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PHYSIOLOGICAL AND GROWTH RESPONSES OF MIDROTATION LOBLOLLY PINE TO TREATMENTS OF FIRE, HERBICIDE, AND FERTILIZER

Emily J. Goodwin, Lisa M. Marino McInnis, Hans M. Williams, Brian P. Oswald, and Kenneth W. Farrish[1]

Abstract—The objectives of this study were to examine the effects of fertilizer and understory vegetation control (herbicide and prescribed fire) on mature tree physiology and to link observed physiological responses with tree growth. Photosynthetic rate (photosynthesis), transpiration, stomatal conductance, stem diameter, and crown area were measured in two midrotation loblolly pine plantations in East Texas. Rates of photosynthesis, E and g_s for the midsummer measurements were significantly reduced by fertilizer treatments on both sites. Drought in east Texas during the last 3 years may have influenced this result. Trees receiving fire at the site with a comparatively more dense live pre-treatment understory exhibited higher rates of photosynthesis; however, prescribed fire had no positive effect on growth. Herbicide treatment significantly increased the change in diameter growth of unfertilized trees at both sites between 1999-2001 by an average of 5 percent, but had no effect on growth of fertilized trees. Increase in diameter growth per unit crown area was significantly greater in unfertilized trees receiving herbicide than in controls.

INTRODUCTION

Intensive silvicultural practices, such as fertilization and competition control, continue to be investigated for potential to induce greater growth in loblolly pine through augmentation or re-allocation of site resources. Chemical control of woody competitors using herbicide has been shown to increase pine tree diameter, basal area, and volume (Bacon and Zedaker 1987, Ezell and others 1997, Hanna 2000, Lauer and others 1993). Prescribed fire has been commonly used in commercial pine plantations to reduce fuel loads and the risk of wildfire. Prescribed fire can increase or decrease growth in mid-rotational loblolly pine, depending on the amount of collateral damage to the trees due to the fire (Wade and Johansen 1986). A positive growth response of midrotation loblolly pine to the use of fertilizer has been documented in various studies (Hanna 2000, Williams and Farrish 1994).

Crown form, size, and function are fundamental determinants of tree growth (Larocque and Marshall 1994a, Rouvinen and Kuuluvainen 1997), but the mechanisms responsible for the effects of silvicultural practices are not fully understood. Larger crown area translates into increased photosynthetic surface area, which can increase stem development and growth (Larocque and Marshall 1994b, Smith and others 1997). Crown growth provides a biological basis for the desired outcome of increased tree growth and optimal use of limited space. Crown growth is therefore a valuable parameter for use in assessing the growth response of trees under various conditions. Some studies have attempted to correlate an increase in site potential through silvicultural manipulation with gains in net photosynthesis (Samuelson and others 2001). To further investigate this potential relationship, this study examined the effects of fertilizer and understory vegetation control on mature tree physiology, and associated observed physiological responses with tree growth.

METHODS

Study Area

The study area consisted of two similar sites located in Cherokee County, TX on land owned by International Paper Company. The first site, Sweet Union (SU), was located within a 45-ha plantation with soils of the Ruston (Typic Paleudalf) and Attoyac (Typic Paleudult) series. The slopes ranged from 3 to 15 percent, and the site index was 71 at base age 25. Prior to planting, the SU site was sheared, windrowed, and burned. The site was then machine planted in 1982 with loblolly pine of unknown, but genetically improved, stock on 1.8 m x 3.7 m spacing (1,495 trees ha^{-1}). In 1998, the site was row-thinned to 833 trees ha^{-1} (basal area of 22 m^2 ha^{-1}).

The second site, Cherokee Ridge (CR), was located within an 80-ha plantation with soils of the Darco (Grossarenic Paleudult), Tenaha (Arenic Hapludult), and Osier (Typic Psammaquent) series. The slopes ranged from 3 to 15 percent, and the site index was 65 at base age 25. Prior to planting, the site received an aerial herbicide application of hexazinone at a rate of 13.6 to 18.1 kg ha^{-1}, followed by a slash disposal aerial burn. The site was hand-planted in 1985 on 1.8 m x 3.1 m spacing at 1,863 trees ha^{-1}, using genetically-improved stock of loblolly pines from two families (3-050-013-CC22L2 and 172-TFS ODHM2). The site was row-thinned and thinned within the rows to 465 trees ha^{-1} (basal area of 13 m^2 ha^{-1}) in 1998.

Five replicates were established in 1999 at each of the two sites. The experimental design was a randomized-block split-plot design. Each replication consisted of 8 subplots each 0.10 ha in size; half of each replicate was randomly chosen for application of fertilizer as the whole plot treatment. Subplot treatments consisted of herbicide, prescribed fire, herbicide and prescribed fire combination and no treatment (control). Each treatment was randomly located

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within the subplot, and 10-m buffer zones separated subplots. The trees within a 0.04-ha measurement area, in the center of each subplot, were used for all analyses. Each central measurement area contained approximately 35 and 20 trees at the SU and CR sites, respectively.

