ELSEVIER

Forest Ecology and Management 94 (1997) 37–46

Forest Ecology and Management

Influence of silvicultural treatments on growth of mature mesquite (*Prosopis glandulosa* var. *glandulosa*) nine years after initiation

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Accepted 22 November 1996

Abstract

The growth of a mature stand of *Prosopis glandulosa* was measured 9 years after thinning, understorey removal, understorey removal plus herbicide resprout treatment, and phosphorus fertilizer treatments had been applied. The volume and weight of growth were estimated with dendrometers installed at the base of 20% of the trees, and regression equations were calculated that related basal area to volume and weight. Mean absolute growth increases were not significantly different among the treatments ($P > 0.05$). However, when volume and biomass growth were compared with difference in initial basal area, some of the treatments were significantly different. The understorey removal + thinning + herbicide + fertilizer treatment resulted in the greatest mean percent weight growth (28.3%, $n = 4$, SD = 3.0647) and percent volume growth (34.9%, $n = 4$, SD = 3.9790) over the 9-year time-period, and was significantly ($P = 0.0001$) different from the control percent weight (11.1%, $n = 4$, SD = 0.5315) growth and control volume (13.3%, $n = 4$, SD = 0.7124) growth. The annual diameter increment for the fertilizer treatment was 0.27 cm year^{-1}, $n = 4$, SD = 0.898, which is comparable with other mature commercial hardwood forests. © 1997 Elsevier Science B.V.

Keywords: Agroforestry; Arid lands; Fuelwood; Hardwoods; Nitrogen-fixing trees

1. Introduction

Nitrogen-fixing trees and shrubs of the genus *Prosopis* are native to the Western Hemisphere, Africa and Asia, where they have been important for fuel and animal fodder (Burkart, 1976). Although the geographic range of *Prosopis* in Texas is generally not thought to have changed in the past 300–500 years (Johnston, 1963), the increased abundance of *Prosopis* in the grasslands of the southern US is thought to coincide with the introduction of cattle (Buffington and Cult, 1965; Madany and West, 1983; Archer and Brown, 1987; Archer et al., 1988). In Texas, in 1987, mesquite occurred on 19.2 million hectares, approximately 50% of the total Texas rangeland (Texas State Soil and Water Conservation Board, 1991). *Prosopis* has also become naturalized in Hawaii, Senegal, Sudan, South Africa, India and Pakistan, where it has been regarded as both a resource and a weed (Felker, 1990).

Prosopis has been recognized worldwide for many

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PII S0378-1127(96)03985-0

valuable uses including soil fertility and stability improvement, fuelwood, forage and fodder, and food for human consumption (Felker, 1981). *Prosopis* has also been recognized as a valuable wood for use in high-value products such as in the furniture and flooring markets (Rogers, 1984; Weldon, 1986; Meyer and Felker, 1990; Felker et al., 1994). In 1993, the National Hardwood Lumber Association approved new grading rules for mesquite lumber to take into account its inherently shorter lengths and narrow widths (Felker et al., 1994).

The exceptional properties of *Prosopis*, its attractive color and grain, its hardness (1010 kg to embed a 1.1 cm ball 0.6 cm deep), and low volumetric shrinkage (4.7%), are equivalent to other fine hardwoods, both domestic and exotic (Weldon, 1986; Felker et al., 1994). In 1995, wholesale prices for mesquite lumber ranged from \$800 to \$1600 m^{-3} (D. Miller, personal communication, 1995). In addition to uses for fine lumber and flooring, a significant industry has developed to use mesquite chips and chunks for use in outdoor cooking to flavor meats and vegetables. In 1995, this industry was estimated to wholesale about 12 million kg of product with a value of about \$5 million (J. Lawson, personal communication, 1995; G. Wartsbaugh, personal communication, 1995). The chip and chunk industry purchased approximately 25 000 m^3 of 20–30 cm diameter, 50 cm length logs for \$22 m^{-3} (J. Lawson, personal communication, 1995; G. Wartsbaugh, personal communication, 1995).

