ESTABLISHMENT, GROWTH AND WATER USE OF QUERCUS VIRGINIANA (MILL.) ON LIGNITE SURFACE-MINED SOILS FOLLOWING IRRIGATION[1]

by

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Abstract. Three different irrigation regimes (100%, 67% and 33% of estimated well-watered conditions) were applied to 12 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 in the 100% treatment than in the 67% and 33% treatments ($P = 0.05$). Favorable water status contributed somewhat greater seedling growth in the 100% treatment than in the 67% and 33% treatments. Greater growth was associated with favorable seedling water potential, high stomatal conductance and rapid transpiration in the 100% treatment. Physiological responses and growth characteristics indicated that an irrigation rate of 1.2 kg d^{-1} per seedling during the dry summer months was sufficient for seedling survival and establishment. An irrigation rate of 3.8 kg d^{-1} per seedling was necessary to promote rapid seedling growth in addition to ensuring establishment.

Additional Key Words: stem flow gauge, stem heat balance

Introduction

More than one million hectares have been leased for surface mining of lignite coal in Texas. The mixed overburden that is replaced during reclamation often has inadequate chemical and physical properties to support establishment and growth of woody species. Poor soil quality, coupled with extreme environmental conditions, has led to failed attempts at revegetation in this region.

A previous study by Messina and Duncan (this proceedings) showed that water was a factor limiting seedling survival on these reclaimed lands. It is likely that seedlings suffer water stress during normal summer summer weather when rainfall can be sparse and infrequent. Water stress can severely affect growth and survival by reduction in transported nutrients, loss of cell turgor, and reduced solar radiation interception. The most obvious and probably 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 useful 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 environmental conditions. 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 to:

1. Evaluate physiology and growth of live oak seedlings in response to three irrigation

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rates by testing the following hypotheses:

a. Height, diameter and leaf area growth will be directly affected by irrigation.
b. Transpiration, plant water potential and stomatal conductance will be directly affected by irrigation.
c. Sub-maximum irrigation rates will result in successful plant establishment even though plant water status and growth parameters will not be maximized.

2. Determine irrigation rates for management objectives.
3. 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 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 an elevation of 85 meters. 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, moist seasons and long hot summers.

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 (Table 1).

On 10 May 1990, sixty 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 m x 2 m spacing. The size of the study plot measured 12 m x 20 m. Site selection characteristics included absence of erosion and nearby obstructions. The 14-month-old seedlings were obtained from the Texas Forest Service in 19-liter containers. Each tree was planted approximately 15 cm

Table 1. Analysis of the top 25 cm of reclaimed soil, Gibbons 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
Magnesium	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.

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 liters twice weekly until 19 June 1990 when 12 trees were randomly selected for this study. Reverse osmosis water was used so that consistent quality was maintained in the irrigation water. 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 saturation level for each tree. Each of the 12 trees was then watered with 12 liters every other day until irrigation treatments began. Fifty grams of 16-4-8 Vigoro 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. The irrigation 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 nil based upon previous research.

The estimated water usage was determined prior to field experimentation by measuring soil 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-liter containers which were well-watered and then drained. The container holding the tree was then sealed with plastic to prevent soil 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 and 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 m^{-2} day^{-1}) was determined which was 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 in well-watered conditions.

Soil evaporation was determined 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 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, again before dawn to minimize evaporation, the microlysimeters were removed and weighed. This was done on June 22 and September 3 to determine soil evaporation rate (about 3 kg m^{-2} d^{-1} or 3 mm d^{-1}).

Application rates for each two-day period were then determined for each of the field trees by multiplying the normalized transpiration rates times leaf area and adding soil 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 minutes
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 nondestructive 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). A leaf area regression equation was derived using length times width for the independent variable and leaf area for the dependent variable: leaf area = 0.8919(length x width) with coefficient of determination = 0.959, standard error of the coefficient = 0.006, and standard error of leaf area = 0.373.

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 hours 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 hours 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-minute intervals. The gauges used the stem heat balance method to determine water flow through the stem (Sakurtani 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 by the following equation:

$$F = (Qh - Qr - Qv)/(Tu - Td)\ Cp \qquad (1)$$

where,

F = sap flow rate (g/s)
Qh = heater power (W)
Qr = radial conduction (W)
Qv = vertical conduction above and below heater (W)
Tu-Td = temperature increase in sap measured above (Tu) and below (Td) the heater (^{o}C)
Cp = specific heat of water (J/g^{o}C)

Stem flow gauges were wired to a CR7 datalogger (Campbell Scientific Inc., Logan, UT) which was in turn wired to a 12-volt 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 hours to minimize power usage and provide relief from the heat applied to the tree stem. This was deemed acceptable since nighttime transpiration during the greenhouse testing from 2100 to 0600 hours 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 ten seconds and averaged hourly by a CR10 datalogger mounted inside the weather station. The weather station was powered by the same deep-cycle marine battery and solar panel that powered the CR7 and stem flow gauges.

