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Sustainable Alfalfa Production on Coastal Plain Soils of the United States

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Abstract: Alfalfa (*Medicago sativa* L.) is rarely grown on the Coastal Plain of southern United States. Production problems include infertile acid soils, inadequate pest control, and high humidity with frequent rainfall events that preclude adequate alfalfa hay drying conditions in spring. Research to overcome soil fertility problems included evaluation of nitrogen (N) rates over alfalfa row spacings and limestone and boron rates in split plot studies; phosphorus (P) rates using a randomized complete block design on eight soil series; and potassium (K), magnesium (Mg), and sulfur (S) rates and zinc (Zn), copper (Cu), and molybdenum (Mo) rates in central composite, rotatable design studies. Field-scale demonstrations were conducted to verify data from small plot research. Results indicate little need for N fertilization of alfalfa on Coastal Plain soils except possibly under cool or dry surface soil conditions. Increasing the between-row planting distance from 23 to 69 cm lowered alfalfa dry matter yield by 2.1 $Mg\,ha^{-1}$ the seedling year. Alfalfa yielded 11 $Mg\,ha^{-1}$ at all row spacings in the drought-affected third year. Dry matter yield was maximized at 49–73 kg applied $P\,ha^{-1}$ on soils testing below 19 $mg\,P\,kg^{-1}$ by the NH_4OAc-EDTA extraction method. The alfalfa stand was lost after one season on plots not fertilized with K. Applied Mg, S, Zn, Mo, and Cu had no significant effect on alfalfa yield. Dry matter increased $>5\,Mg\,ha^{-1}$ as pH was increased from 6.0 to 7.5. Boron applied at 3.4 $kg\,ha^{-1}$ increased alfalfa yields 3.9 $Mg\,ha^{-1}$. With improved methods for site selection and adequate fertility, sustainable economic production of alfalfa is possible with rain-fed conditions on selected, limed Coastal Plain soils.

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INTRODUCTION

The Coastal Plain of East Texas and the southern and southeastern United States is largely composed of highly leached and poorly buffered acid soils. Alfalfa has not been a common forage on the Coastal Plain due to its intolerance to soil acidity, competition from bermudagrass (*Cynodon dactylon* [L.] Pers.), and poor, early season hay-drying conditions. Alfalfa requires a neutral to alkaline soil. The soil pH range of 6.6–7.5 is a standard recommendation for alfalfa production (1). A summary of some midwestern U.S. studies showed 93% of maximum yield was attained at pH 6 and 100% at pH 6.6 (2). The optimum pH can vary with soil texture, organic matter, and other soil chemical properties (3, 4). Plant growth in soil can be expected to decrease when the pH is <5.2 in the presence of aluminum (Al) and/or manganese (Mn) (5, 6). The amount of soil Al extracted by salt solutions may be a better indicator of the potential for alfalfa production than pH (7). Nitrogen is made available to well-inoculated alfalfa by symbiotic N_2 fixation. Small amounts of N may be recommended at seeding time to aid seedling establishment prior to the development of effective nodulation (8). Phosphorus application at seeding is an accepted practice in the United States and Canada, particularly on soils testing low in P. However, rates of $45\,kg\,P\,ha^{-1}$ applied at planting resulted in decreased seedling growth measured after 10 weeks in both low and high testing soils (9). Smith and Powell (10) concluded that $57\,kg\,ha^{-1}$ Bray P1-P was an adequate soil level for yields of $7–8\,Mg\,ha^{-1}$. In the humid eastern United States, fertilizer recommendations based on soil test results indicate the need for K application (11), particularly in low buffer capacity, acid sandy soils testing low to medium in plant-available K. Coarse-textured soils sometimes are better suppliers of K for plant growth than would be expected based on exchangeable K concentrations (12). Splitting $372\,kg\,K\,ha^{-1}$ at rates of one-half each in fall or spring, or one-fourth for each cutting, starting in early spring, did not increase the 3-yr average yields of alfalfa on a loam soil at a yield level of $17\,Mg\,ha^{-1}$ (13). Calcitic and dolomitic limestones are the principal sources of Ca, and dolomitic limestone supplies Mg when applied to acid soils. Deep, coarse-texture soils low in organic matter have the greatest supplemental S requirement for crop production. An application of $28\,kg\,S\,ha^{-1}$ was optimum for alfalfa growth on responsive sites (14). Inorganic soil S is mobile and susceptible to leaching. Percolating sulfate S (SO_4-S) can accumulate in fine-textured subsoils and be available to deep-rooted crops such as alfalfa (15). Wear and Patterson (16) showed that alfalfa grown on coarse-textured soil had the highest uptake of B per unit of water-soluble B in the soil and the plants grown in fine-textured soil had the least. As soil acidity decreased from pH 5 to 7, less B was available at any level of water-soluble B in three soils (16). Haby et al. (17) reported that increasing the limestone fineness to 100% effective calcium carbonate equivalence (ECCE) doubled extractable Ca, increased Mg and P, and lowered the level of hot water-soluble B compared to 62% ECCE limestone applied to a Darco soil (loamy, siliceous, semiactive, thermic Grossarenic Paleudult). Only a small percentage of the adsorbed B was retained by the soil against leaching with water at pH 5.8, but as soil pH was increased, the amount of B retained against leaching increased (17). From 1 to 3 kg B ha^{-1} are generally recommended for alfalfa. Alfalfa intensively managed for high yields should receive annual applications of B if deficiencies have previously been noted (15). Deficiencies of other micronutrients such as Mo, Cu, Mn, Zn, Fe, and Co are not major problems in alfalfa production (15).