As of 1995, there were no commercial plantations of mesquite in the southwestern USA. The wood used in the barbecue, lumber and flooring industry in Texas has come from natural stands. Thus, management guidelines are needed to best utilize the mature mesquite forests that exist in Texas and elsewhere in the world. Previous mesquite research has resulted in several techniques that enable management guidelines to be developed. Regression equations are available to estimate lumber yields from harvested logs (Rogers, 1984).

Regression equations are also available to predict biomass and volume from basal diameters and canopy measurements (El Fadl et al., 1989). Thinning techniques have been developed for sapling mesquite (Cornejo Oviedo et al., 1991). Swath biomass harvesters are under development to thin sapling mesquite (McLauchlan et al., 1994). Grafting techniques are available to genetically upgrade existing stands (Wojtusik et al., 1993). In addition, a preliminary analysis on the effect of thinning, understorey removal and phosphorus fertilization on a mature mesquite stand found that understorey removal had a greater effect in stimulating growth than either thinning or fertilization (Cornejo Oviedo et al., 1992). The study by Cornejo Oviedo et al. (1992) examined treatment effects after 2.5 years. The current study examined the influence of the same treatments on growth after 9 years.

Field fertilizer trials with trees have generally observed that N and P fertilizers provide the greatest growth response (Pritchett, 1979). Assuming nitrogen-fixing plants such as *Prosopis* can provide their basic nitrogen requirements, phosphorus would be the limiting nutrient due to its high demand in the energetics of the nitrogen-fixing process (Hopkins, 1995). In greenhouse studies (Cline et al., 1986), *Prosopis* leaf phosphorus concentrations were significantly correlated with nitrogen concentrations. This correlation and the high N/P ratio in the foliage on an inert media containing little N suggests the importance of phosphorous in the nitrogen-fixing process. A one-unit increase in *Prosopis* leaf P was associated with a 20-unit increase in leaf N and a 120-unit increase in crude leaf protein (Cline et al., 1986). *Prosopis* field trials also indicated that copper may be a limiting nutrient (Wightman and Felker, 1990; Muthaiya and Felker, 1996).

The more intensive management practices that accompany plantation forestry have resulted in greater growth of *Prosopis* (Felker et al., 1989; Duff et al., 1994) than growth observed in natural stands (Cornejo Oviedo et al., 1991, 1992). The objective of this study was to determine the long-term effects of different management practices on *Prosopis*, which will enable managers to make appropriate silvicultural decisions for mature *Prosopis* forest management.

2. Materials and methods

A study area was established in 1986, 32 km west of Kingsville, Texas. Climate and soil information is given in detail in Cornejo Oviedo et al. (1992).

A randomized complete block design with four blocks and four treatments was established in the summer of 1986 (Cornejo Oviedo et al., 1992). A thinning treatment was added in 1988 that decreased the number of initial stems (356 stems ha^{-1} for 196 trees) to one stem per tree. The thinning was implemented to bring the density closer to the desired 100 crop trees ha^{-1} (Felker et al., 1990). The final field trial included four replicates and five treatments. The treatments were: (1) control; (2) thinning to single stems; (3) thinning to single stems plus manual understorey removal (chainsaw) and mowing (PTO-driven rotary shredder); (4) thinning to single stems, understorey removal, and Grazon ET herbicide (3,5,6,trichloror-2-pyrdinyloxacetic acid) to control resprouts and other understorey vegetation; (5) thinning, understorey removal, herbicide treatment, fertilizer application (triple superphosphate 0–46–0, at a rate of 100 kg ha^{-1} of P_2O_5 fertilizer (44 kg P) to the entire plot.

Repeated plots due to 1986 edge analysis and 1988 thinning were excluded from this study, with the result that the total area included was 2.18 ha (20 plots). Dendrometers were installed on 100 trees and 116 stems. The total number of stems, after thinning, that were included in the analysis was 486.

Muthaiya and Felker (1996) found that Cu may have been limiting the growth of the trees at this study site. In 1995, 10 trees in the phosphorus treatment were randomly assigned to receive an additional application of phosphorus (46% P_2O_5) and 10 trees were randomly assigned a phosphorus + copper sulfate (22% Cu) treatment.

