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Influence of elemental sulfur, micronutrients, phosphorus, calcium, magnesium and potassium on growth of *Prosopis alba* on high pH soils in Argentina

M. Velarde[a], P. Felker[a,b,*], D. Gardiner[c]

[a]*Universidad Católica de Santiago del Estero, Santiago del Estero, Argentina*
[b]*INSIBIO, Universidad Nacional de Tucuman, Tucuman, Argentina*
[c]*Department of Agronomy and Resource Sciences, Texas A&M University-Kingsville, Kingsville, TX 78363, USA*

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Abstract

A field trial on 3-year-old *Prosopis alba* growing on pH 8.5 soils in Argentina was conducted to identify mineral nutrients that were most limiting growth and to determine correlations among these nutrients. As applications of nutrients such as Zn, Cu and P would be soon rendered unavailable due to the high pH, combinations of elemental S to decrease the pH were examined along with macro and micronutrient soil additions. Thirty trees were selected with stem diameters ranging from 2.8 to 4.5 cm and divided into five treatments in a completely randomized design with 1 tree per replicate. The treatments were: (1) control, (2) addition of elemental S to lower the pH, (3) addition of S and triple superphosphate (P), (4) addition of S, P and a complete blend of micronutrients and (5) addition of S, P, micronutrients and K and Mg. Biomass increases were estimated using regression equations on stem diameter increases. A small non-significant decrease in pH of about 0.3 pH was obtained in the treatments with S, except for treatment which contained micronutrients in the form of strong base oxides. There was a significant increase in electrical conductivity due to the oxidation of the S. The best treatment containing S, P and micronutrients had a 42% increase significant biomass increase over the control. Growth was positively correlated with leaf levels (decreasing order of

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*Corresponding author. D'Arrigo Bros, P.O. Box 850, Salinas, CA 93902, USA. Tel.: +1 831 235 2847.
E-mail address: Peter_Felker@hotmail.com (P. Felker).

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significance) of K, S, P, and Zn and negatively correlated with leaf Na and Ca. The leaf K, which had the highest positive correlation with growth, was highly significantly positively correlated with leaf S, P, N, and Zn and highly significantly but negatively correlated with leaf Ca, Mg and Mn. Leaf N was very highly correlated with leaf Zn, S and P concentrations. Indian workers have found that 20 years after establishment *Prosopis juliflora* changed the soil pH from 10.4 to 8.0. Since trees on 10 m × 10 m spacings are suggested to be ultimate climax density for these ecosystems, apparently it will only necessary to add inexpensive small quantities of elemental S, Zn and K directly around 100 small trees ha^{-1} to effect a major soil reclamation over the entire ha.

Keywords: Agroforestry; Alkali; Nitrogen fixation; Reclamation; Sodic

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1. Introduction

The nitrogen fixing trees of the genus *Prosopis* are native or have been naturalized to virtually all of the semi-arid regions of the world (Pasiecznik et al., 2001). While some species have been regarded as a weed due to their "invasive" nature, other species have been highly regarded for fine quality timber, pods for livestock and human food, production of charcoal and firewood and enrichment of soil by nitrogen fixation (Geesing et al., 2000).

Prosopis is a very adaptable species being able to grow in salinities close to seawater (Velarde et al., 2003), in Death Valley California with daily maximum summer temperatures of 45 °C (Mooney, 1977) and on soils in India with soils of pH 9.0 (Singh et al., 1988). In the subtropical center of *Prosopis* biodiversity in Argentina, the most economically useful species *Prosopis alba*, often grows on soils with pH values up to 9.0.

High pH soils, that are often the result of mismanagement are common in the world's arid regions. In Argentina the saline/sodic soils have been estimated to occupy 800,000 ha (Ragonese, 1951) and in India about 2.5 million ha (Singh et al., 1989a). While the Argentine sodic soils have been much less well characterized than the Indian soils, to our knowledge there are no reports of sodic soils in Argentina with the extremes of pH (10.4) and sodicity (99% exchangeable sodium percentage) as reported for India. The Argentine partially reclaimed soils where these experiments were conducted were substantially less sodic and almost non-saline in comparison to the Indian soils without reclamation.

The research initiative lead by the Central Soil Salinity Research Institute in Karnal, India (Grewal and Abrol, 1986; Singh et al., 1988; Singh et al., 1989a, b; Singh, 1995; Bhojvaid et al., 1996) have been world leaders in using combinations of trees and grasses to reclaim these high pH soils. *Prosopis juliflora* was able to grow satisfactorily without amendments up to pH 9.0, but these authors found that when the soil pH was 10.4 it was necessary to plant the trees in auger holes with amendments of 3 kg gypsum and 8 kg of farmyard manure per hole (Singh, 1996). Twenty years after such treatments the initial soil pH of 10.4 decreased to 9.18 under

Eucalyptus tereticornis, 9.03 under *Acacia nilotica*, 8.67 under *Albizia lebbek* , 8.15 under *Terminalia arjuna* and 8.03 under *P. juliflora*. This group also found that zinc was a limiting factor to growth of wheat and rice under these high pH soils (Singh, 1985)

Research on soil treatments to improve tree growth for reclamation of sodic soils has focused on long-term effects of soil amendments on tree growth and soil chemical properties. In contrast our approach was to seek more detailed information on which nutrients were responsible for growth, which might be antagonistic to other nutrients and which had a high likelihood of being involved with interactions with other nutrients. To accomplish this we conducted regressions of the growth per tree against all nutrients measured and then examined correlation matrices between all nutrients and growth.

