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Irrigation effects on growth and water use of *Quercus virginiana* (Mill.) on a Texas lignite surface-mined site

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ABSTRACT

Three different irrigation regimes (100%-high, 67%-medium and 33%-low of estimated well-watered conditions) were applied to *Quercus virginiana* (live oak) seedlings on reclaimed lignite surface-mined soils in central Texas as a means to study the physiology and growth of seedlings during establishment. The study period was 4 July 1990 through 30 September 1990. Transpiration, stomatal conductance and water potential were significantly higher ($\alpha = 0.05$) in the high treatment than in the low and medium treatments. Favorable water status contributed to somewhat greater seedling growth in the high treatment than in the low and medium treatments. Greater growth was associated with favorable seedling water potential, high stomatal conductance and rapid transpiration in the high treatment. Physiological responses and growth characteristics indicated that an irrigation rate of 1.2 $kg \cdot d^{-1}$ per seedling during the dry summer months was sufficient for seedling survival and establishment. An irrigation rate of 3.8 $kg \cdot d^{-1}$ per seedling promoted rapid seedling growth in addition to ensuring establishment.

INTRODUCTION

Surface mining for lignite coal in Texas has occurred on more than one million hectares. The reclaimed sites are often difficult to regenerate due to inadequate chemical and physical soil properties as well as the extreme exposure to climatic variables. Texas reclamation law requires that permanent vegetation be established and considerable interest exists in establishing native vegetation, particularly woody species that offer wildlife and aesthetic value. Research has shown that hardwoods have ample potential for revegetation (Vogel, 1981; McMinn et al., 1982; Cunningham and Wittwer, 1984), but most research in Texas has dealt with chemical and physical characteristics of the overburden (Dixon et al., 1980) or establishment with herbaceous

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species (Hons et al., 1980; Chichester and Hauser, 1984; Skousen and Call, 1987; Skousen et al., 1990). Information on woody plant establishment in Texas is limited (Davies and Call, 1990).

Previous work concerning hardwood tree and shrub establishment in Texas (Messina and Duncan, 1992) has shown that water was a factor limiting seedling survival on these reclaimed lands. Seedlings suffer water stress during summer if rainfall is sparse and infrequent. Water deficit can severely affect growth and survival by reduction in transported nutrients, loss of cell turgor, and reduced solar radiation interception (Fitter and Hay, 1987). The most obvious, and probably most effective, method of reducing seedling water stress is through irrigation. Although research has shown that irrigation can substantially increase survival, little data exist on tree seedling physiological response to irrigation on reclaimed sites. Quantification of water use by irrigated seedlings is necessary for determining amount and timing of irrigation.

This study was concerned with optimizing irrigation to aid establishment of live oak seedlings on reclaimed lignite surface mine lands in east-central Texas. Live oak was selected because it is common in the area and has shown hardiness in these adverse environmental conditions (Harms, 1990). Its sclerophyllous leaves are typical of many other semiarid woody species, implying that it has a natural ability to survive in this seasonally water-stressed area. The objectives of this study were: (1) to evaluate physiology and growth of live oak seedlings in response to three irrigation rates; (2) to determine irrigation rates to meet management objectives; and (3) to relate diurnal transpiration fluctuations to stomatal conductance and meteorological changes.

MATERIALS AND METHODS

The study area was on a reclaimed lignite surface mine at the Texas Municipal Power Agency's Gibbon Creek Lignite Mine in Grimes County, Texas (30°35′ N, 96°06′ W). The original topsoil was replaced on the reclaimed area in 1986. At that time, the site was also limed at a rate of 2240 $kg \cdot ha^{-1}$ and revegetated mostly with native bunchgrasses which leave a high percent of exposed soil surface. The study plot was established on a hillside with a 1% slope, an aspect of 95°, and a mean elevation of 85 m. The mine is in the Post Oak Savannah region of Texas which is characterized by gently rolling to hilly topography and an average annual rainfall of about 100 cm in the study area. The climate is humid subtropical with mild winters, long hot summers, and fairly evenly-distributed precipitation (although summer drought is common).

The top 25 cm of soil was analyzed prior to study establishment for texture, pH and nutrient content by the Soil Testing Laboratory, Texas Agricultural Extension Service, Texas A&M University System (Anon, 1980) (Table 1).

