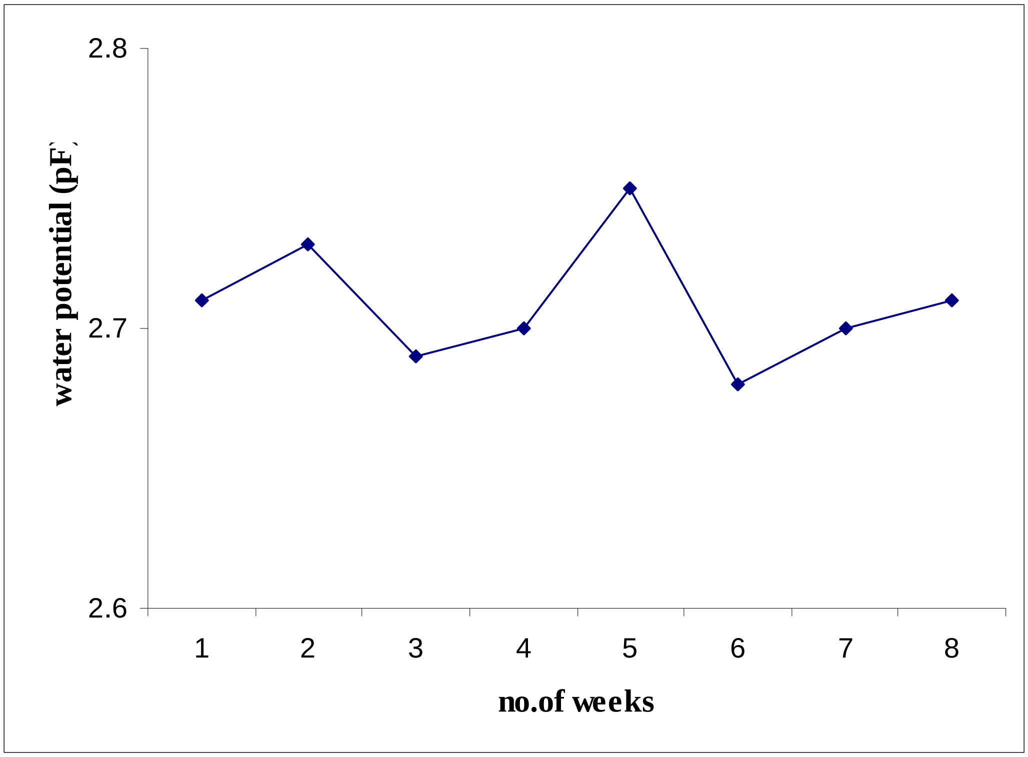

Fig A2. Moisture pattern in high water potential treatment plants

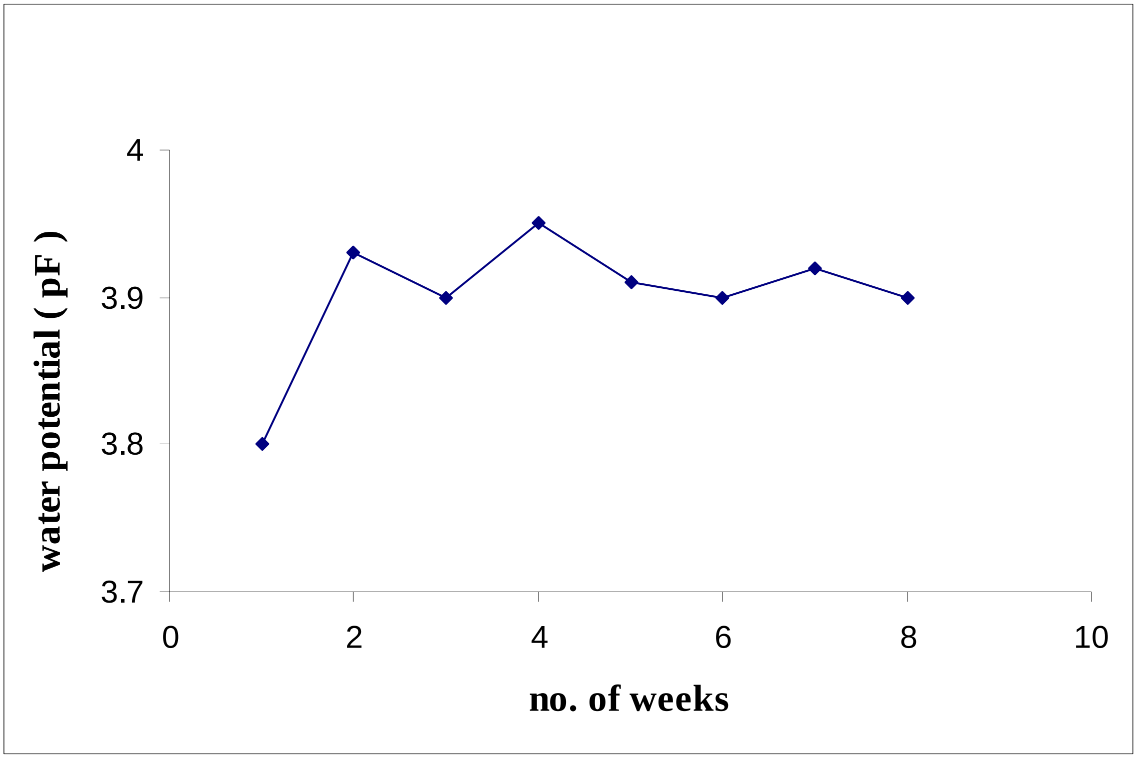

Fig A3. Moisture pattern in low water potential treatment plants