If *Prosopis* seedlings can be established, ultimately the litter fall from the trees will change the soil pH without costly massive amendments of gypsum, manure, etc. Thus we wished to determine which nutrients were most limiting growth of *Prosopis* in high pH soils and to examine low application rates of selected amendments in banded applications near the trees to maximize the benefit/cost ratio. Trace elements such as Fe, Mn, Zn and Cu and the very important macronutrient for leguminous plants, phosphorus, have limited availability with pH values above 8. According to the classic work of Lucas and Davis (1961) the availability of 12 nutrients was highest in the pH 6.5–7.0 range. While these nutrients could be added to the soil, they would be rapidly converted into insoluble unavailable forms at pH values greater than 8. However addition of elemental sulfur, which is oxidized by soil bacteria to sulfuric acid, causes a permanent change in the pH and should make micronutrients and phosphorus more available thus leading to more rapid growth. Our objective was not apply S to correct S deficiencies but rather to use S as an inexpensive way to lower the pH. S has the advantage over phosphoric acid as acidifying agent in that if increased growth occurred with phosphoric acid, one would not know if it was because of lowered pH or increased soil P concentrations.

In a greenhouse experiment in which soil pH was increased from 6.0 to 9.0 through calcium hydroxide additions, with and without phosphorus and a complete blend of micronutrient additions, biomass at the highest pH was strongly dependent on micronutrient amendments (Cline et al., 1986). Furthermore the blend of all micronutrient additions to the soil was most associated with increased zinc concentrations in the leaves (from 13 to 29 $\mathrm{mg\,kg^{-1}}$) and a decrease in the leaf sodium level (from 19,000 to 4600 $\mathrm{mg\,kg^{-1}}$). Thus these authors hypothesized that zinc was one of the more important limiting micronutrients and that this nutrient was somehow related to an active sodium exclusion mechanism.

This experiment was conducted to measure the influence of elemental sulfur, micronutrients, phosphorus and the cations calcium, magnesium and potassium on the growth and leaf nutrient concentrations of 3-year-old *P. alba* trees on a high pH soil. Further, with use of regression analyses we wished to determine which of the leaf nutrients were most correlated with increased growth.

2. Materials and methods

The experiment was conducted on a 3-year-old *P. alba* plantation, established by H. Ochoa, located 80 km south of the capital city of Santiago del Estero, Province of Santiago del Estero, Argentina on the fringes of an extensive salt flat with a 0–1% slope drained by the River "Rio Saladillo". The natraqualf alluvial, silty clay soils had low permeability. To overcome the high initial salinity in this area, earth-moving equipment was used to create water catchment basins in which runoff water was used to leach the soils (Ochoa et al., 1977). Before the earth treatments were conducted, the electrical conductivity and exchangeable sodium percentage (ESP) were; 61 $dS\,m^{-1}$ and 47% for the 0–30 cm depth, 59 $dS\,m^{-1}$ and 46% for the 30–60 cm depth and 56 $dS\,m^{-1}$ and 46% for the 60–90 cm depth(Ochoa, L. pers. comm.). There was permanent ground-water at the 2.2–2.4 m depth. After the leaching had taken place (entirely from rainfall—no irrigation was provided), alfalfa was grown in the bottom of the basins and *P. alba* trees were planted on the sides of the ridges on a $2\,m \times 5\,m$ spacing. Three years after the catchment basins were created, at the initiation of this experiment, the soils were only slightly saline (ca 3.8 $dS\,m^{-1}$) although they were quite alkaline (pH 8.0–8.5).

A completely randomized design was used with single tree replicates for the following treatments: (1) control, (2) addition of elemental S to lower the pH, (3) addition of S and triple superphosphate (P), (4) addition of S, P and a complete blend of micronutrients and (5) addition of S, P, micros and K and Mg. At the initiation of this experiment, 30 trees were selected from this planting that had diameters in the 2.8–4.5 cm range. Due to unavailability of trees of this diameter size class, the number of trees per treatment were 6 for the control, 5 for the S only treatment, 6 for the P+S treatment, 8 for the S+P+ micros treatment and 5 for treatment with S+P+micros+K+Mg. The tree spacing was $2 \times 8\,m$ for 625 trees ha^{-1}. Since the canopies were less than 1.5 m in radius and since the fertilizer applications were made in band applications within a 1 m radius of the trees, there was little likelihood of either aerial or root competition.

The S treatment was 200 g per tree since the titration of the soils from the initial pH of about 8.5 (depending on the particular tree) to 6.5 indicated this amount of elemental sulfur would be required to make this pH change for a 1.0 m radius to a depth of 20 cm. The other macronutrients were used a rate of 50 $kg\,ha^{-1}$ of actual element which for 625 plants ha^{-1} was 80 $g\,tree^{-1}$. P was supplied as triple superphosphate, K as K_2SO_4 and Mg as $MgSO_4$. Calcium was not added separately as it was present in the triple superphosphate. The micronutrients were supplied in a commercial formulation of Nutrimix 2 designed for fertigation which contained; FeO-10%, MnO-5%, ZnO-0.9%, CuO-0.5%, B-0.035% and Mo-0.035% and 40 g plant $^{-1}$ of this formulation was superficially incorporated into the soil