TABLE 1

Analysis of the top 25 m of reclaimed soil, Gibons Creek Lignite Mine

Soil characteristic	Analysis*	
Textural class	Loam	
pH	6.2	
Nutrients		
Nitrogen	1 ppm	– low
Phosphorus	13 ppm	– moderate
Potassium	306 ppm	– very high
Calcium	3001 ppm	– high
Maganesium	500 ppm	– high
Salinity	136 ppm	– none
Zinc	0.60 ppm	– high
Iron	33.67 ppm	– high
Manganese	5.34 ppm	– high
Copper	0.33 ppm	– high
Sodium	353 ppm	– low
Sulphur	39 ppm	– high
Boron	0.10 ppm	– low

*Characterizations (high, low, etc.) from Soil Characterization Lab, Texas A&M University.

On 10 May 1990, 60 planting holes were dug with a power auger to a depth of approximately 1 m into which live oak seedlings were planted at a 2 ×2 m spacing. The size of the study plot was 12 ×20 m. Site selection criteria included absence of erosion and nearby obstructions. The 14-month-old seedlings were obtained from the Texas Forest Service in 19-l containers. Each tree was planted approximately 15 cm below the original soil surface in order to create a small water-holding basin (microcatchment). Water treated by reverse osmosis was manually applied at a rate of 6 l twice weekly until 19 June 1990 when 12 trees were randomly selected for this study. Reverse osmosis water was used so that consistent irrigation water quality was maintained. On 19 June 1990, the soil surrounding each of the study trees was saturated until standing water appeared in the microcatchments. This was done in order to begin the study at the same soil water content for each tree. Each of the 12 trees was then watered with 12 l every other day until irrigation treatments began. Fifty grams of 16–4–8 fertilizer were applied twice to each tree before the treatments began on 4 July 1990.

After study commencement, watering was done every other day, unless it rained, beginning 4 July 1990 and proceeding through 30 September 1990. The treatments consisted of 100, 67 and 33% of estimated water usage in well-watered conditions determined prior to treatment initiation. It was realized that these irrigation levels were only approximations of actual water usage which depends upon seedling characteristics and daily weather fluctuations.

Therefore, the 100, 67 and 33% levels will henceforth be referred to as high, medium and low levels of irrigation. These treatments were selected to determine physiological and growth responses of the seedlings across a range of water-stressed conditions. No control treatment (0%) was included because without water the seedlings' chances for survival were expected to be negligible based upon previous research (Messina and Duncan, 1992).

The estimated water usage was determined prior to field experimentation by measuring soil water evaporation and transpiration from six well-watered trees from the same lot as those in the field. The gravimetric water loss of the six test trees was determined 32 km west of the study site when environmental conditions were sunny and hot, typical of the region's summer weather. The trees were in a potting soil mixture in 19-l containers which were well-watered and then drained. The container holding the tree was then sealed with plastic to prevent soil water evaporation and placed into soil holes outdoors such that the rim of the container was at the soil surface. After sunset each day, the trees within their sealed containers were removed from the holes, weighed, watered, drained, reweighed, and placed back into the holes. This was continued for 3 days, after which the average transpiration for the 3 days was determined gravimetrically. Per-tree leaf area was obtained by measuring the length and width of 150 leaves from each tree and applying a regression equation discussed later. A daily transpiration rate per unit leaf area ($5.65\ kg \cdot m^{-2} \cdot d^{-1}$) was calculated and multiplied by the leaf area of each of the 12 trees in the study to determine, in combination with estimates of soil water evaporation, the estimated irrigation rate for well-watered conditions.

Soil water evaporation at the study site was determined twice during the study (June 22 and September 3) using microlysimeters (35.5 cm inside diameter) in soil surrounding the trees at the study site. Before dawn, two microlysimeters were placed in the microcatchments of each of five trees in the high irrigation treatment which were well-watered the previous day. The microlysimeters were installed level with the soil surface, removed with the soil inside, placed in plastic bags to prevent evaporative loss and weighed. The microlysimeters were kept in the plastic bags and placed back in their holes flush with the surrounding soil and with their surface exposed. Twenty-four hours later the microlysimeters were removed and weighed. Average evaporation rate was approximately $3\ kg \cdot m^{-2} \cdot d^{-1}$ or $3\ mm \cdot d^{-1}$.

Application rates for each 2-day period were then determined for each of the field trees by multiplying the normalized transpiration rates times leaf area and adding soil water evaporation. Application rates were adjusted every 3 weeks for changes in leaf area. Water was transported to the field and applied manually. The watering application treatments were randomly assigned to each of the 12 trees for the entire treatment period.