New varieties of alfalfa with improved disease tolerance and insect resistance have increased the potential for successful alfalfa production on Coastal Plain soils. The advent of grazing-tolerant alfalfa varieties (18) and the large expanse of hybrid bermudagrass on Coastal Plain soils shifted alfalfa research to overseeding and co-production with hybrid bermudagrasses in the 1990s (19–21). Additional research was needed to allow sustainable alfalfa production on Coastal Plain soils. The objective of our research was to define and overcome soil acidity and acidity-related fertility problems that limited sustainable alfalfa production on Coastal Plain soils.

MATERIALS AND METHODS

Soil Variation

The variability of surface soil acidity in a 4 ha field of Thenas fine sandy loam (Fluvaquentic Eutrochrept; $\approx 32^\circ$ 21′N, 94° 57′W) on the North Farm of the Texas A&M University Agricultural Research and Extension Center was evaluated by sampling the 0 to 15-cm depth in a 15.2-m grid pattern. At each location, five subsamples were composited by sampling at the corners and center of a 0.91-m^2 area. Samples of the composited soil were dried at 60°C and analyzed for pH in a 1 : 2 soil to water suspension.

Nitrogen

A study was conducted to evaluate the response of alfalfa, seeded into a stand of Coastal bermudagrass (*Cynodon dactylon* [L.] Pers), to main-plot alfalfa rows spaced 23, 46, 69, and 91 cm apart at seeding rates equivalent to 22.4, 11.2, 7.5, and 5.6 kg ha^{-1}, respectively, on Darco soil ($\approx 32^\circ$ 18′N, 94° 59′W). Subplot N rates were applied for each regrowth of the bermudagrass in a split-plot study. Total N added ranged from zero to 448 kg ha^{-1} split applied four times at incremental rates that were increased by 28 kg ha^{-1} to the maximum of 112 kg ha^{-1} for each regrowth of bermudagrass the first and third seasons and from zero to 560 kg ha^{-1} the second season. Because alfalfa initiated growth earlier than the bermudagrass, N was not applied for the first regrowth of alfalfa each season.

Soil pH and Boron

A study to evaluate alfalfa response to soil pH and B was conducted at a 0.7-m alfalfa row spacing overseeded into a stand of Coastal bermudagrass. Plots in this research site were previously treated with three applications of 64% and 100% ECCE limestones from the same source, each at rates of 2.24 and 4.48 Mg ha^{-1} and with boron rates of 0, 1.12, and 2.24 kg ha^{-1} for rose clover (*Trifolium hirtum* All.) production over a 4-yr period. For alfalfa, B rates of 0, 2.24, and 4.48 kg ha^{-1} were applied over a soil pH range from 5.4 to >7.0 in a randomized complete block design on Darco loamy fine sand (≈32° 18′N, 94° 59′W) in plots measuring 2.7 × 4.6 m. Hot water-soluble boron ranged from <0.3 to >0.7 mg kg^{-1}, and pH varied from about 5.5 to near 8.0 in the surface 0 to 15-cm depth. Because warm season N applications had previously been made to this site during a clover bermudagrass cropping system study, we sampled the surface 15-cm soil depth at 0–5, 0–15, and 5–15 cm for pH and B analysis.

Phosphorus

Alfalfa response to P rates of 0, 24, 49, and 73 kg ha^{-1} annually applied as triple superphosphate in late winter was evaluated on eight soils using a randomized complete block design in plots measuring 3 × 6 m. These thermic soils included Bowie fine sandy loam (Plinthic Paleudult), Cuthbert fine sandy loam (Typic Hapludult), Darco loamy fine sand, Sawtown fine sandy loam (Glossic Paleudalf), Kirvin very fine sandy loam (Typic Hapludult), Lilbert loamy fine sand (Arenic Plinthic Paleudult), Redsprings gravelly loam (Ultic Hapludalf), and Thenas fine sandy loam. These soils were located north of Overton from ≈32° 21′N, 94° 57′W to ≈32° 18′N, 94° 59′W, and within 1 km east and west of FM 3053. In addition to collecting a sample of the 0 to 15-cm surface soil from which to determine P availability (Table 1), lime, and fertilizer recommendations, these soils were presampled to 1.8-m depths by 0.3-m intervals prior to site treatment and planting. These samples of the subsoil were analyzed for pH (1:2 soil to water) and to determine depth of phytotoxic levels of 0.01 M $CaCl_2$ extractable Al (Table 2) by the method of Hoyt and Nyborg (22, 23).