After the trees were selected, the biomass of competing herbaceous vegetation was removed within a 1.5 m radius and the herbicide diuron applied at a rate of 1.5 $kg\,ha^{-1}$ with a backpack sprayer. The location of the diameter measurement was painted on the trunk. Biomass estimations were made using the previously described regression equation. The basal diameter measurements were used to estimate biomass per tree with previously described regression equations (Felker et al., 1989), for 192 *P. alba* trees with a 7.7 cm mean diameter and a 2.1–16.4 cm diameter range):

$$\log_{10} \text{biomass(kg.)} = 2.7027 \log_{10} \text{diameter basal(cm)} - 1.1085.$$

Three soil samples of 30 cm depth were taken at 120° angles from each tree, pooled and analysed. The electrical conductivity was measured on the saturation paste extract and the pH was measured on a 1–2.5 dilution of the soil with distilled water (Richards, 1954).

For foliar analyses, the youngest fully expanded leaves were collected, briefly dipped in distilled water to remove aerial deposited contaminants, ground in a Wiley mill with stainless steel knives and sent to A&L Labs in Lubbock, Texas for analyses.

A Pearson correlation matrix was constructed for all the variables of the 30 trees using SPSS. The most important variables that were significantly correlated (using a one tailed *t*-test) were presented in graphic form using the estimated regression.

3. Results

The effects of the various soil treatments on the soil pH are shown in Fig. 1. While none of the before and after treatments were significantly different at the 5% probability level, they were close to being significant at this level. In contrast to the

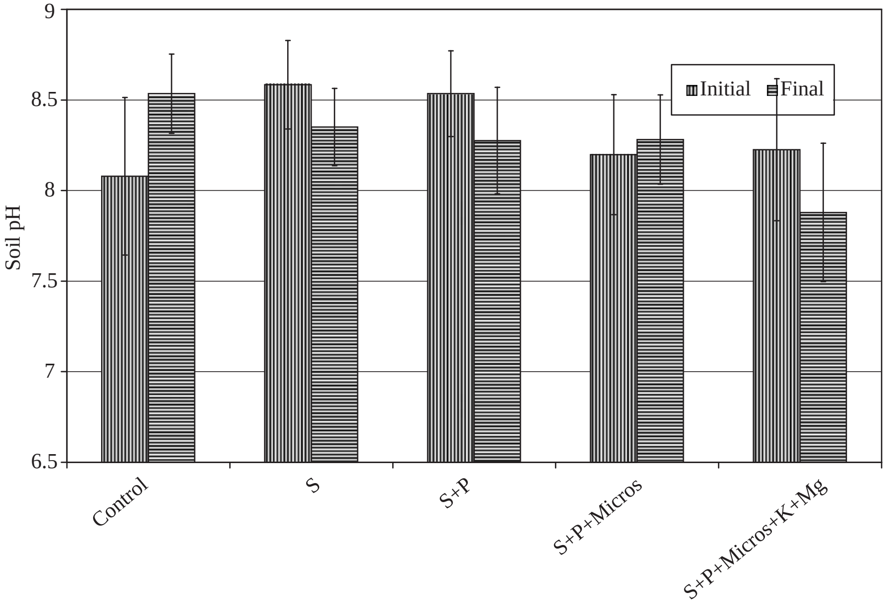

Fig. 1. Influence of the soil amendments elemental sulfur (S), sulfur + triple superphosphate(S + P), sulfur + triple superphosphate + miconutrient blend (S + P + Micros) and sulfur + triple superphosphate + micronutrients + potassium and magnesium sulfate (S + P + Micros + K + Mg) on the soil pH before and after treatment. The bars represnt 95% confidence intervals.

control treatment that showed a 0.4 increase in pH, three of the treatments that contained S had a modest 0.3 unit decrease in pH. As the micronutrients were present in the form of oxides, some of which are strong bases, it is not surprising that the micronutrient addition increased the soil pH.

As shown in Fig. 2, all of the treatments were associated with an increase in the electrical conductivity and in the majority of the cases, these differences were significant at the 5% probability level. We suspect this increase in EC was partially due to the clearing of the grassy type vegetation which may have lead to a capillary rise in salts (and thus pH in the case of the control) and also the transformation of the elemental S into various sulfates and dissolution of various carbonates. Slaton et al. (2001) who examined the kinetics of oxidation of commercial elemental S products on alkaline soils in Arkansas also found an increase in electrical conductivity that they attributed to the oxidation products of the elemental S.

The response in growth of the various treatments in Fig. 3 shows that the S treatment, and the S + P + complete micronutrient mix were significantly different than the control. There was a tendency for the treatment that included P and Ca (in the form of superphosphate) to produce less biomass than the treatment without P