On 21 July 1990, a spot treatment of glyphosate was applied around the trees to eliminate herbaceous competition for the applied water. Stem expansion and flushing during the season attracted deer to the trees so an ammonia-based repellant was applied 30 July 1990.

Measurements were made as follows during the treatment period:

Factor	Frequency
Leaf area	Every 3 weeks
Heights and diameters	Monthly
Stomatal conductance	Every 2 weeks
Plant water potential	Every 2 weeks
Transpiration	Every 15 min
Meteorological data	Every hour

Leaf areas were needed in order to normalize transpiration and to indicate tree vigor. Initially, a regression equation was established to be used for non-destructive leaf area determination in the field. Every leaf on three randomly selected live oaks was measured for length, width and leaf area. Leaf area was determined with a LI-3000 and LI-3050A (LI-COR Inc., Lincoln, NE). The following leaf area regression equation was derived using length times width for the independent variable and leaf area for the dependent variable: leaf area = 0.892 (length × width in cm) with coefficient of determination = 0.959, standard error of the coefficient = 0.006 cm^2, and standard error of leaf area = 0.373 cm^2.

Every 3 weeks during the study period a sample of leaves from each of the 12 trees in the field was measured for length and width, and then leaf area was derived using the regression equation shown above. The number of leaves to be sampled was determined from statistical evaluation of variation. The number of sample leaves was increased to 300 as the trees grew larger. The first leaf area measurements were made 12 June and the last 1 October 1990.

Monthly measurements of heights and diameters were made from 4 July 1990 through 26 September 1990. Height was determined from the soil surface at the bottom of the microcatchment to the top of the highest leaf. Diameter measurements were made at the root collar. Placement marks were made on the stem to maintain consistent measurements of stem diameter.

Diurnal stomatal conductance measurements were made every 2 weeks from 4 July 1990 through 26 September 1990 with a LI-1600 steady state porometer (LI-COR Inc., Lincoln, NE). Measurements were made at 1000, 1400, and 1800 h on calendar days 185, 200, 213, 227, 245 and 269.

Diurnal measurements of plant water potential began 4 July 1990 and continued every 2 weeks to 26 September 1990. Diurnal measurements were made on fully expanded leaves before dawn, and at 1000, 1400, and 1800 h using a pressure chamber (PMS Instrument Co., Corvallis, OR). Tests performed prior to the study period indicated that plant water potentials measured on leaves and twigs were approximately equal. Therefore leaves were used for plant water potential determination to minimize loss of seedling tissue.

Stem flow gauges (Dynamax Inc., Houston, TX) were used to measure transpiration continually and accumulated at 15-min intervals. The gauges used the stem heat balance method to determine water flow through the stem (Sakuratani, 1981; Baker and Nieber, 1989; Ham and Heilman, 1990; Steinberg et al., 1990). With this method, a steady, known amount of heat is applied to a small segment of the stem from a flexible insulated heater encircling the stem. The heat input to the stem is balanced by conductive losses and convective losses due to sap movement in the stem. Thermocouples are placed to account for heat transfer. The difference between estimated conductive losses and heat input yields the heat transported by the moving sap which in turn can be used to calculate sap mass flow rate.

Stem flow gauges were wired to a CR7 datalogger (Campbell Scientific Inc., Logan, UT) which was in turn wired to a 12-V deep-cycle marine battery connected to a solar panel supplying power to both the CR7, gauge heaters and thermocouples. A timer turned the power off between 2100 and 0600 h to minimize power usage and provide relief from the heat applied to the tree stem. This was deemed acceptable since nighttime transpiration during greenhouse testing from 2100 to 0600 h ranged from 7 to 25 g.

Hourly micrometeorological variables were measured with a CS-012 weather station (Campbell Scientific, Inc.) centered on the plot to measure ambient air temperature, global radiation, relative humidity, wind speed, and rainfall. The measurements were executed every 10 s and averaged hourly by a CR10 datalogger mounted inside the weather station.

The stem flow gauges, solar panel, battery and weather station were tested in the greenhouse before use in the field to compare gauge transpiration measurements to gravimetric transpiration. Ten trees from the same lot as those planted in the field were used in the greenhouse for measuring transpiration with the stem flow gauge. Gauges were attached to trees whose transpiration rates were measured gravimetrically daily. Accuracy and precision of the gauges were acceptable.