Potassium, Magnesium, Sulfur, Zinc, Copper, and Molybdenum

Alfalfa response to K, Mg, and S and to Zn, Cu, and Mo was evaluated on adjacent sites on the Darco loamy fine sand near the pH and B study.

Table 1. Alfalfa yield and P uptake response to applied P on eight Coastal Plain soils over 3 yr.

Soil series	Initial soil test P[a] ($mg\ kg^{-1}$)	Yield and P uptake responses by yr[b]					
		Year 1		Year 2		Year 3	
		Yield	P uptake	Yield	P uptake	Yield	P uptake
Bowie	7.7	No	No	No	Yes	No	Yes
Cuthbert	27.2	No	Yes	No	No	No	No
Darco	6.0	No	No	Yes	Yes	Yes	Yes
Sawtown	1.9	Yes	Yes	Yes	Yes	Yes	Yes
Kirvin	42.6	No	No	No	No	No	No
Lilbert	14.4	No	Yes	Yes	Yes	Yes	Yes
Redsprings	18.8	No	No	No	No	No	No
Thenas	36.2	No	No	No	No	No	No

[a]0 to 15 cm depth extracted by NH_4OAc-EDTA buffered at pH 4.2 by HCl (25).
[b]Yield response to 24, 49, or 73 $kg\ P\ ha^{-1}$ rates applied annually compared to the zero check.

Alfalfa rows were spaced 0.18 m apart in central composite rotatable design (CCRD) studies in plots measuring 3 × 6 m. Five rates of K ranged from 0 to 400, Mg from 0 to 100, and S from 0 to 100 $kg\ ha^{-1}$ according to the requirements of the CCRD (24). Five rates of Zn ranged from 0 to 16 and

Table 2. Effect of soil test P and depth of critical-level, phytotoxic Al concentrations on alfalfa dry matter yield

Soil series	Dry matter yield[a] ($Mg\ ha^{-1}$)	Soil test P[b] ($mg\ kg^{-1}$)	Depth of Al concentration[c] (cm)
Bowie fine sandy loam	8.0	9.1	>183
Cuthbert fine sandy loam	6.3	18.1	61–91
Darco loamy fine sand	5.2	6.7	122–152
Sawtown fine sandy loam	5.8	5.9	91–122
Kirvin fine sandy loam	3.0	40.3	31–61
Lilbert loamy fine sand	5.8	8.4	152–183
Redsprings gravelly loam	3.7	9.9	31–61
Thenas fine sandy loam	6.1	52.0	91–122
R^2 (Pr > F)		−0.24 (0.56)	0.57 (0.02)

[a]Mean yield from the 49 and 73 $kg\ P\ ha^{-1}$ rates averaged over 3 yr.
[b]0 to 15-cm depth extracted by NH_4OAc-EDTA buffered at pH 4.2 by HCl (25).
[c]Depth at which 0.01 M $CaCl_2$ extractable Al concentration was $\geq 1\ mg\ kg^{-1}$. ($\geq 1\ mg\ kg^{-1}$ is considered potentially phytotoxic to alfalfa root growth.)

Cu from 0 to 8 kg ha^{-1}, whereas Mo rates ranged from 0 to 200 g ha^{-1} using the same CCRD.

Soil Analysis, Fertilization, and Statistical Analysis

Soil pH was determined by using a glass pH indicating electrode combined with a calomel reference electrode in a 1 : 2 soil to water suspension 30 min after stirring. Phosphorus and potassium were extracted from 1.5 g of soil with 30 mL of 0.025 M H_4EDTA in 1.4 M ammonium acetate and 1.0 M HCl buffered at pH 4.2 (25) in disposable cups on a rotating shaker. The deck of the shaker was designed with a 6% slope from horizontal to provide a slight upward pitch to the soil suspension as the shaker rotated at 220 oscillations per min for 60 min. The stannous chloride reduced molybdenum blue color method was used to analyze P in the extracts (26) Potassium was determined by flame emission on an atomic absorption spectrophotometer. Soil B was extracted with hot water (27) and analyzed colorimetrically by using azomethine H (28). Soil Al extracted from 10 g soil with 20 mL of 0.01 M $CaCl_2$ for 5 min (22) was determined by electrothermal atomization atomic absorption spectroscopy using a graphite furnace.