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. Results varied among trees, but accuracy and precision were acceptable.

Data were analyzed using Statistical Analysis Systems (SAS Institute Inc. 1985). 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 100% irrigation treatment produced significantly different results (P = 0.05) from those of the 33% and 67% treatments for all measurements except height and leaf area, and diameter in the 33% treatment (Table 2). The 33% treatment was not significantly different from the 67% treatment.

Plant water potential, stomatal conductance and transpiration were significantly different (P = 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 Figure 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 (Figure 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 100% showed the highest (less negative) water potential (Figure 1a), stomatal conductance (Figure 1b) and transpiration (Figure 1c), whereas treatments 67% and 33% showed minimal differences between each other and were more water stressed than the 100% treatment. Toward the end of the study 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.

On day 199 water potential was higher while stomatal conductance and transpiration were lower than on the previous day. In addition, responses among treatments did not vary greatly. A low VPD contributed to lower transpiration rates and higher water potentials. Rainfall of 2.2 cm on day 198 also contributed to the higher water potentials.

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 33% and 67% treatments than in the 100% treatment, indicative of more stressful conditions. The 100% treatment responses did not vary much

Table 2. Mean irrigation effects on response variables. Diameter, height and leaf area represent growth over the study period.

Treatment	Transpiration	Water Potential	Stomatal Conductance	Diameter	Height	Leaf Area
	($kg\ m^{-2}\ d^{-1}$)	(MPa)	($cm\ s^{-1}$)	(mm)	(cm)	(m^2)
100	3.164 a	-1.3752 a	1.119 a	4.8 a	23.3 a	0.1511 a
67	2.496 b	-1.5758 b	0.844 b	2.1 b	7.6 a	0.0574 a
33	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 P = 0.05 level.