Data were analyzed using Statistical Analysis Systems (SAS Institute Inc., 1985). Irrigation effects on leaf area, height and diameter were determined through analysis of covariance using initial measurements as covariates. Effects on stomatal conductance, water potential, and transpiration were determined through a repeated measures analysis. Meteorological data were examined graphically and through regression, and not with repeated measures models due to insufficient degrees of freedom and multicollinearity.

RESULTS AND DISCUSSION

The high irrigation treatment produced significantly different results ($\alpha = 0.05$) from those of the low and medium treatments for all measurements except height and leaf area, and diameter in the low treatment (Table 2). The low treatment was not significantly different from the medium treatment.

Plant water potential, stomatal conductance and transpiration were significantly different ($\alpha = 0.05$) among days, likely due to changing micrometeorological conditions. The daily mean of physiological responses are compared to global radiation, temperature, relative humidity and windspeed in Fig. 1. Measurements depicted on the graphs were made on calendar days 185, 200, 213, 227, 241, 255 and 269. Measurements on day 241 did not include stomatal conductance because of equipment malfunction so they were made on day 245 instead. Weather data were omitted on day 255 again due to equipment problems.

Physiological responses on days 185 and 200 generally showed no difference among treatments (Fig. 1a–c) because of the early stage in the study. Trees then were at approximately the same water status, plus there was substantial rainfall on days 186 and 198 which contributed to lessening the treatment differences. Later in the study on days 213, 227 and 241, treatment high showed the highest (least negative) water potential (Fig. 1a), stomatal conductance (Fig. 1b) and transpiration (Fig. 1c), whereas the low and medium treatments showed minimal differences between each other and were more water stressed than the high treatment. On days 255 and 269 there were no noticeable differences among the treatments. This was likely a result of heavy rainfall on days 244 and 254 which alleviated water stress and provided more favorable meteorological conditions.

No rainfall occurred during the 29-day period from day 213 through 241 when water potential, stomatal conductance and transpiration were lower in both the low and medium treatments than in the high treatment, indicative

TABLE 2

Mean irrigation effects on response variables. Diameter, height and leaf area represent growth over the study period

Treatment	Transpiration ($kg \cdot m^{-2} \cdot d^{-1}$)	Water potential (MPa)	Stomatal conductance ($cm \cdot s^{-1}$)	Diameter (mm)	Height (cm)	Leaf area (m^2)
High	3.164^{a}	-1.3752^{a}	1.119^{a}	4.8^{a}	23.3^{a}	0.1511^{a}
Medium	2.496^{b}	-1.5758^{b}	0.844^{b}	2.1^{b}	7.6^{a}	0.0574^{a}
Low	2.459^{b}	-1.5866^{b}	0.837^{b}	3.4^{ab}	9.0^{a}	0.0756^{a}

Note: Means in columns with the same letters are not significantly different at the $\alpha = 0.05$ level.