Other than where individual plant nutrients were treatment variables, fertilizer rates were based on soil analysis. Soil samples from the 0 to 15-cm surface depth were collected by using a hand-push soil probe, dried at 60°C for 48 hr in a forced-draft oven, and analyzed to determine the level of residual plant nutrients and the resulting fertilizer recommendations. A hydraulically powered probe was used to collect soil samples from subsurface depths.

In the initial fertility investigations on alfalfa, fertilizer treatments included P, K, Mg, S, B, Cu, and Zn. Except in the limestone variable plots, experimental sites were treated with limestone to raise surface soil pH to about 7.0 using calcitic limestone. In the initial studies, most nontreatment plant nutrients were applied to ensure that alfalfa was not deficient. As data became available from individual nutrient studies described in this article, fertilizer rates were adjusted according to experimental results.

Data from these studies were evaluated by using PROC GLM and PROC REG in SAS (29).

On-Farm Validation Studies

Results from these small plot fertilizer trials were applied to two-plus hectare plantings of alfalfa on farms and ranches in five counties within 80-km road distance of the Texas Agricultural Experiment Station headquarters at Overton. These field-scale alfalfa studies, funded by the United States Department of Agriculture Southern Region Sustainable Agriculture Research and

Education Program (SARE), included "Amerigraze 702" and "GrazeKing" alfalfa varieties in side-by-side comparisons. Each site was selected on the basis of subsoil evaluation to 120 cm for pH and Al in addition to the normal selection criteria for alfalfa. Bermudagrass was removed by disking and application of glyphosate where needed during seedbed preparation. Each variety was planted at 28 kg ha^{-1} using preinoculated alfalfa seed. These field sites were located north of Overton on the Kilgore College Farm in Rusk County (≈32° 18′N, 94° 57′W), north of Kilgore in Greg County (≈32° 24′N, 94° 46′W), northeast of Tyler in Smith County (≈32° 24′N, 95° 06′W), north of Jacksonville in Cherokee County (≈32° 03′N, 95° 12′W), and south of Frankston in Anderson County (≈32° 01′N, 95° 29′W). Samples for yield estimation were clipped from four 1.0-m^2 quadrants in each variety, and a separate subsample was clipped next to each m^2 harvest for chemical analysis before the alfalfa was grazed or cut and baled. Alfalfa yield data and samples for dry matter and chemical analysis were collected by using a Hege 211-B, self-propelled forage plot harvester on small plot research sites.

RESULTS AND DISCUSSION

Soil Variation

Variation of soil acidity in Coastal Plain soils is an important consideration when sampling soils to determine limestone recommendations. Soil pH in the 0 to 15-cm depth across a 4-ha field of a Thenas fine sandy loam varied from 4.1 to 6.0, whereas the average of the pH values was 5.1 (Fig. 1). These results indicate the importance of adequate sampling to attempt to manage acidity in Coastal Plain soils. The wide variation in pH across this small field emphasizes the difficulty encountered when attempting to make a single recommendation for lime application to correct soil acidity. When a single limestone rate is recommended based on analysis of one soil sample composited from numerous subsamples, parts of the field will be over limed and parts will not receive sufficient limestone to modify soil pH for acid-sensitive crops. Variation of acidity in soils across fields may be adequately resolved by lime requirement analysis of soils collected by grid sampling and use of variable-rate technology for lime application. The ultimate resolution of plant nutrient variability in soils will occur when on-the-go analyses are made continuously by instruments connected to tillage implements with the data stream flowing to computers that adjust the nutrient distribution from individual nutrient supplies according to soil test levels. Even then, efficiency factors will be needed to correct for changes in availability of applied nutrients to plants over changing application rates and soil types.

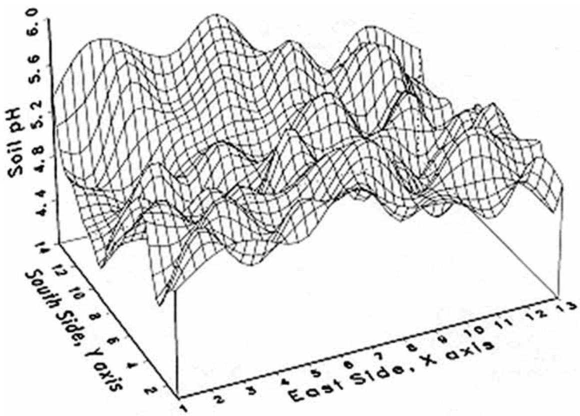

Figure 1. Soil pH spaliol variability map at 4 ha of Thenas soil (Fluvaquentie Eutrudept) 0 - 15 slope.