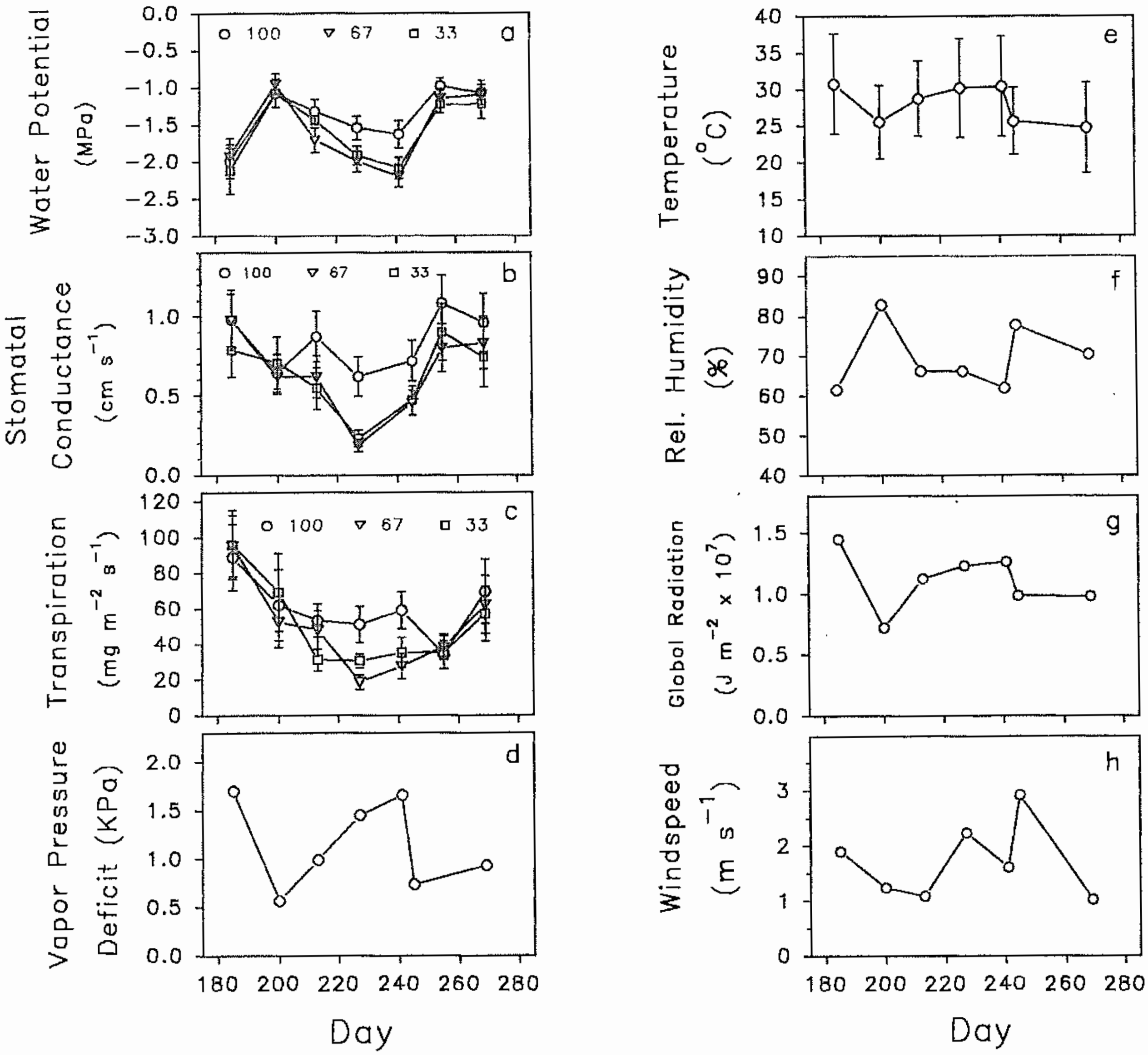

Figure 1. Daily average measurements and daily total global radiation for the period 4 July through 30 September 1990 for live oak seedlings under three irrigation regimes. (Vertical bars represent standard errors on a, b, and c and range on e. Total global radiation was determined using the trapezoidal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

during the period. The highest transpiration and lowest water potential during the period for the 100% 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 day^{-1} g^{-1} dry weight of leaf tissue while in September when water potentials were -5.24 MPa photosynthesis was 9 mg CO_2 day^{-1} 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 67% and 33% treatments, while the 100% treatment transpiration changed only slightly.

Drought-hardy plants like creosotebush are capable of adaptation to water stress. Selection of plants which retain foliage under drought would permit continued photosynthesis and growth in environments characterized by substantial and transient drought periods. This would allow increased productivity. Selection of families with substantial osmotic or elastic adjustment potential could result in plants that possess greater capacity for turgor maintenance, and consequently sustained gas exchange, and an increased capacity to absorb a greater total amount of water from the soil. Variation within species would allow for selection of both of these characteristics.

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

Treatment 100% had the highest water potential (Figure 2a), stomatal conductance (Figure 2b), and transpiration (Figure 2c) through the daytime hours of day 227 which together indicated less water stress and greater growth potential than experienced in treatments 67% and 33%. The transpiration rate and plant water potentials of the 100% treatment closely followed the global radiation trend, but lagged somewhat behind the VPD trend. The 67% and 33% treatments' transpiration and stomatal conductance did not change substantially during the day due to less available water and more water stressed conditions. In treatments 67% and 33% as stomatal conductance declined transpiration also declined; however, treatment 100% transpiration increased from 1000 hours to 1400 hours 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 67% and 33% 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 treatment 100% was -0.625 MPa, approximately half as low as that in treatments 67% (-1.11 MPa) and 33% (-1.25 MPa).

Predawn water potential, stomatal conductance and transpiration on day 227 were 90%, 200% and 170% higher, respectively, in the 100% treatment than the mean values in the 67% and 33% treatments (Table 3). Favorable water status contributed significantly greater seedling growth in the 100% treatment. Stem diameter, seedling height and leaf area were 128, 207 and 163% greater than in the 67% treatment and 41, 159 and 100% greater than in the 33% treatment, respectively. The water balance of the plant ultimately affects the survival and growth. Jarvis (1985) noted that the effect of water stress on conversion efficiency (conversion of intercepted solar radiation into biomass) had its greatest impact on sustained leaf area as opposed to yearly biomass production.