The triple superphosphate was applied at a rate of 100 kg ha^{-1} (20 kg P) to the entire plot on 25 July 1995. The copper sulfate was applied at a rate of 32 kg ha^{-1} (7 kg Cu ha^{-1}) to 10 trees that were stratified according to crown size. The copper sulfate was applied at rates of 90, 160, 250 and 360 g per tree for mean tree crown diameters of 6, 8, 10 and 12 m. The copper sulfate was applied on 21 June 1995. Growth was measured from the initial diameter in May 1995 to the final diameter in September 1995.

Total weight and volume growth were estimated for each of the treatments a well as percent relative growth. ANOVAs were performed on the untransformed and arcsine transformed data. A chronology of treatment establishment is provided in Table 1. To measure the growth in weight and volume, dendrometer bands were permanently mounted around the base of 228 sample stems in 1987. The dendrometer bands were constructed following a modification of the method of Liming (1957). The vernier was capable of measuring to 0.25 mm. As the dendrometers were installed prior to the thinning, the number of dendrometer bands decreased from 228 to 120 (Cornejo Oviedo et al., 1992). Dendrometers that exceeded their maximum circumference measuring capability (7.6 cm, or 3 inches) were replaced in 1995. Initial diameters were measured in September 1986 before dendrometers were placed on the trees. Increment readings were recorded for all trees in the fall from 1987 to 1995, with the exception of 1994. The mesquite sample tree weight (kg) and volume (m^3) were estimated from the basal area using re-

Table 1
Chronology of preparation and silvicultural treatment application for a mature *Prosopis glandulosa* stand from 1986 to 1995

Treatment [a]	Date
1. Plots laid out and understory removed	April–July 1986
2. All trees inventoried for basal diameter	September 1986
3. 228 dendrometers installed on 120 trees	January 1987
4. First dendrometer readings (readings continued annually except for 1994)	May 1987
5. Herbicides applied to understory resprouts	July–August 1987
6. Thinning treatment applied	April–June 1988
7. Herbicide treatment repeated	July–August 1988July–August 1989
8. Copper and phosphorus treatments applied	June–July 1995
9. Final dendrometer readings	September 1995

[a] Activities 1–7 implemented by Cornejo Oviedo et al. (1991).

Table 2
Percent change in diameter frequency distribution (5-cm classes) from 1986 to 1995 for five treatments in a mature *Prosopis* stand

Size classes	Treatments [a]				
	Control (%)	Thinning (%)	UR + T (%)	UR + T + H (%)	UR + T + H (%)
5–10	−2.63	No trees	No trees	No trees	No trees
10–15	−7.89	−17.65	−5.0	−10.0	−14.29
15–20	+7.89	+5.88	−5.0	−5.0	−9.52
20–25	0.0	+11.76	+10.0	−5.0	+14.28
25–30	−2.63	0.0	0.0	+15.0	+9.53
30–35	+5.26	No trees	0.0	+5.0	0.0
35–40	0.0	No trees	0.0	No trees	No trees

Percent change means 1995 percent distribution by treatment minus 1986 percent distribution by treatment.
[a] UR + T, understory removal, and thinned; UR + H + T, understory removal, herbicide, and thinned; UR + H + F + T, understory removal, herbicide, fertilizer, and thinned.

gression equations from El Fadl et al. (1989). The published equations were

$$\log_{10} W = 3.827 + 1.052 \log_{10}(BA), \ (R^2 = 0.80)$$

$$\log_{10} V = 0.718 + 1.273 \log_{10}(BA), \ (R^2 = 0.91)$$

where W is the total fresh weight (kg), V is the tree volume (m^3) excluding branches less than 7.5 cm in diameter, and BA is the basal area (m^2).

To estimate growth for the entire stand, new regression equations were developed for each treatment that related the initial basal area of the trees with dendrometers to growth for each year from 1987 to 1995. The power function ($\log_{10} y = a + b\log_{10} x$) was used for the new equations where y is the increase in biomass (volume) and x is the initial basal area. The coefficient of determination (R^2) for the new regression equations were obtained with original untransformed units (kg and m^3).