Nitrogen

Increasing N rates split applied for each bermudagrass growth period significantly increased bermudagrass dry matter at yield levels that declined annually but had little effect on total annual yield of alfalfa dry matter production on a Darco loamy fine sand (21). Applied N significantly increased alfalfa dry matter production at specific harvests. There were no significant alfalfa yield differences at higher rates of N application compared with yield at the 28 kg N ha^{-1} rate. Significant response of alfalfa to N occurred only in harvests affected by cold or dry conditions. The effect of these extremes in temperature and drought may have slowed the activity of rhizobia that fix atmospheric N_2 in nodules on alfalfa roots near the soil surface. A decline in N_2 fixation could contribute to the alfalfa response to applied N. These results are consistent with data reported by Feigenbaum and Hadas (30) that showed increased alfalfa yields in field studies when N was applied to a coarse-textured soil but not to a fine–textured soil. Data reported from several other studies in the United States indicated no response of alfalfa to application of N (31–33). Haby et al. (21) reported that N applied to a coarse-textured soil limed two years earlier with ECCE 72% limestone for alfalfa production significantly decreased soil pH in samples collected from the surface 15-cm midway through the second growing season. Nitrogen application for alfalfa production on Coastal Plain soils is not a common recommendation except possibly at a low rate for seedling growth on coarse-textured, low organic matter soils and when postseeding soil temperatures are expected to remain unseasonably cold.

Phosphorus

Data in Table 1 indicate that alfalfa yield was increased in the first season of production by P application only on the Sawtown soil even though several other soils showed potentially low levels of soil test P (34). A severe drought in the seedling year limited alfalfa yields and the potential response to applied P. Alfalfa grown on the Darco, Sawtown, and Lilbert soils responded to fertilization with P in years 2 and 3. Field trials on these P-deficient soils indicated that 19 mg kg^{-1} was the approximate critical soil test P level to predict alfalfa response to applied P based on P extraction using the NH_4OAc-EDTA extractant. These data corroborate results determined by Walworth and Sumner (35) and Bouton et al. (36) who reported alfalfa response to applied P on Coastal Plain Ultisols. Uptake of P by alfalfa was increased by P application on the Cuthbert, Sawtown, and Lilbert soils in year 1 and on the Bowie, Darco, Sawtown, and Lilbert soils in years 2 and 3 (34). Based on the low soil test P levels, increased uptake of P by alfalfa should have also occurred in the first year on the Bowie and Darco soils, but not on the Cuthbert.

Comparison of the NH_4OAc-EDTA extractant to the Mehlich III method (37) using samples collected from the variable P-rate plots on these eight soils in the third year of the study on alfalfa response to applied P was reported by Haby (38). The generated regression equation:

$$\text{NH}_4\text{OAc-EDTA soil test P} = 0.551(\text{Mehlich III soil test P}) - 6.58, \quad R^2 = 0.73 \qquad (1)$$

indicates that the NH_4OAc-EDTA extractant removes about half as much extractable P from limed acid soils as does the Mehlich III extracting solution. The R^2 of 0.73 for this method comparison is excessively weak and indicates that soil test data developed for alfalfa response to applied P using the NH_4OAc-EDTA extractant cannot be transferred for use with the Mehlich III method.

Soil properties other than the supply of plant-available nutrients control alfalfa response to fertilizer on acid Coastal Plain soils. Data in Table 2 show 3-yr average maximum alfalfa dry matter yield by soil series, soil test P, and depth of potentially phytotoxic concentrations of Al. The coefficient of determination ($R^2 = -0.24$) indicates a poor relationship of soil test P to alfalfa yield response to fertilizer P over these eight soils. Regression of 3-yr total alfalfa yield response to depth of phytotoxic Al concentrations in the subsoil is indicated in the following:

$$\text{Dry matter yield, kg ha}^{-1} = 7740 + 2180(x), \quad R^2 = 0.57 \qquad (2)$$

where "x" refers to depth of a phytotoxic level of aluminum, considered ≥ 1.0 mg kg^{-1} extracted using 0.01 M $CaCl_2$. An "x" value of 2 represents the 0.3 to 0.6-m depth, and 6 represents the 1.5 to 1.8-m depth. For the Bowie soil, we used an "x" value of 6.05 because there was no phytotoxic level of Al in the 0 to 1.8-m depth. Depth of a phytotoxic level of Al accounted for 57% of the dry matter yield variation on these limed acid soils. Each 0.3 m increase in depth of a phytotoxic level of Al added 2180 kg ha^{-1} additional alfalfa dry matter to the 3-yr total yield. The Kirvin and Redsprings soils produced the lowest yields of alfalfa. Both soils contained potentially phytotoxic levels of Al in the 0.3 to 0.6-m depth. Data on the effects of depth of phytotoxic levels of subsoil Al on alfalfa yield add an additional site selection criterion to the search for suitable soils for alfalfa production on Coastal Plain soils.