Figure 3 compares transpiration to VPD for day 227. The transpiration rate peaks for treatments 67% and 33% were much lower than those for treatment 100% due to water stress. Maximum transpiration for treatment 100% was reached about 1200 hours, and shortly after 0900 hours for the 67% and 33% treatments. Transpiration followed global radiation in the

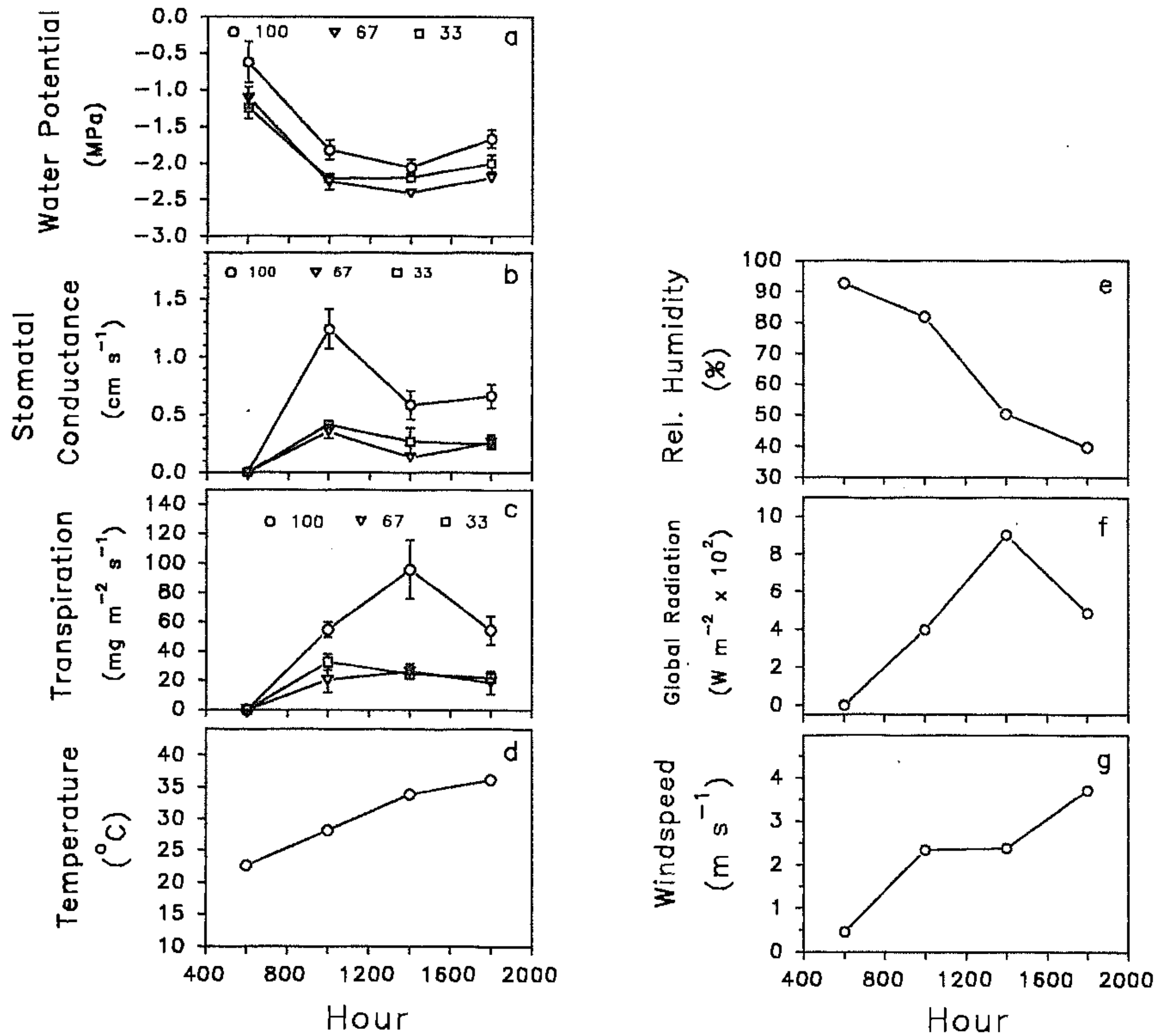

Figure 2. Diurnal measurements for day 227 for live oak seedlings watered under three watering regimes (vertical bars represent standard errors.)