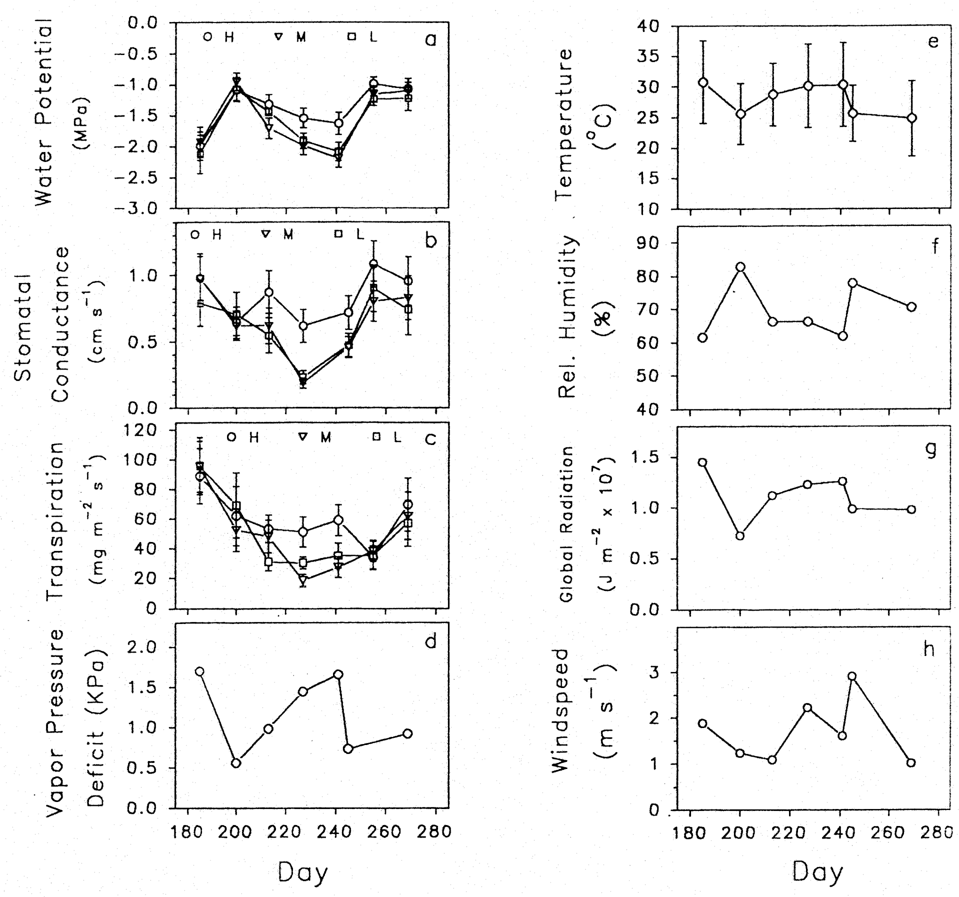

Fig. 1. Daily average measurements and daily total global radiation for the period 4 July through 30 September 1990 for live oak seedlings under three irrigation regimes. (Vertical bars represent 1 SE on a, b, and c and range on e. Total global radiation was determined using the trapezoidal rule.)

of more stressful conditions. The high treatment responses did not vary much during the period. The highest transpiration and lowest water potential during the period for the high treatment occurred on day 241 when VPD was very high. Total global radiation and average temperature also did not vary greatly during the period. However the average VPD increased sharply and relative humidity declined. Windspeed fluctuated but averaged above 1 m·s^{-1}.

Rainfall of 4.3 cm on day 244 and 4.1 cm on day 254 resulted in reducing or eliminating any significant treatment response differences for the remainder of the study.

Low water potential effect on transpiration and growth or photosynthesis varies among species. The photosynthetic rate of loblolly pine seedlings declined when water potentials dropped below −0.4 MPa, and became negligible at −1.1 MPa (Kramer and Kozlowski, 1979). In arid-land plants like the creosotebush (*Larrea divariacata* Cav.) growing in Palm Desert, California, net photosynthesis was highly correlated with dawn water potentials (Oechal et al., 1972). In February when dawn water potentials were −2.45 MPa net photosynthesis was 75 mg $CO_2 \cdot d^{-1} \cdot g^{-1}$ dry weight of leaf tissue, while in September when water potentials were −5.24 MPa photosynthesis was 9 mg $CO_2 \cdot d^{-1} \cdot g^{-1}$. There is uncertainty as to what extent decreased photosynthesis is due to stomatal closure or to decreased photosynthetic capacity (Boyer, 1976). Brix (1962) found that photosynthesis and transpiration decreased to the same extent in loblolly pine as water stress increased, suggesting that both were reduced by stomatal closure. In our study as water stress increased on days 213, 227 and 241 there was a trend of decreasing transpiration in the low and medium treatments, while the high treatment transpiration changed only slightly.

Day 227 was selected to show the relationship among the different physiological measurements and micrometeorological data (Fig. 2). By day 227, sufficient time had passed to show treatment responses and the weather was typical of the summer season.

The high treatment had the highest water potential (Fig. 2a), stomatal conductance (Fig. 2b), and transpiration (Fig. 2c) through the daytime hours of day 227 which together indicated less water stress and greater growth potential than experienced in the low and medium treatments. The transpiration rate and plant water potentials of the high treatment closely followed the global radiation trend, but lagged somewhat behind the VPD trend. The low and medium treatments' transpiration and stomatal conductance did not change substantially during the day due to less available water and more water stressed conditions. In the low and medium treatments, as stomatal conductance declined transpiration also declined; however, the high treatment transpiration increased from 1000 h to 1400 h as conductance decreased indicating that stomatal resistances had less effect. A feedback mechanism of stomatal closure in response to water stress is evident in the low and medium treatments. Threshold diurnal water potentials causing midday stomatal closure have been found by Federer (1976) and Federer and Geer (1976) in hardwoods ranging from −1.5 MPa in *Betula populifolia* (Marsh.) to −2.5 MPa in *Prunus serotina* (Ehrh.). If the threshold water potential is not reached, stomatal conductance is controlled by predawn water potentials and/or humidity (Hinckley et al., 1978). Predawn water potential for the high treatment was −0.625 MPa, approximately half as low as that in the medium (−1.11 MPa) and low treatments (−1.25 MPa).