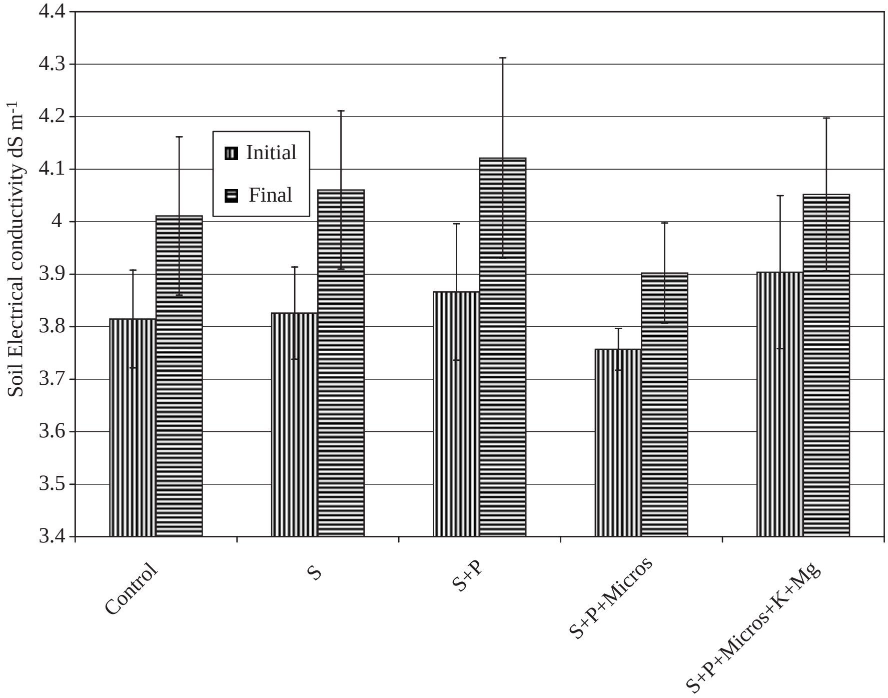

Fig. 2. Influence of the soil amendments elemental sulfur (S), sulfur + triple superphosphate(S + P), sulfur + triple superphosphate + miconutrient blend (S + P + Micros) and sulfur + triple superphosphate + micronutrients + potassium and magnesium sulfate (S + P + Micros + K + Mg) on the soil electrical conductivity before and after treatment. The bars represnt 95% confidence intervals.

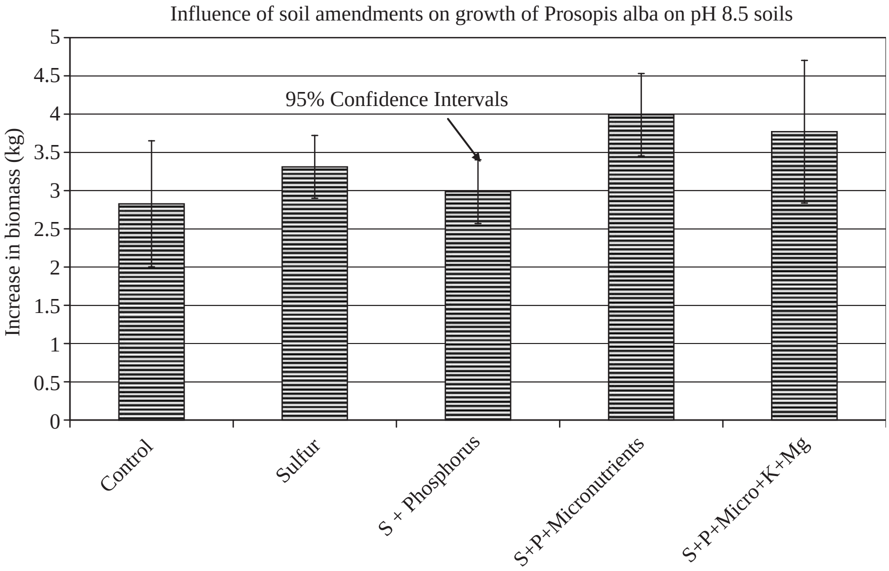

Fig. 3. Influence of the soil amendments elemental sulfur (S), sulfur + triple superphosphate(S + P), sulfur + triple superphosphate + miconutrient blend (S + P + Micros) and sulfur + triple superphosphate + micronutrients + potassium and magnesium sulfate (S + P + Micros + K + Mg) on the increase in biomass of *Prosopis alba* trees. The bars represnt 95% confidence intervals.

and Ca. The treatment that contained K and Mg in addition to the S, P, Ca and micronutrients produced less biomass than the corresponding treatment without these elements, but the difference was not significant. The best treatment, the S + P + micronutrients, treatment had a 42% increase in biomass production over the control.

The correlation matrix in Table 1 provides an overview of the possible correlations between soil pH, growth and the various leaf nutrients. Growth was positively correlated with leaf levels (decreasing order of significance) of K, S, P, and Zn and negatively correlated with leaf Na and Ca. The leaf K, which had the highest positive correlation with growth, was highly significantly correlated with leaf S, P, N, and Zn and highly significantly but negatively correlated with leaf Ca, Mg and Mn.

The highly significant regression between growth and leaf K presented in Fig. 4 would indicate that leaf K levels of less than 1% are probably deficient and that fertilization programs should try to achieve leaf K levels of about 1.5%. The negative regressions between growth and leaf Na and Ca presented in Figs. 5 and 6 suggest that leaf Na and Ca levels above 0.04% and 0.8%, respectively are probably indicative of reduced *Prosopis* growth due to excessive quantities of these minerals. Evidently in this soil, the K was limiting growth and the addition of competing cations such as Ca, Mg, and Mn outcompeted the K for the uptake sites by the plant. This is borne out by the highly significant negative regression between leaf K and leaf Ca as illustrated in Fig. 7.