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 ($cm\ s^{-1}$)	Average Transpiration ($kg\ m^{-2}\ d^{-1}$)	Diameter Growth (mm)	Height Growth (cm)	Leaf Area Growth (m^2)
100	-0.625	0.621	51.1	4.8	23.3	0.1511
67	-1.110	0.188	18.5	2.1	7.6	0.0574
33	-1.250	0.232	19.7	3.4	9.0	0.0756

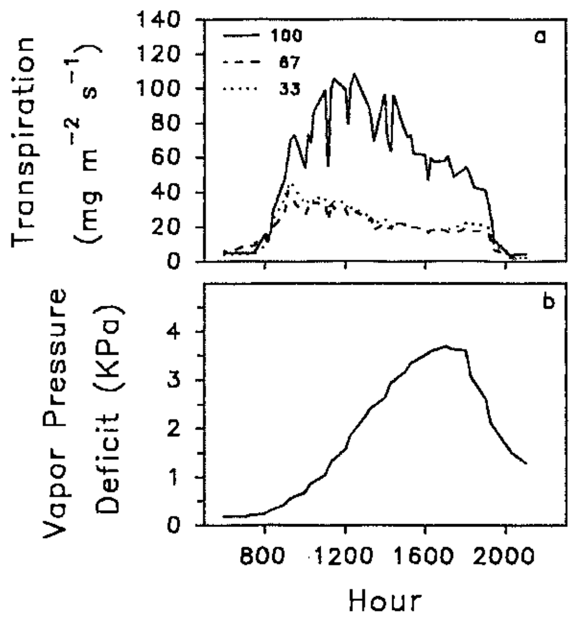

Figure 3. Transpiration (a) and vapor pressure deficit (b) for day 227 for live oak seedlings under three watering regimes.

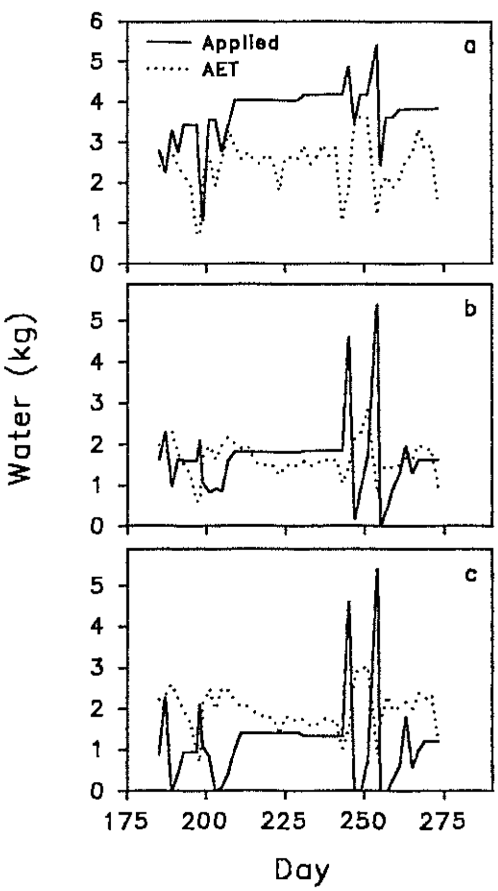

Figure 4. Daily irrigation and evapotranspiration for 100% (a), 67% (b) and 33% (c) regimes.

100% treatments, whereas stomatal closure and available water limited transpiration in the 67% and 33% 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 100% 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 each 2-day period. Evapotranspiration (AET) is the total of the average transpiration for each treatment plus the soil evaporation as measured by microlysimeters.

The AET decreased on rainy days (Figure 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 treatment 100% the AET remained below the applied water level between days 209 through 241 by about the same amount (Figure 4a) indicating sufficient water supply. Water applied for treatments 67% and 33% were similar to AET during the entire season. Actual evapotranspiration for treatments 67% and 33% was well below that of treatment 100% 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 normal. Therefore water stress was most pronounced during August.

Table 4 shows ratios between leaf area growth (m^2) and total transpiration (kg) during the study for the different irrigation treatments. Since destructive sampling was not implemented in this study, leaf area growth was

Table 4. Ratio of leaf area growth to transpiration for the entire study period for each irrigation treatment.

	Treatment		
	100%	67%	33%
Leaf area (m^2)	0.1511	0.0574	0.0756
Transpiration (kg)	68.1	31.5	45.6
Ratio (m^2 kg^{-1})	0.0022	0.0018	0.0017

used to represent aboveground production. The ratios were 0.0022, 0.0018 and 0.0017 m^2 kg^{-1} for treatments 100%, 67% and 33%, respectively. These ratios indicate that larger amounts of applied water fostered greater aboveground production per unit of water transpired, perhaps signifying that trees receiving less water experienced water stress.