Predawn water potential, stomatal conductance and transpiration on day 227 were 90, 200 and 170% higher, respectively, in the high treatment than the mean values in the low and medium treatments (Table 3). Favorable

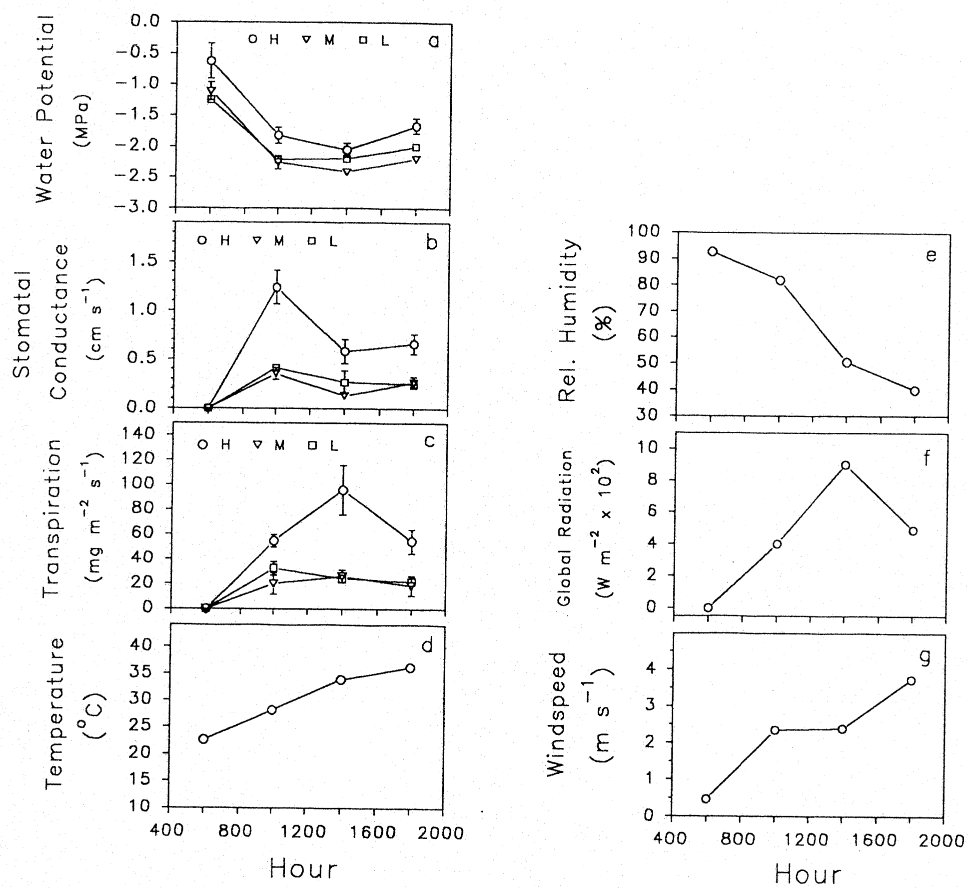

Fig. 2. Diurnal measurements for day 227 for live oak seedlings watered under three watering regimes (vertical bars represent 1 SE).

TABLE 3

Physiological and morphological comparisons of live oak seedlings for three irrigation regimes on day 227 of 1990

Treatment	Predawn water potential (MPa)	Average stomatal conductance ($cm \cdot s^{-1}$)	Average transpiration ($kg \cdot m^{-2} \cdot d^{-1}$)	Diameter growth (mm)	Height growth (cm)	leaf area growth (m^2)
High	−0.625	0.621	51.1	4.8	23.3	0.1511
Medium	−1.110	0.188	18.5	2.1	7.6	0.0574
Low	−1.250	0.232	19.7	3.4	9.0	0.0756

water status contributed to significantly greater seedling growth in the high treatment. Stem diameter, seedling height and leaf area were 128, 207 and 163% greater than in the medium treatment and 41, 159 and 100% greater than in the low treatment, respectively. The water balance of the plant ultimately affects the survival and growth.