Percent relative weight and volume growth were determined from the increase in weight or volume divided by the total weight or volume prior to treatment initiation in 1986. The percent weight and volume were used to compensate for the 25% initial differences in basal area among some of the treatments. Analysis of variance was used to test for treatment differences of the percent relative weight growth and volume growth for each year from 1986 to 1995. Both untransformed and arcsine transformed data were used in the analysis. Where treatment

Table 3
Regression equations for the increase in the estimated weight (W, kg) and volume (V, m^3) of the sample trees, coefficients of determination (R^2) and P-values of the models for five treatments after 9 years (1995) in a mature *Prosopis* stand

Treatment [a]	n	Equation [b]	R^2	P-value
Control	23	$\log_{10} W = 2.471633 + 0.771903 \times \log_{10}\mathrm{BAI}$	0.4207	0.0008
		$\log_{10} V = 0.989489 - 0.553893 \times \log_{10}\mathrm{BAI}$	0.5396	0.0001
Thinned	17	$\log_{10} W = 1.391449 - 0.028337 \times \log_{10}\mathrm{BAI}$	0.0011	0.9013
		$\log_{10} V = -1.657949 + 0.171922 \times \log_{10}\mathrm{BAI}$	0.0366	0.4620
UR + T	20	$\log_{10} W = 2.581251 + 0.659332 \times \log_{10}\mathrm{BAI}$	0.7773	0.0001
		$\log_{10} V = -0.448001 + 0.871910 \times \log_{10}\mathrm{BAI}$	0.8537	0.0001
UR + T + H	20	$\log_{10} W = 2.559538 + 0.668076 \times \log_{10}\mathrm{BAI}$	0.3139	0.0102
		$\log_{10} V = -0.471432 + 0.879519 \times \log_{10}\mathrm{BAI}$	0.4319	0.0016
UR + T + H + F	21	$\log_{10} W = 3.132841 + 0.970393 \times \log_{10}\mathrm{BAI}$	0.5731	0.0001
		$\log_{10} V = 0.113739 + 1.188205 \times \log_{10}\mathrm{BAI}$	0.6574	0.0001

[a] UR + T, understory removal, and thinned; UR + H + T, understory removal, herbicide, and thinned; UR + H + F + T, understory removal, herbicide, fertilizer, and thinned.
[b] BAI, Basal area initial (m^2).

Table 4
Mean total weight growth and mean total volume growth after 2.5 (1989) and 9 (1995) years, annual volume growth (volume growth/9), and value per ha in a mature mesquite stand

Treatment [a]	Fresh weight growth (kg ha^{-1})		Volume growth (m^3 ha^{-1})		Annual volume growth (m^3 ha^{-1})	Annual [b] \$ ha^{-1}
	1989 [c]	1995	1989 [c]	1995		
Control	1158	5330	0.568	2.618	0.291	56.05
Thinned	1283	5210	0.552	2.212	0.248	47.76
UR + T	1880	7311	0.857	3.354	0.373	71.84
UR + T + H	1640	6177	0.725	2.761	0.307	59.13
UR + T + H + F	1894	7640	0.850	3.479	0.387	74.54
P-value	0.0992	0.1934	0.1484	0.1863		
MSE	184 107.8	2 751 230	0.0418	0.6051		

[a] UR + T, understory removal, and thinned; UR + H + T, understory removal, herbicide, and thinned; UR + H + F + T, understory removal, herbicide, fertilizer, and thinned.
[b] Price per ha based on \$428.00 m^3 for *Prosopis* lumber multiplied by 45% of annual volume growth; 45% is the mean percentage of total sawn lumber to total tree volume (El Fadl et al., 1989).
[c] 1989 data reported from Cornejo Oviedo et al. (1991).

differences ($P < 0.05$) were determined, mean separations were performed with Tukey's HSD test.

3. Results

The initial mean basal diameter of the total number of stems after thinning was 17.6 cm per stem with a range of 5.7–40.7 cm per stem. The sample (dendrometer) mean basal diameter was 18.1 cm per stem, with a range of 9.7–36.8 cm per stem. The sample stems were classified into 5 cm basal diameter size classes. The majority of the stems (96%) were less than 30 cm; 68% were less than 20 cm. The diameter frequency distribution within treatments changed over the 9 years (Table 2). All treatments experienced a decrease in the lower diameter classes, but the control had the least change over the lower three diameter classes (−2.63%). The four silvicultural treatments had a range from 10 to 23.81% decrease in the lower three diameter classes, with mow + thinning + herbicide + phosphorus exhibiting the greatest decrease.