We have successfully used depth of potentially phytotoxic levels of subsoil Al, in addition to locating adequately well-drained soils, to select suitable sites for field planting of alfalfa on five farms and ranches. This added site selection criterion is recommended to potential growers who request information about alfalfa production on Coastal Plain soils. Our recommendation, in addition to sampling the field soils from 0 to 15 cm for the standard fertility analyses, is to collect subsamples by 30-cm depths to at least 120 cm from no less than five locations in each field to be considered for alfalfa. Common 30-cm depth subsamples are to be collected into individual containers, homogenized, and a sample from each depth sent to a soil testing laboratory for analysis of pH. The site is suitable for production of alfalfa if a 1 : 2 soil to water pH is 5.5 or higher, provided that the site meets all other selection criteria for alfalfa. Depth samples testing $<$pH 5.5 are recommended for Al analysis using 0.01 M $CaCl_2$ extraction. Aluminum concentrations >1.0 mg kg^{-1} in these depth samples are considered probable reason to reject the field site for alfalfa production, particularly when the phytotoxic level of Al is located nearer to the soil surface (i.e., in the 0.3 to 0.6-m depth). McKenzie and Nyborg (7) reported impairment of barley and alfalfa root growth when Al extractable in 0.02 M $CaCl_2$ was as low as 2–3 mg Al kg^{-1} and root yields were reduced by 50% when Al levels in the subsoil were 20 mg Al kg^{-1}.

The Coastal Plain of the southern and southeastern United States is described as a humid or high rainfall area, but total rainfall varies substantially in the region (39) and by season. Average monthly rainfall declines to its lowest level in July and August in the western region of the Coastal Plain. Maximum air temperatures can exceed 38°C during these months. These intense drying conditions and evapotranspiration deplete plant-available water in the limed surface soil and to even deeper depths in severely dry years. Drying of the surface soil restricts root uptake of nutrients concentrated near the soil surface, inhibits N_2 fixation and transfer in the plant, and phytotoxic levels of Al restrict growth of alfalfa roots, preventing the plants from obtaining soil water at deeper depths. Inability of the root system to obtain water causes the alfalfa to enter a summer dormancy that will end only when adequate rainfall resumes or irrigation water is applied.

Potassium, Magnesium, Sulfur, Zinc, Copper, and Molybdenum

Analysis of variance followed by regression analysis both indicated a statistically significant yield response of alfalfa to K applied as KCl (Fig. 2). The yield response was linear between 0 and 400 kg K ha^{-1}. Yields from replicated treatments varied due to stand thinning when inadequate amounts of K were provided. Data points from yields by replication are grouped much tighter at the 400 kg ha^{-1} K rate. Plots that represented the zero K treatment lost the stand of alfalfa after one production season. Deep sandy soils such as this Darco usually test low and sometimes medium in plant-available K. Coastal Plain acid-sandy soils rarely test in the high K category by soil analysis. The best use of the soil test for K on these soils may be to initially estimate the plant-available soil K level and then recommend K application based on requirements for the crop to be grown plus an additional amount to compensate for plant use efficiency and potential soil fixation of applied K. Burmester et al. (40) reported the highest alfalfa yields were attained at the rate of 484 kg K ha^{-1} on two Ultisols on the Coastal Plain, and that there was no advantage to split application of K on established stands of alfalfa. Kafkafi et al. (41) concluded that K applications should be split applied, allowing for two alfalfa harvests between each application of K for sandy loam soils with low cation exchange capacity.

Soil pH and Boron

Alfalfa is known to require a surface soil pH near neutral to slightly alkaline for optimum yield. Data supporting this were reported by Haby (38) (Table 3) and indicate that alfalfa dry matter yield was increased by 3.9 Mg ha^{-1} as pH in the

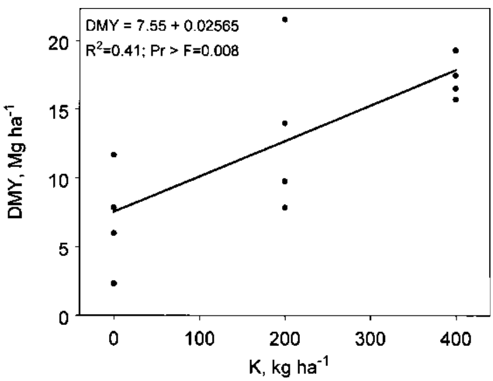

Figure 2. Response of alfalfa to applied potassium on a Darco loamy fine sand (Grossarenic Paleudult).