Table 1
Pearson correlation coefficients and level of significance (*P*-value) for correlations between *Prosopis alba* leaf nutrient concentrations, growth and soil pH on high pH soils in Argentina

	Growth	Ca	Na	Al	B	Cu	Fe	K	Mg	Mn	N	P	pH	S
Growth														
Ca	−0.335* *P*(0.035)													
Na	−0.409* *P*(0.012)	0.112 *P*(0.278)												
Al	0.097 *P*(0.306)	0.095 *P*(0.309)	0.325* *P*(0.040)											
B	−0.233 *P*(0.108)	0.395* *P*(0.015)	−0.346* *P*(0.031)	−0.256 *P*(0.086)										
Cu	0.228 *P*(0.113)	0.176 *P*(0.176)	−0.289 *P*(0.061)	0.233 *P*(0.107)	0.058 *P*(0.381)									
Fe	0.063 *P*(0.370)	0.047 *P*(0.402)	0.442** *P*(0.007)	0.910** *P*(0.000)	−0.388* *P*(0.017)	0.081 *P*(0.335)								
K	0.445** *P*(0.007)	−0.899** *P*(0.000)	−0.112 *P*(0.278)	−0.028 *P*(0.442)	−0.485** *P*(0.003)	−0.163 *P*(0.195)	0.017 *P*(0.465)							
Mg	−0.294 *P*(0.057)	0.738** *P*(0.000)	0.205 *P*(0.139)	0.030 *P*(0.438)	0.417* *P*(0.011)	0.121 *P*(0.262)	0.029 *P*(0.440)	−0.763** *P*(0.000)						
Mn	−0.288 *P*(0.061)	0.816** *P*(0.000)	−0.046 *P*(0.404)	−0.076 *P*(0.344)	0.398* *P*(0.015)	0.200 *P*(0.144)	−0.113 *P*(0.277)	−0.787** *P*(0.000)	0.673** *P*(0.000)					
N	0.267 *P*(0.077)	−0.758** *P*(0.000)	−0.114 *P*(0.274)	−0.084 *P*(0.330)	−0.340* *P*(0.033)	−0.077 *P*(0.343)	0.021 *P*(0.456)	0.681** *P*(0.000)	−0.638** *P*(0.000)	−0.634** *P*(0.000)				
P	0.332* *P*(0.036)	−0.838** *P*(0.000)	−0.014 *P*(0.471)	−0.065 *P*(0.366)	−0.447** *P*(0.007)	−0.148 *P*(0.218)	0.035 *P*(0.427)	0.806** *P*(0.000)	−0.676** *P*(0.000)	−0.791** *P*(0.000)	0.867** *P*(0.000)			
pH	−0.195 *P*(0.150)	−0.118 *P*(0.268)	−0.003 *P*(0.494)	−0.041 *P*(0.415)	−0.389* *P*(0.017)	0.170 *P*(0.184)	−0.008 *P*(0.483)	0.075 *P*(0.347)	−0.173 *P*(0.180)	−0.085 *P*(0.327)	0.155 *P*(0.206)	0.239 *P*(0.102)		
S	0.309* *P*(0.048)	−0.825** *P*(0.000)	−0.025 *P*(0.447)	−0.027 *P*(0.443)	−0.489** *P*(0.003)	−0.137 *P*(0.234)	−0.014 *P*(0.471)	0.779** *P*(0.000)	−0.678** *P*(0.000)	−0.774** *P*(0.000)	0.735** *P*(0.000)	0.877** *P*(0.000)	0.312* *P*(0.047)	
Zn	0.268 *P*(0.076)	−0.691** *P*(0.000)	−0.124 *P*(0.258)	−0.063 *P*(0.371)	−0.384* *P*(0.018)	−0.062 *P*(0.373)	0.058 *P*(0.380)	0.697** *P*(0.000)	−0.488** *P*(0.003)	−0.586** *P*(0.000)	0.684** *P*(0.000)	0.746** *P*(0.000)	0.132 *P*(0.243)	0.663** *P*(0.000)

*Correlation is significant at the 0.005 level (1-tailed).

**Correlation is significant at the 0.001 level (1-tailed).

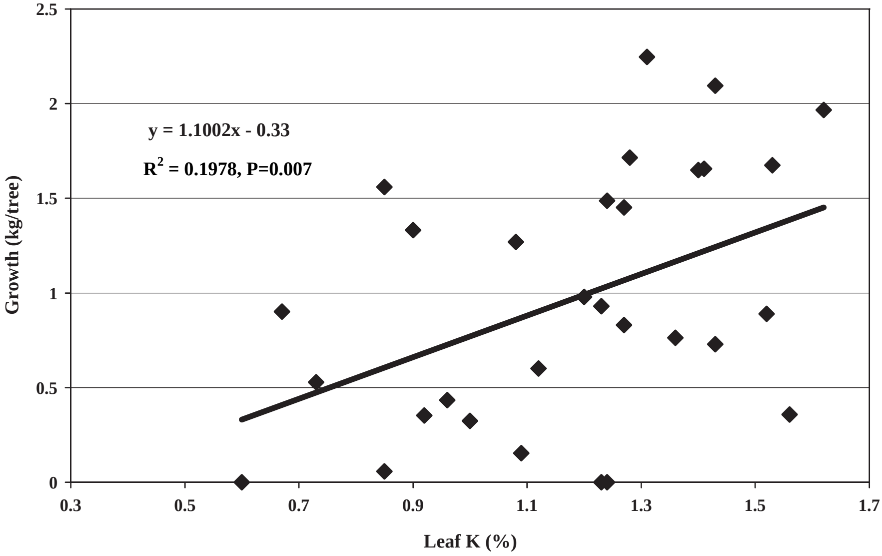

Fig. 4. The relationship between leaf K after treatment and the growth of all 30 *Prosopis alba* trees growing on alkaline soils.