Figure 3 compares transpiration to VPD for day 227. The transpiration rate peaks for the low and medium treatments were much lower than those for the high treatment due to water stress. Maximum transpiration for the high treatment was reached at about 1200 h, and shortly after 0900 h for the low and medium treatments. Transpiration followed global radiation in the high treatment, whereas stomatal closure and available water limited transpiration in the low and medium treatments. Atmospheric VPD is shown for only a general comparison to transpiration as leaf-to-atmosphere vapor pressure gradients drive transpiration. Generally, the leaf-to-atmosphere VPD increases faster and to a higher level during the day than atmospheric VPD as solar heat is absorbed by the leaf. Transpiration in the high treatment declined in the afternoon resulting from stomatal closure feedback response to water stress within the plant and decreasing VPD.

Figure 4 shows evapotranspiration and the amount of water applied for every 2-day period. The applied water consisted of the actual irrigation treatments as they were applied to each tree, plotted as a treatment average for

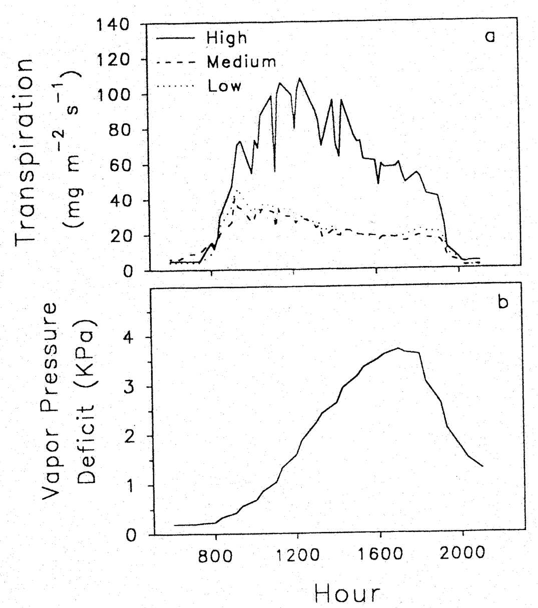

Fig. 3. Comparison of transpiration (a) and vapor pressure deficit (b) for day 227 for live oak seedlings under three watering regimes.

each 2-day period. Evapotranspiration (AET) is the total of the average transpiration for each treatment plus the soil water evaporation as measured by microlysimeters.

The AET decreased on rainy days (Fig. 4). The larger rainfalls occurred on days 186, 198, 244 and 254. The peaks in the applied water curves result from either rainfall or additional water applied to compensate for insufficient rainfall in previous days. Water was not applied on rainy days unless rainfall occurred after watering. For the high treatment, the AET remained below the applied water level between days 209 through 241 by about the same amount (Fig. 4a) indicating sufficient water supply. Water applied for the low and medium treatments were similar to AET during the entire season. Actual evapotranspiration for the low and medium treatments was well below that of the high treatment indicating water-stressed conditions. Rainfall during July and September was slightly greater than the monthly averages whereas rainfall during August was 5.7 cm less than average. Therefore, water stress was most pronounced during August.

Figure 5 shows basal diameter, height and leaf area growth during the sampling period. Diameter (Fig. 5a) for the high treatment was greater by the

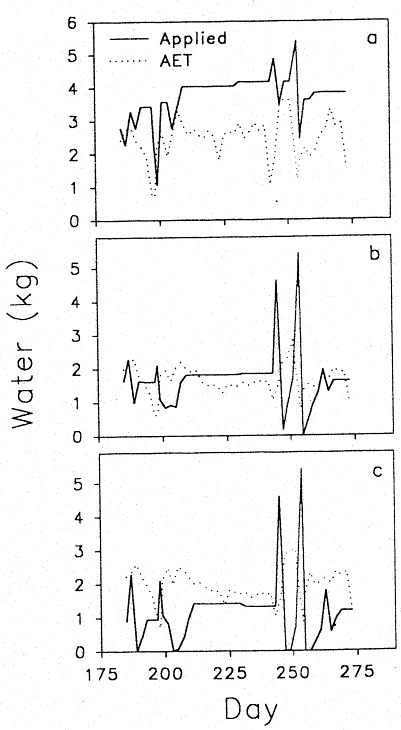

Fig. 4. Daily water applications for three watering regimes versus evapotranspiration (a = high, b = medium, and c = low irrigation rates).