Table 3. Predicted response of alfalfa to soil pH 1 : 2 soil to water in the 5.1- to 15.2-cm depth and to boron applied to a Darco loamy fine sand with hot water-soluble boron at 0.5 mg kg^{-1} and DTPA-extractable Mn at 7.5 mg kg^{-1} in 1994

	Applied B (kg ha^{-1})				
Soil pH	0	1.12	2.24	3.36	4.48
		Dry matter (Mg ha^{-1})[a]			
6.0	2.46	4.44	5.74	6.36	6.31
6.5	4.61	6.59	7.89	8.52	8.46
7.0	6.35	8.33	9.63	10.25	10.20
7.5	7.67	9.65	10.95	11.58	11.52
8.0	8.58	10.56	11.86	12.48	12.43

[a] $Y = -54.36 + 2.07 \times B - 0.27 \times B^2 - 37.06 \times 0.5 + 59.29 \times 0.5^2 + 14.68 \times pH - 0.83 \times pH^2 + 0.31 \times 7.5$.
$R^2 = 0.76$.

5- to 15-cm depth of a Darco soil was raised from 6 to 7, regardless of the B rate applied and with soil B and Mn levels held constant in the regression equation. This regression generated from data collected in the second year of the limestone-rate, limestone-ECCE, and B-rate study included, in addition to pH, applied B, hot water soluble-B, and DTPA-extractable Mn in the 5- to 15-cm soil depth. These factors were responsible for 76% of the variability in alfalfa yield. Attempts to develop relationships using the same soil properties determined in the 0- to 15-cm or 0- to 5-cm depths failed, possibly due to B mineralized from the organic layer at the surface of the Darco soil.

Alfalfa yield increased with each level of applied B to 4.2 kg B ha^{-1}. Response to soil B increased exponentially with increasing levels of hot water-soluble boron in the 5- to 15-cm soil depth regardless of the amount of B applied (Fig. 3). The yield response to soil B continued exponentially to 0.7 mg B kg^{-1} (data not shown) which was the highest level determined in the Darco soil. This indicates the importance of building and maintaining adequate fertility levels in soils for maximum crop production.

Magnesium, Sulfur, Zinc, Copper, and Molybdenum

In a 3-yr study, alfalfa yield failed to significantly respond to applied Mg, S, Zn, Cu, or Mo on lime-treated Coastal Plain Darco loamy fine sand in the central composite, rotatable design studies conducted (data not shown). Ultisols such as the Darco contain a B-horizon, or zone of accumulation of clay and nutrients. Plant nutrient elements such as S and Mg are often concentrated in the B horizon. Deep rooting crops such as alfalfa are able to take up nutrients from this horizon if it is within uninhibited rooting depth of the crop. Lanyon

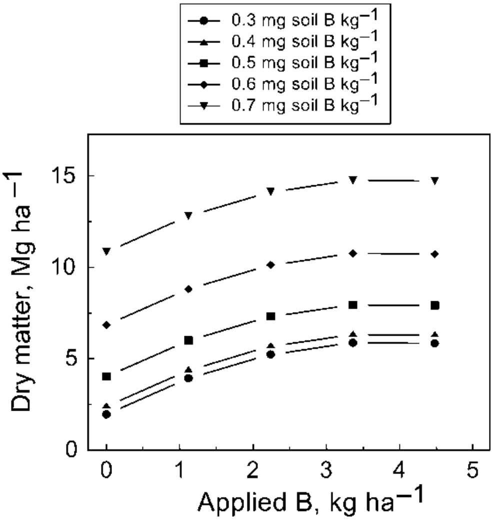

Figure 3. Alfalfa response to applied B at increasing levels of B in the 5- to 15-cm depth of Darco loamy fine sand.

et al. (42) reported that alfalfa yields of 9 to $>$17.9 Mg ha^{-1} took up 18–47 kg S ha^{-1} and 17–39 kg Mg ha^{-1}. The lack of alfalfa yield response to Zn and Cu indicates that these nutrient elements were adequately plant available in the Darco soil. Lanyon et al. (42) reported uptake by alfalfa of 0.4 kg Zn and 0.12 kg Cu ha^{-1} in an 18 Mg ha^{-1} yield of alfalfa. Lack of yield response to applied Mo agrees with results reported by Walworth and Sumner (35). Molybdenum is known to increase in availability as soil pH is raised by liming.

Field-Scale Demonstration of Alfalfa Production

Data from the first 2-yr indicate both varieties produced comparable total yields varying from 13 to 21 Mg ha^{-1}, depending on soil and management factors (Table 4). Nitrogen fixation, as indicated by crude protein, was increased the second year. Yields were mainly higher the second production season except for the KC site that was dropped from the study due to declining stand caused by wet soil from excessive rainfall and an increasing infestation of common bermudagrass.

Alfalfa from these on-farm field trials was harvested mainly as small square bales approximating 30 kg each. For economic evaluations, the alfalfa was valued at \$149 Mg^{-1} (Table 5). Cost of establishment varied from \$556 to \$871 ha^{-1}. Establishment costs varied primarily due to the amount of limestone needed to raise the initial soil pH to approximately 7.0 and site-selective, preseeding weed control using Roundup™. Other

Table 4. Two-yr summary of SARE-site, on-farm alfalfa production on Texas Coastal Plain soils for seedling years 2000 and 2001.