The mean annual diameter increments by treatment of the sample trees after 9 years were: control, 0.12 cm year^{-1}, $n = 4$, SD = 0.0196; thinning, 0.22 cm year^{-1}, $n = 4$, SD = 0.0618; understorey removal + thinning, 0.22 cm year^{-1}, $n = 4$, SD = 0.0066; understorey removal + thinning + herbicide, 0.23 cm year^{-1}, $n = 4$, SD = −0.0554; understorey removal + thinning + herbicide + fertilizer, 0.27 cm year^{-1}, $n = 4$, *SD* = 0.0890.

The regression equations used to estimate the growth in weight and volume of the trees without dendrometer bands are listed in Table 3. These re-

Table 5
Mean percent relative weight growth (%) [a] in a mature *Prosopis* stand, by treatment for each year from 1986 to 1995, except 1994

Treatment [b]	Year 1	Year 2	Year 3	Year 4 (T) [c]
Control	1.31 C	1.85 D	2.24 D	4.40 C D
Thinning	1.90 B	3.19 C	4.24 C	7.18 B C
UR+T	1.93 B	3.92 BC	5.54 B	8.84 B AB
UR+T+H	2.11 AB	4.30 AB	5.57 B	9.25 AB AB
UR+T+H+F	2.50 A	5.06 A	6.91 A	11.27 A A
P-value	0.0001	0.0001	0.0001	0.0001
MSE	0.0424	0.1239	0.2668	0.9185

	Year 5	Year 6	Year 7	Year 9
Control	5.67 C	8.17 C	8.78 C	11.05 C
Thinning	9.12 B	13.01 B	14.01 B	18.44 B
UR+T	10.93 B	15.53 AB	16.42 AB	21.49 AB
UR+T+H	11.58 AB	15.68 AB	16.54 AB	21.69 AB
UR+T+H+F	14.29 A	19.15 A	20.42 A	28.38 A
P-value	0.0001	0.0001	0.0001	0.0001
MSE	1.6773	3.6446	4.3262	10.0024

For year and treatment, means followed by the same letter are not significantly different at the 0.05 level ($n = 4$) as determined by Tukey's HSD.
Data from 1994 (Year 8) were not complete and so were not included.
[a] Percent weight growth is the increase in weight/total weight prior to treatment initiation in 1986.
[b] UR+T, understory removal, and thinned; UR+H+T, understory removal, herbicide, and thinned; UR+H+F+T, understory removal, herbicide, fertilizer, and thinned.
[c] (T), arcsine mean separation using transformed data.

gression equations related initial basal diameter to growth in weight and volume for each of the five treatments. Most of these regressions were significant ($P < 0.01$) except for the regressions in the thinned treatment and the regression for increase in weight estimation in the understorey removal + herbicide + thinning treatment ($P = 0.0102$).

The overall ANOVA indicated that there was no significant treatment effect for the total growth in estimated fresh weight ($P = 0.1934$) or volume ($P = 0.1863$) after 9 years of growth (Table 4). Treatment differences in total weight and volume were not detected by Cornejo Oviedo et al. (1992), nor in any subsequent year since the study began. The highest total estimated weight increase was 1894 kg ha^{-1} in 1989 for the understorey removal + herbicide + fertilizer + thinning, and 7640 kg ha^{-1} in 1995, for the same treatment. The lowest weight growth was 1158 kg ha^{-1} in 1989 for the control and 5210 kg ha^{-1} in 1995 for the thinned treatment. The lowest volume growths, 0.5519 m^3 ha^{-1} in 1989 and 2.212 m^3 ha^{-1} in 1995, were in the thinned treatment. The control contained a larger number of stems per hectare, which probably accounts for the slightly greater growth rates observed in the control over the thinned treatment.

Percent relative weight growth per hectare (Table 5) and percent relative volume growth (Table 6) were tested for treatment differences. An overall ANOVA for untransformed and arcsine transformed data found significant treatment differences for each of the 9 years of the study for both percent weight and volume growth. A Tukey's mean separation test performed for each year exhibited a changing trend for individual treatment differences over the 9 years. Both the transformed and untransformed data had the same pattern of significant differences for the percent relative weight growth, with the exception of 1990. The transformed data resulted in slightly more treatment differences than the untransformed data. The arcsine transformed data for percent relative volume growth also resulted in more treatment differences than the untransformed data for the last 3 years reported: 1992, 1993, 1995.