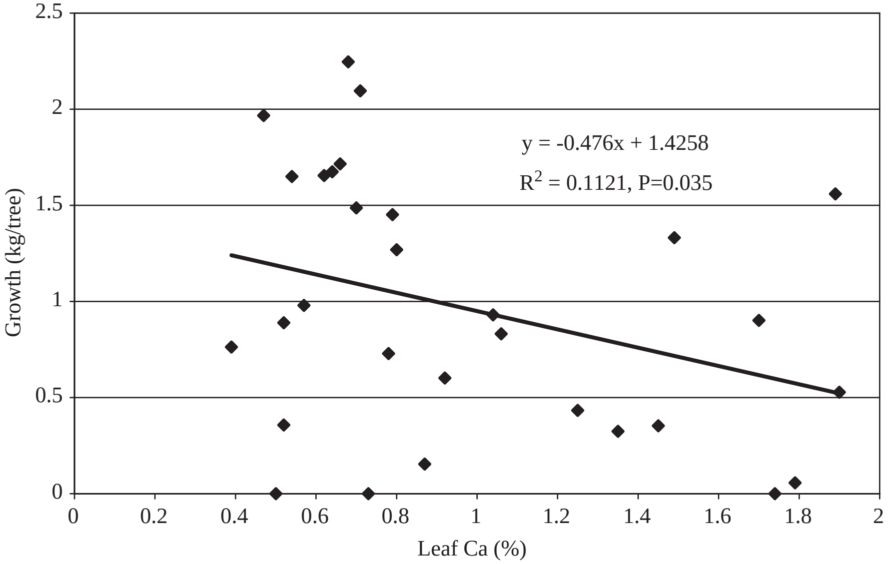

Fig. 5. The relationship between leaf Ca after treatment and the growth of all 30 *Prosopis alba* trees growing on alkaline soils.

The highly significant relationship between leaf N and P confirms previous reports of the significance of this relationship (Cline et al., 1986) in which leaf P values of about 0.3% were associated with an optimum leaf N concentration of about 4.5%.

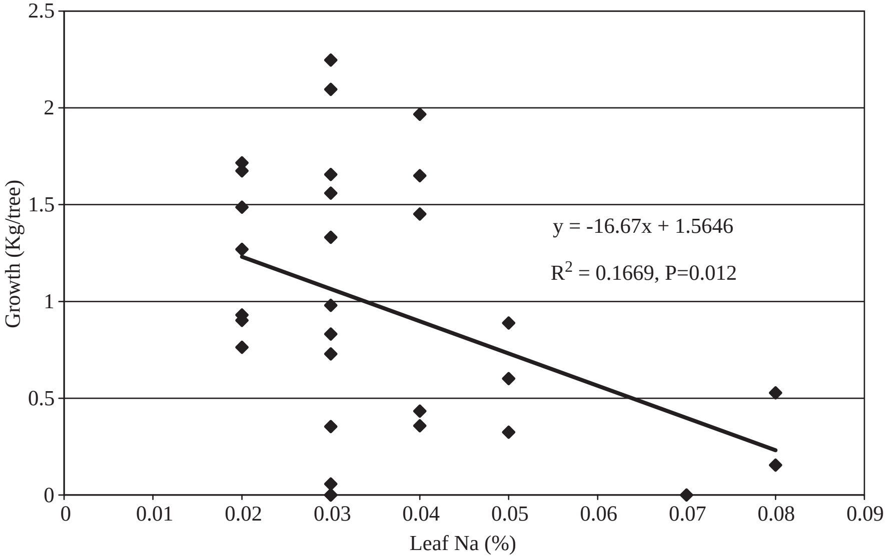

Fig. 6. The relationship between leaf Na after treatment and the growth of all 30 *Prosopis alba* trees growing on alkaline soils.

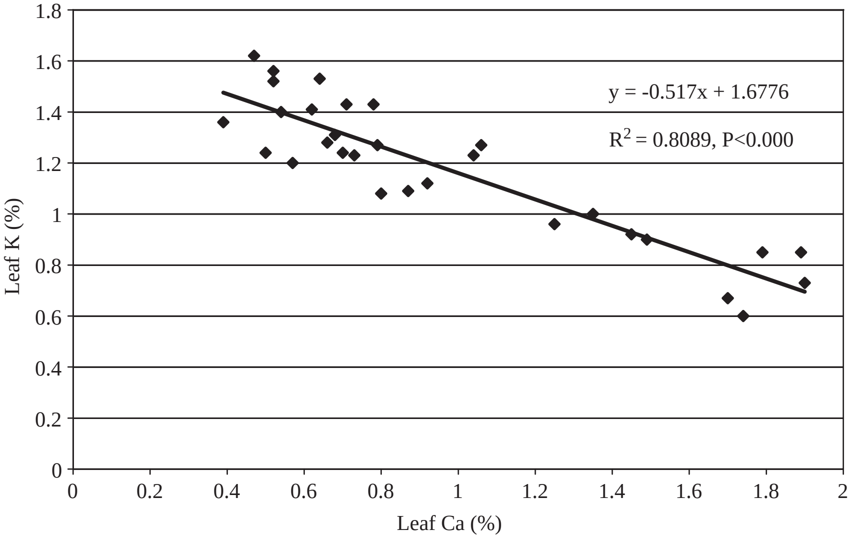

Fig. 7. The relationship between leaf K and leaf Ca of all 30 *Prosopis alba* trees growing on alkaline soils.