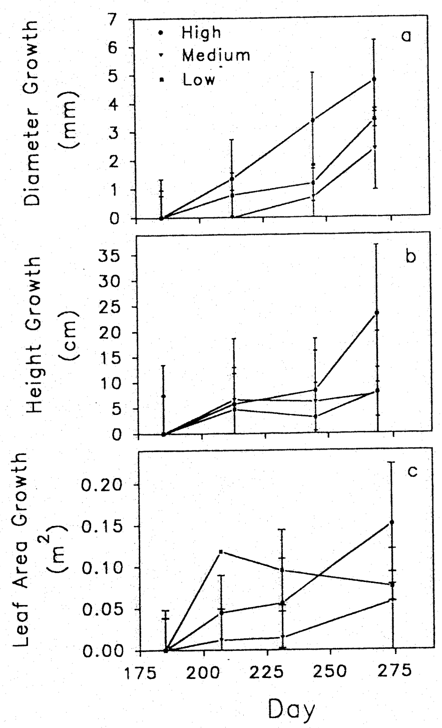

Fig. 5. Diameter, height and leaf area growth for the period from day 185 to day 273 for live oak seedlings under three watering regimes (vertical bars represent 1 SE.)

end of the period. The high treatment diameter was significantly greater than that of the medium treatment, but not the low treatment at the $\alpha=0.05$ level. However, at the $\alpha=0.10$ level, the high treatment diameter was also significantly higher than that of the low treatment.

Height (Fig. 5b) increases were slight for all treatments until the last month when the high treatment grew much more than the others. Height was not significantly different among treatments at the $\alpha=0.05$ level, but the high treatment was significantly greater than the other treatments at the $\alpha=0.10$ level.

Leaf area (Fig. 5c) increased in the high and medium treatments mostly in the last month. The low treatment leaf area initially increased and then showed a decline. A plant's response to water deficit is sometimes to decrease its leaf area by producing smaller leaves and/or dropping its leaves (Kozlowski, 1976). The sharp increase in leaf area in the low treatment between days 185 and 207 occurred early in the growing season when weather conditions were more favorable for growth. Leaf area growth was not significantly different among treatments at the $\alpha=0.05$ level, but at the $\alpha=0.10$ level, the high treatment had significantly greater leaf area than did the low and medium treatments.

Plants subjected to water deficit usually have lower leaf area than plants with adequate water supply which means their assimilation capacity is lowered resulting in less growth. Leaf expansion is reduced by low turgor pressures, and expansion will stop when turgor equals the yield threshold pressure of cell walls (Davies et al., 1981). Leaf production and leaf retention may decrease under chronic water stress. There are many reports of massive leaf shedding under water stress (Kozlowski, 1976). However, water stress has resulted in smaller crowns and fewer second- and third-order branches as well as reductions in the length of internodes (Fisher, 1986). In fact, water stress is known to strengthen apical dominance (McIntyre, 1977).

CONCLUSION

Diurnal transpiration, water potential, and stomatal conductance for the high irrigation treatment were significantly higher ($\alpha=0.05$) than those of both the low and medium water treatments during the study period. However, these variables were not significantly different between the low and medium treatments ($\alpha=0.05$). Seedling height and leaf area growth during the study period in the high treatment were significantly ($\alpha=0.10$) greater than those for the low and medium treatments, while the same variables did not differ significantly between the low and medium treatments ($\alpha=0.05$). All seedlings in the study survived regardless of irrigation treatment. Growth was greatest in the high irrigation treatment and was associated with favorable seedling water potential, high stomatal conductance and rapid transpiration.

These growth responses were produced by irrigation rates of 5.65 $kg \cdot m^{-2} \cdot d^{-1}$ for the high treatment and adjusted accordingly for the low and medium treatments. The irrigation rate on a seedling basis was approximately 3.8 $kg \cdot d^{-1}$ for the high treatment, 1.7 for the medium treatment and 1.2 for the low treatment. Depending on the objectives of the manager, an irrigation rate of 1.2 $kg \cdot d^{-1}$ per seedling is sufficient for survival and establishment of live oak seedlings. However if the objective is to promote rapid growth in addition to survival, an irrigation rate of 3.8 $kg \cdot d^{-1}$ per seedling would be more desirable.

Energy dissipation varied among irrigation treatments in response to decreasing stomatal conductance and transpiration in the more water-stressed treatments. During August when natural rainfall was 5.7 cm below average, stomatal conductance and transpiration were significantly lower in the medium (70 and 63%, respectively) and low (63 and 61%, respectively) treatments than in the high treatment, indicating greater stomatal control over transpiration in these treatments. Less energy was dissipated from leaves by transpiration in these treatments which would increase leaf temperature and promote energy dissipation by convection and reradiation. Seedling stomatal conductance dominated over the vapor pressure gradient and decreased transpiration in the low and medium treatments when compared to the high treatment.

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