Throughout the 9 years the relative growth rates for the control remained significantly different from

Table 6
Mean percent relative volume growth (%) [a] in a mature *Prosopis* stand, by treatment for each year from 1986 to 1995, except 1994

Treatment [b]	Year 1	Year 2	Year 3	Year 4
Control	1.56 C	2.20 D	2.67 D	5.28 D
Thinning	2.20 B	3.70 C	4.93 C	8.31 C
UR + T	2.27 B	4.66 B	6.60 B	10.54 BC
UR + T + H	2.52 AB	5.12 B	6.63 B	11.08 AB
UR + T + H + F	3.00 A	6.11 A	8.37 A	13.62 A
P-value	0.0001	0.0001	0.0001	0.0001
MSE	0.0630	0.1791	0.3892	1.3958

Treatment [b]	Year 5	Year 6 (T) [c]	Year 7 (T)	Year 9 (T)
Control	6.82 C	9.85 C C	10.58 C C	13.27 C C
Thinning	10.57 B	15.11 BC B	16.29 BC B	21.43 BC B
UR + T	13.05 B	18.60 AB AB	19.66 AB AB	25.92 B AB
UR + T + H	13.91 AB	18.96 AB AB	19.99 AB AB	26.60 AB AB
UR + T + H + F	17.29 A	23.29 A A	24.80 A A	34.94 A A
P-value	0.0001	0.0001	0.0001	0.0001
MSE	2.6039	5.7585	6.8790	15.7643

For year and treatment, means followed by the same letter are not significantly different at the 0.05 level ($n = 4$) as determined by Tukey's HSD.
Data from 1994 (Year 8) were not complete and so were not included.
[a] Percent volume growth is the increase in volume/total volume prior to treatment initiation in 1986.
[b] UR + T, understory removal, and thinned; UR + H + T, understory removal, herbicide, and thinned; UR + H + F + T, understory removal, herbicide, fertilizer, and thinned.
[c] (T), arcsine mean separation using transformed data.

the other treatments. The greatest mean separation occurred in 1989 for the relative weight growth, and in 1988 and 1989 for the relative volume growth. The thinning was implemented in 1988 and may possibly account for the greater significance in years immediately following. The years following 1989 exhibited a trend for the mean separation difference to become less significant, and in 1995 only the relative weight growth in the control treatment was significantly ($P = 0.0001$) different from the other treatments. The thinning treatment and the fertilizer treatment also indicated a significant ($P = 0.0001$) difference. By 1992, the percent volume growth no longer exhibited a significant difference between the control and the thinning treatment, although the control did remain significantly ($P = 0.0001$) different from the other three treatments.

A post-hoc T-test ($\alpha = 0.05$) was performed to test for treatment differences between the understorey removal + thinning + herbicide treatment, and the understorey removal + thinning + herbicide + fertilizer treatment for percent relative weight and percent relative volume in the final year (1995). The percent relative weight growth for these two treatments was significantly ($P = 0.0497$) different. The percent relative volume growth was also significantly different ($P = 0.0460$).

An ANOVA for the weight ($P = 0.9699$) and volume growth ($P = 0.6997$) of the phosphorus, and copper + phosphorus treatments indicated that there was no significant treatment effect (Table 7). An ANOVA of the relative growth also indicated no relative weight growth ($P = 0.6469$) or relative volume growth ($P = 0.6985$) differences. Application of the fertilizers were applied only 2 and 3 months prior to the end of the study. It is possible that insufficient time had passed to observe treatment differences.

4. Discussion

The greatest periodic annual increment (PAI) was achieved by the understorey removal + thinning + herbicide + fertilizer treatment for both 1989 (0.61 cm year^{-1}) and 1995 (0.27 cm year^{-1}). The periodic annual diameter increment after 9 years was approximately 50% of the PAI measured 2.5 years from the initiation of the study in 1986. It appears that the treatment effect diminished over time. The trend of diminishing treatment effect is also observed in the percent relative weight and volume growth over the 9 years (Tables 5 and 6).