Farm/ranch site	Griffin	Riley	Taylor	KC	7P
Year 2000; no. of cuttings	4	3	3	4	4
Amerigraze 702, $Mg\,ha^{-1}$	10.2	7.6	8.0	8.9	9.5
Crude protein, $g\,kg^{-1}$	183	171	165	192	183
GrazeKing, $Mg\,ha^{-1}$	9.6	8.3	7.9	8.8	9.4
Crude protein, $g\,kg^{-1}$	185	175	188	194	199
Year 2001; no. of cuttings	6	5	5	3	5
Amerigraze 702, $Mg\,ha^{-1}$	10.6	9.2	10.9	4.3	9.6
Crude protein, $g\,kg^{-1}$	214	191	221	237	196
GrazeKing, $Mg\,ha^{-1}$	10.5	9.0	8.5	5.0	9.6
Crude protein, $g\,kg^{-1}$	222	196	214	228	212
Two-yr total yields:					
Amerigraze 702, $Mg\,ha^{-1}$	20.8	16.8	18.9	13.2	19.1
GrazeKing, $Mg\,ha^{-1}$	20.1	17.3	16.4	13.8	19.0

operations included in establishment costs were soil sample analysis of the 0 to 15 cm depth and samples collected in 30-cm increments to the 120-cm soil depth, seedbed preparation, seeding, fertilizers, pest control, and alfalfa seed planted at 28 $kg\,ha^{-1}$. Limestone was estimated to cost \$30.86 Mg^{-1} spread on the field and alfalfa seed was priced at \$8.16 kg^{-1}. Fertilizer and

Table 5. Production economics for alfalfa grown on two-plus ha on-farm field sites.

Farm/ranch site	Griffin (\$ ha^{-1})	Riley (\$ ha^{-1})	Taylor (\$ ha^{-1})	KC (\$ ha^{-1})	7P (\$ ha^{-1})
Establishment cost	556	871	806	620	624
Year 2000 hay value[a]	1671	1344	1351	1494	1481
Production expenses	407	373	274	395	234
Haying, hauling, and interest	338	274	271	304	295
Overhead, 5-yr prorated	173	236	223	310	187
Net return ha^{-1}	753	461	583	485	765
Year 2001 hay value[a]	1781	1534	1641	791	1731
Production expenses	344	354	337	369	335
Haying, hauling, and interest	357	310	330	167	347
Overhead, 5-yr prorated	173	236	223	310	187
Net return ha^{-1}	908	634	752	-55	863
Two-yr total net return	1661	1095	1335	430	1628

[a]Alfalfa valued at \$148.81 Mg^{-1} of 12% moisture hay. Study funded by USDA Southern SARE.

limestone costs varied between \$118.61 and \$197.68 ha^{-1}, depending on the initial soil fertility and acidity levels at each site. Establishment costs were prorated over only 2 yr for the KC site. At the remaining sites, establishment costs, initially prorated over 5 years, should be adjusted based on duration of the alfalfa stand. Two-year total net returns ranged from \$307 ha^{-1} on the terminated KC site to \$1661 ha^{-1} on the Griffin site.

CONCLUSIONS

Net return due to production of alfalfa on farm and ranch fields in year 1 varied between \$424 and \$765 ha^{-1}. Net return the second year was increased due to greater yield at four of the five field sites. The 2-yr total estimated net return on the remaining four sites ranged from \$1095 to \$1661 ha^{-1}. These data from field production verify the increased economic opportunity provided by production of alfalfa as a hay crop compared to current grass hay crops such as Coastal bermudagrass that has an estimated annual net return approximating \$150 ha^{-1} (personal communication, G. Clary, agricultural economist, Texas A&M Univ.).

Based on results from soil fertility and fertilizer trials, alfalfa is a promising alternative forage crop for production on Coastal Plain soils. On soils testing low in P and K, applied rates approximating 60 kg P and 400 kg K ha^{-1} improved seedling year and second year yields. In addition to P, K, and possibly S and Mg, fertilization with B at rates up to 4.2 kg ha^{-1} must be considered on Coastal Plain, low buffer capacity, acid soils limed to pH near 7.0. If the criteria presented are to be used for providing recommendations for B to alfalfa producers based on soil analysis, the surface organic layer should be removed before the sub samples for B are collected.

Site selection must be based on evaluation of subsoil acidity as well as choosing well-drained soils. Subsoil acidity can be evaluated by collecting samples by 30-cm increments to at least 120 cm for evaluation of pH and exchangeable Al. If pH in these depth samples is 5.5 (1 : 2 soil to water) and above and 0.01 M $CaCl_2$ exchangeable Al is 1.0 mg kg^{-1} or less, a Coastal Plain sandy acid soil has the potential for sustainable economic alfalfa production as long as other site-selection criteria are favorable.

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