The highly significant relationship between leaf S and leaf N in Fig. 8 would suggest that leaf S levels about 0.2% are in the deficit range and that one should attempt to manage the nutrient relations to obtain leaf S concentrations of about 0.3%. Similarly the highly significant relationship between leaf N and leaf Zn presented in

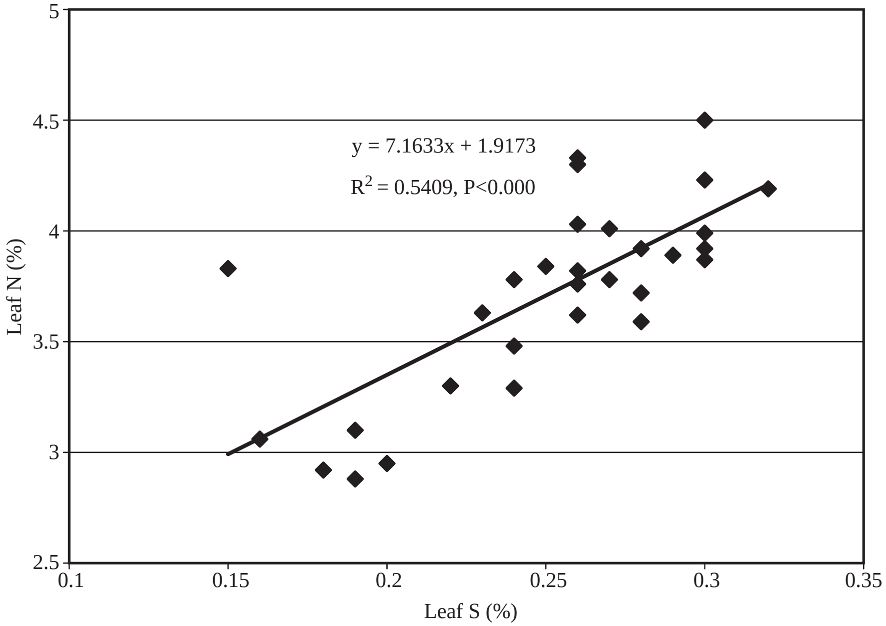

Fig. 8. The relationship between leaf N and leaf S of all 30 *Prosopis alba* trees growing on alkaline soils.

Fig. 9 would suggest that leaf Zn levels of about 10 mg kg^{-1} are in the deficit range and that the goal should be to obtain leaf levels of about 30 mg kg^{-1}. Although growth was not significantly correlated with the total leaf N content, perhaps the fact that correlation coefficients between both leaf S and leaf Zn vs. leaf N were much higher for protein than growth, was attributable to stimulation of production of a group of proteins responsible for alleviation of high pH stress.

4. Discussion

In spite of the fact that our titrations of the soil from pH 8.5 to 6.0 indicated that 200 g of S would make this pH change, we only observed pH decreases of about 0.3 pH units, albeit this addition did stimulate a growth increase. For the 1 m radius around the plant this would have been a 637 kg ha^{-1} application. In a comparison of various commercial formulations of elemental S on pH 8.3 soils in Arkansas, Slaton et al. (2001) found very great differences on their efficiency in decreasing the pH. These authors found the S oxidation rate was independent of the S concentration and suggested the differences in oxidation were primarily due to the S particle size (unit area). The formulation with the smallest particle size was 60% oxidized in 10 days and a 500 kg ha^{-1} application rate changed the soil pH from 8.3 to 7.5. In contrast, the formulations with particle sizes greater than 0.84 mm diameter had less than 10% oxidization in 90 days. In addition to utility of elemental S in decreasing

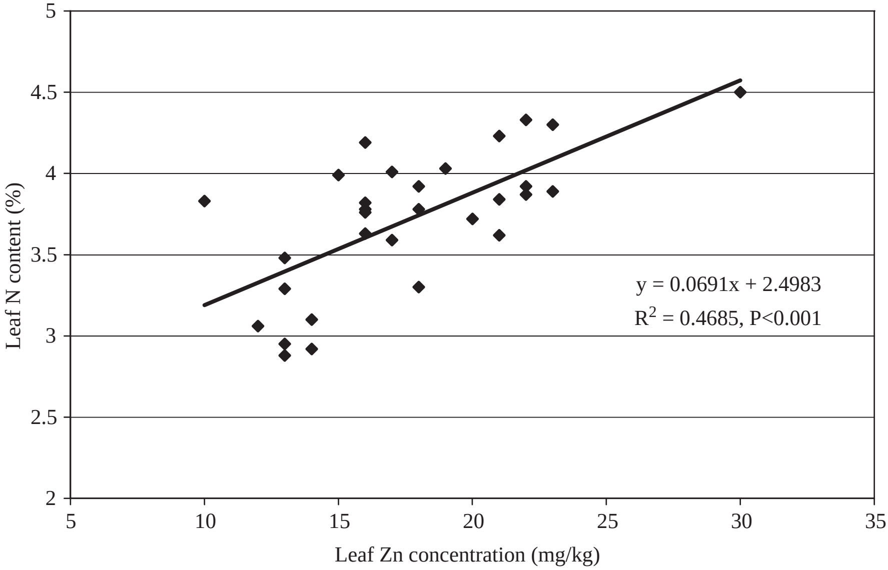

Fig. 9. The relationship between leaf N and leaf Zn of all 30 *Prosopis alba* trees growing on alkaline soils.

pH, there was a highly significant stimulation of the protein concentration in *Prosopis* leaves indicating that S additions seem to have value in addition to its effect on pH changes. Obviously there is much need for applied research to optimize the agronomic effectiveness of elemental S additions.