The PAI of the treatment with the greatest growth compared favorably with growth data in other mature stands of commercial hardwoods in temperate and tropical areas. The greater growth rates achieved soon after release (2.5 years) are more closely related to the growth rates reported in other studies which were also measured within a few years from treatment implementation. Growth rates after 9 years were comparably slower. In a 50-year-old thinned Allegheny hardwood stand (*Prunus serotina*, *Acer rubrum*, *Acer saccharum*, *Fagus grandifolia*), trees with an initial mean diameter equal to the initial mean diameter of trees in this study had growth rates that ranged from about 0.12 cm year^{-1} for the control plot to about 0.23 cm year^{-1} for the fastest growth thinning treatment (Marquis and Ernst, 1991). This diameter class represented the more tolerant slow-growing trees (*Acer saccharum*, *Fagus grandifoli*) in the stand.

Ellis (1979) reported annual growth rates after 5 years in 40–45-year-old northern hardwood stands. *Prunus serotina* had a mean annual increment (MAI) of 0.37 cm year^{-1}, with a range of 0.22–0.54 cm year^{-1}; *Fraxinus americana* had a MAI of 0.50 cm year^{-1} with a range of 0.33–0.68 cm year^{-1}) after

Table 7
Paired T-test results for mean weight growth, volume growth, and mean percent relative weight and percent relative volume growth for phosphorus, and copper + phosphorus treatments from May to September 1995, in a mature *Prosopis* stand

Treatment	Mean weight growth (kg)	Mean volume growth (m^3)	Relative weight growth (%)	Relative volume growth (%)
Phosphorus	0.3362	0.0467	0.82	207
Copper + phosphorus	0.3630	0.0614	0.69	204
P-value	0.9699	0.6997	0.6469	0.6985

release and fertilization. After three growing seasons, the MAI for 50–60-year-old released, well-drained northern hardwoods (*Acer saccharum*, *Betula alleghaniensis*, and *Acer rubrum*) was 0.51 cm $year^{-1}$ (Stone, 1977).

The mesquite growth rates obtained in this study also compare favorably with mean annual growth rates of a mature native forest with 195 species, 32 of which are commercial species in the Brazilian Amazon. Thirteen years after logging, the PAI was 0.3 cm $year^{-1}$ over the 5-year study (Silva et al., 1995).

Archer (1995) found different growth rates for *Prosopis* on upland landscapes in South Texas. Trees growing in clusters were found on soils with an argillic inclusion. The mean age of the cluster type was 49 years and the MAI was 0.05 cm $year^{-1}$. *Prosopis* growing in continuous groves lacked the argillic horizon. The grove trees had a mean age of 75 years and a MAI of 0.12 cm $year^{-1}$. The MAI of the *Prosopis* grove (Archer, 1995) is the same as the PAI of the control in this study (0.12 cm $year^{-1}$). The *Prosopis* in this study were growing in a continuous forest and not in a cluster arrangement. It is not known if there is or is not an argillic horizon in the soil profile. The trees in the Archer (1995) study were not treated silviculturally and so are best compared with the control.

In an immature *Prosopis* sapling stand, basal diameters of 1.21 cm $year^{-1}$ were obtained when trees were thinned to 100 trees ha^{-1}, pruned to a single stem, and the interstitial area disked (Patch and Felker, 1997). A greater MAI of 1.69 cm $year^{-1}$ was obtained in the first 9 years of a cultivated plantation of *Prosopis* (Duff et al., 1994)

No significant treatment differences were detected for the absolute values of the biomass growth and yield growth. The greatest growth occurred in the phosphorus treatment. When the data were analyzed for percent relative weight and volume growth, the phosphorus treatment was significantly different from each of the other treatments in the third year, but did not remain so after 1989. The phosphorus treatment was still the greatest of all the treatments in 1995 and significantly different from the control and thinning treatments.

Messina (1992) found that thinning and nitrogen fertilizer treatments applied to *Eucalyptus regnans* had no interaction and growth increment was additive. In this study, the thinning treatment in 1995 had a 7.39% greater weight growth increment than the control. The understorey removal + thinning + herbicide + fertilizer treatment had a 17.33% greater weight growth increment than the control. Of this 17.33%, thinning contributed 43% of the total effect, while the fertilizer contributed 39% of the growth effect. Thinning had a larger effect than the fertilizer treatment, but only by a small percentage. In the Messina (1992) study, thinning contributed 1.8 cm $year^{-1}$ (60%) to the combined treatment effect. The fertilizer treatment contributed 1.2 cm $year^{-1}$, (40%).