Figure 5 shows basal diameter, height and leaf area growth during the sampling period. Diameter (Figure 5a) for the 100% treatment was much greater by the end of the period. The 100% treatment diameter was significantly greater than that of the 67% treatment, but not the 33% treatment at the P = 0.05 level. However, at the P = 0.10 level, treatment 100% diameter was also significantly higher than that of treatment 33%.

Height (Figure 5b) increases were slight for all treatments until the last month when treatment 100% grew much more than the others. Height was not significantly different among treatments at the P = 0.05 level, but treatment 100% was significantly greater than the other treatments at the P = 0.10 level.

Leaf area (Figure 5c) increased in treatments 100% and 67% mostly in the last month. Treatment 33% leaf area initially increased and then showed a decline. A plant's response to water stress 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 treatment 33% 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 P = 0.05 level, but at the P = 0.10 level, treatment 100% had significantly greater leaf area than did treatments 67% and 33%.

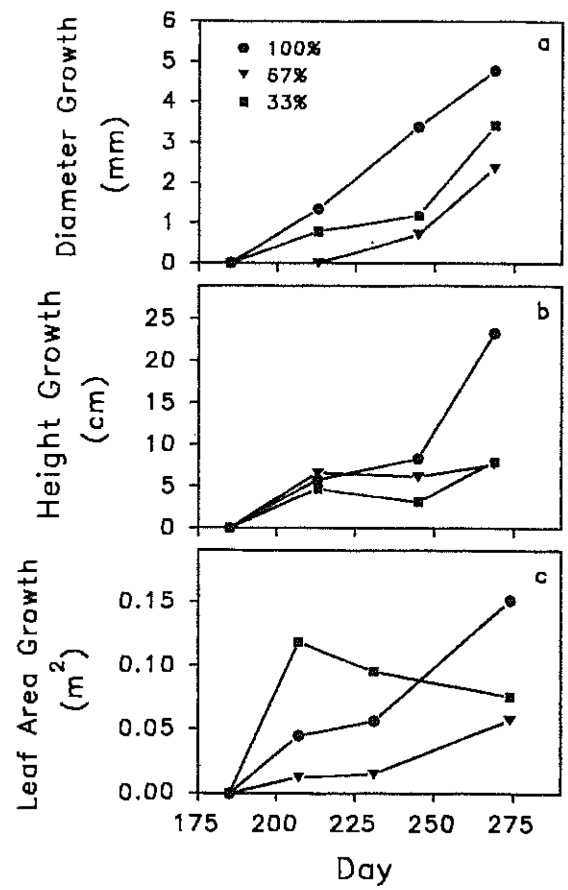

Figure 5. Diameter, height and leaf area growth for the period from day 185 to day 273 for live oak seedlings under three irrigation regimes.

Plants subjected to water stress 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, stomatal conductance, and stem diameter growth for the 100% watering treatment were significantly higher (P = 0.05) than those of both the 67% and 33% water treatments during the study period. However, these variables were not significantly different between the 67% and 33% treatments (P = 0.05). Seedling height and leaf area growth during the study period in the 100% treatment were significantly (P = 0.10) greater than those for the 67% and 33%, while the same variables did not differ significantly between the 67% and 33% treatments (P = 0.05). All seedlings in the study survived regardless of irrigation treatment. Growth was greatest in the 100% 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 m^{-2} d^{-1} for the 100% treatment and adjusted accordingly for the 67% and 33% treatments. The irrigation rate on a seedling basis was approximately 3.8 kg d^{-1} for the 100% treatment, 1.7 for the 67% treatment and 1.2 for the 33% treatment. Depending on the objectives of the manager, an irrigation rate of 1.2 kg 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 d^{-1} per seedling would be more desirable. Further study of the additive effect of fertilizer and water on seedling growth is necessary.

Energy dissipation varied between irrigation treatments in response to decreasing stomatal conductance and transpiration values in the more water-stressed treatments. During the month of August when natural rainfall was 5.7 cm below the monthly average, stomatal conductance and transpiration were significantly lower in the 67% (70% and 63%, respectively) and 33% (63% and 61%, respectively) treatments than in the 100% treatment, indicating greater stomatal control over transpiration in these treatments. Less energy was being 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 67% and 33% treatments when compared to the 100% treatment.

Relationships exist between plant water potential, transpiration, stomatal conductance and meteorological factors which act as indicators of the plant water status and ultimately the growth of the plant. These relationships in response to irrigation rates will reveal the amount of irrigation needed to meet management objectives of reclaiming lignite surface-mined soils with woody species.

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