In a field trial that examined the influence of 0, 7, 5 and 15.0 tons of gypsum per ha on growth and leaf concentrations of various macro and micronutrients of *P. juliflora* on pH 10.4 soils in India, Singh et al. (1989a, b) observed an 8-fold increase in leaf biomass for the 15 ton ha^{-1} treatment 12 months after planting. They measured a change in leaf Ca from 0.66% for the control to 1.39% for the high gypsum application and also an increase in potassium from 1.25% to 2.0% for the high gypsum treatment. Thus they did not observe the Ca/K antagonism we observed. However in a later report 6 years after establishment Singh (1995) found the mean nutrient concentrations were N-2.56%, P-0.31%, K-1.47%, Ca-1.22%, Mg-0.55%, S-0.46% and Na-0.17%. The *K* value of Singh (1995) is virtually the same as the optimum value we obtained. However at his Ca concentration of 1.22%, we observed a suboptimal level of both growth (Fig. 5) and leaf K% (Fig. 7). However the Indian soil pH of 10.4 was much more extreme than our initial 8.5 pH. Obviously with soil pH values above 10, the first priority must be to decrease the exchangeable sodium percentage of the soil and then to optimize relations among the cationic nutrients such as Mg, K and Ca. In this light, Singh et al. (1989a, b) found that the leaf Zn changed from 10 mg kg^{-1} in the control and 7.5 ton ha^{-1} gypsum treatment to 20 mg kg^{-1} the 15 ton ha^{-1} gypsum treatment which was similar to the value we found that stimulated leaf protein in *Prosopis*.

Although the role of Zn in increasing the growth of *Prosopis* on alkaline soils is not conclusive, there is a growing body of literature suggesting that this micronutrient is important on high pH soils. For example in a greenhouse study examining the influence of micronutrients of *P. alba* from pH 6 to 9, Cline et al., (1986) found that without micronutrients the biomass was 46% of the value with micronutrients, that the micronutrients decreased the leaf Na levels by 4-fold and that Zn was apparently responsible for this effect. For rice plants on alkaline soils, Singh (1985) reported that rice shoots that contained 10–15 mg kg^{-1} exhibited severe deficiency symptoms at the tillering stage, but that rice plants with more than 20 mg kg^{-1} had normal growth. Also in India 20 g of zinc sulphate are added per tree to new *Prosopis* plantings on high pH soils (Singh, 1995). Thus while we did not observe a significant relationship between Zn and growth, the highly significant ($P<0.001$, $R = 0.684$) correlation between leaf Zn and protein suggests that Zn may have secondary effects on survival or growth. Obviously furthermore detailed studies are needed on the role of this micronutrient on the survival and growth of various plants on high pH soils.

Numerous papers (Singh et al., 1988, 1989a, b) have shown that once established *Prosopis* can decrease the soil pH, evidently by leaf litter drop and subsequent decomposition. This would suggest that it is only necessary to provide sufficient fertility conditions to get young plants started and thereafter they can generate these positive soil changes on their own. The increases in growth reported by Singh et al. (1989a) for *Prosopis* with use of auger hole planting and/or incorporation of 7.5 or 15 ton ha^{-1} of gypsum are indeed impressive. Since our data suggest that a mature *Prosopis* stand of 40 cm diameter trees cannot be obtained in rainfed situations at densities of more than 100 trees ha^{-1}, then the 200 g S application per tree would correspond to an application of only 200 kg ha^{-1}. Obviously for pH 10 soils, this dose would have to be increased and it would be necessary to apply the S some months before the plantings were made. Siddhu and Behl (1997) have demonstrated that mycorrhizae greatly improved the growth of *P. juliflora* on high pH soils, and this would be another low-cost opportunity to improve *Prosopis* growth under these adverse conditions.

The hyper alkaline/sodic soils of Argentina known as "Salinas" which have EC values and pH values greater than 50 and 8.5 dS m^{-1}, respectively, occupy approximately 800,000 ha (Ragonese, 1951) and are far too problematic for growth of crops or trees without substantial reclamation. There are also extensive, less problematic areas with EC values from 10 to 30 dS m^{-1} range and pH values from 8.0 to 9.0 which are more amenable to these techniques but still outside the range of use for traditional crops. Singh et al. (1988) reported that alkali soils also occupy more than 2.5 million ha in the Indo-Gangetic alluvial plains of India. As the climate of these areas is suitable for *Prosopis*, reclamation of vast areas through cultivation of *Prosopis* is technically possible. The recent reports of improved multipurpose tropical *Prosopis pallida* (Alban et al., 2001), multipurpose subtropical *P. alba* (Felker et al., 2001), strains capable of growing at salinities of 45 dS m^{-1} (Velarde et al., 2003) combined with an economic analyses suggesting internal rates of return of 11–30% for *Prosopis* lumber plantations (Felker and Guevara, 2003) suggests that reclamation with *Prosopis* is not only technically possible but also capable of yielding an attractive return on the investment.

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