The repeat of the phosphorus treatment and the addition of a copper + phosphorus treatment in 1995 had no observable effect in the time-frame analyzed. The phosphorus amendment applied in 1986 showed significance after 3 years from application. The growth of the 20 sample trees that received the copper application should be evaluated over a longer period of time.

Annual yields obtained in this study were very low compared with other hardwood stands. Possible explanations for the lower yield when diameters are similar are: lower density of *Prosopis* in a semi-arid region compared with temperate forest stand structure; shorter log length per tree; lower lumber yield due to defects (Rogers, 1984). Annual cubic volume growth in an Allegheny hardwood stand ranged from 2.49 m^3 $year^{-1}$ to 4.86 m^3 $year^{-1}$ for different thinning treatments. The value of the lumber in the Allegheny hardwood study ranged from \$43.74 ha^{-1} to \$161.46 ha^{-1} (Marquis and Ernst, 1991).

Although the volume growth per hectare for *Prosopis* is lower than for US temperate hardwoods, the attractive red/orange color and the high wood technical characteristics, i.e. above-average hardness combined with low shrinkage, should command a higher price per unit volume. Current wholesale prices of lumber in Texas are at least \$1200 m^{-3} due both to the quality and the labor in harvesting small logs. With conservative prices for *Prosopis* of \$428 m^{-3}, and even with much lower volume growth compared to Allegheny hardwoods, the annual returns of this stand result in a high value with a range of \$47.76–\$74.54 ha^{-1}. New methods for utilizing the short logs commonly found in native *Prosopis* stands for dimension lumber have been developed

(Dunmire et al., 1972; Rosen et al., 1980; Reynolds and Gatchell, 1982; Wiedenbeck and Araman, 1995). The price of *Prosopis* lumber and appropriate milling techniques may allow *Prosopis* to be competitive with other commercial hardwoods.

5. Conclusions

The mean annual diameter increments obtained in the different silvicultural treatments in this mature *Prosopis* stand are comparable with other commercial species in temperate and tropical areas, although the volume yield per hectare was lower than for other commercial species. Nevertheless, the greater price of *Prosopis* lumber partially compensates for lower yields per hectare. Yield may be improved through silvicultural practices that favor straighter stems for final crop trees, pruning, resprout control, and reducing competition (Cornejo Oviedo et al., 1991; Meyer and Felker, 1990; Patch and Felker, 1997).

The addition of phosphorus fertilizer has potential for increasing diameter growth in *Prosopis*. The addition of phosphorus fertilizer had an important additive effect to the understorey removal and herbicide treatments on the percent weight and volume growth, and was significant in the thinning treatment. It is too early to determine if the addition of copper will affect stand growth.

This study demonstrated the value in analysing long-term studies on a yearly basis. The results from individual years enabled us to determine the time-frame in which certain applications continued to significantly affect stand growth in relation to the other treatments. After 9 years, all treatment effects were still significantly different from the control, and the fertilizer treatment and thinning treatment were also significantly different from each other.

The initial thinning reduced the stand density to about 196 stems ha^{-1}. Felker et al. (1990) predicted that a maximum *Prosopis* lumber volume of 22 m^3 ha^{-1} would occur with 42 cm diameter stems at 9.5 m spacings (111 trees ha^{-1}). To achieve this objective the stand will have to be thinned about 50% in one or two stages. The value of the thinnings for firewood (less labor) was estimated to be \$403 ha^{-1} for the first thinning (Cornejo Oviedo et al., 1992). To maximize economic returns for the stand, it is recommended that future thinnings focus on crop tree selection based on stem quality.

Acknowledgements

We acknowledge the financial assistance of the USDA/CSRS Agreement No. 92-34284-7392, and the Driscoll Foundation. We thank the Driscoll Foundation for the use of their property for this ongoing research. We would also like to thank Guillermo Lopez and John Parish for their field assistance.

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