Vegetation Control Treatments

Herbicide—The herbicide treatment was applied in October, 1999. At CR, the herbicide was a mixture of 4.5 L ha^{-1} Chopper® (imazapyr) (American Cyanamid, Parsippany, NJ), 2.2 L ha^{-1} Accord® (glyphosate) (Monsanto, St. Louis, MO) 11.2 L ha^{-1} Sun-It® II oil (Agsco, Grand Forks, ND), and 76.7 L ha^{-1} water. The same mixture was applied at SU, except that the amount of Accord® was increased to 2.5 L ha^{-1} in an attempt to control a denser understory. To simulate aerial application, the mixtures were broadcast using a CO_2 backpack sprayer with a 3.66 m boom. Competing woody vegetation taller than 3.66 m was injected with a mixture of 100 ml Arsenal© AC (imazapyr) (American Cyanamid, Parsippany, NJ) diluted in 300 ml of water.

Fire—Firelines were installed with hand tools around each burn plot to preserve the 10-m buffer, and firelines were bulldozed around the site as a safety precaution. Prior to burning, ceramic tiles coated with strips of heat-sensitive paint (Tempilaq©, South Plainfield, NJ) were installed at each plot center to allow for an estimate of fire intensities. The subplots were burned in March, 2000 using strip backfires to limit scorch damage to the trees. Each site was burned on a separate day. On the burn days, the relative humidity was 58 percent and 49 percent at the SU and CR sites, respectively. The scorch height (vertical length of the crown in which needle death was evident) was determined for each tagged tree using a clinometer.

Fertilizer—In April 2001, the fertilizer treatment was applied using a crank spreader (Ev-N-Spred® Model 3100, Bristol, TN). Diammonium phosphate (DAP) and urea were applied at a rate of 224 kg ha^{-1} N and 28 kg ha^{-1} P, respectively. These rates were considered standard for operational fertilization in the region. Each site was fertilized on 2 successive days.

Measurements and Statistical Design

Physiology—Three trees per subplot were randomly selected for sampling during the first growing season following treatment applications. Branches in the upper one-third of the south-facing crown were excised using a 12-gauge shotgun. During the summer 2000, the first round of analysis consisted of 1-year-old needles from the first-flush of the 1999 growing season. Winter 2001 sampling consisted of two samples per plot, examining first-flush needles that expanded during the 2000 growing season. Summer 2001 testing used two samples per plot and included measurements of the current flush as well as fully expanded needles from the first-flush of the 2000 growing season.

Net photosynthesis, transpiration, and stomatal conductance were determined using six needles from each sample tree within 5 minutes of separation to minimize the influence of detachment (Samuelson 1998). Measurements were taken in the field with an infrared gas analyzer (Li-6400, LI-COR, Lincoln, NE, USA). An LED light source provided saturating irradiance at 1,600 $\mu mol\ m^{-2}s^{-1}$; CO_2 (400 $\mu mol\ mol^{-1}$) and humidity (50 to 60 percent) were controlled within the needle chamber. Midday measurements were taken from 11 a.m. to 3 p.m.

Treatment effects were tested using an analysis of variance (ANOVA) for a randomized block design (SAS Institute, Cary, NC). Results were considered significant at $\alpha = 0.10$ acceptance level. Tukey's multiple range test was used to examine mean differences.

Tree growth—Baseline outside bark diameter at breast height (d.b.h.) measurements were made on each tagged tree in each measurement plot in July, 1999. The trees were remeasured in December 2000 and in December 2001. For each tree, the increase in diameter growth ("%T") was expressed as follows:

$$\%T_{2001} = [(\text{d.b.h. in } 2001)^2/(\text{d.b.h. in } 1999)^2] \times 100 \qquad (1)$$

The %T value is, in effect, equivalent to a ratio of the basal areas of the trees converted to a percent. Because of the usage of d.b.h.^{2} in growth and yield models and various competition indices, the decision was made to use d.b.h.^{2} as opposed to d.b.h. alone (Biging and Dobbertin 1992, Ellis 1979, Moore and others 1973, Smith 1987).

In June of 2000, the crown area of each tree was determined from measurements of the length of the longest branch in each cardinal direction. The lengths of the branches between the branch tip and tree stem were estimated by measuring their vertical projection on the ground with an electronic distance meter (Forestor Vertex, Haglof, Sweden) (Farr and others 1989, Larocque and Marshall 1994a, Minor 1954, Peterson and others 1997, USFS 1970). The area of the polygon resulting from the four measurements was calculated, after correcting for the radius of the tree.

To facilitate hypothesis-testing regarding the possible role of the crown in mediating the effect of the treatments on growth, a novel metric ("LT") was formed as follows:

$$LT = [\%T_{2001}]/[\text{crown area}_{2000}] \qquad (2)$$

Although past studies have examined tree diameter growth in conjunction with some crown parameter (Binkley and Reid 1984, Curtin 1964, Lamson 1988, Larocque and Marshall 1994b, Sprinz and Burkhart 1987, Strub and others 1975, Waring and others 1980), no studies have characterized the variable in exactly this manner.

Hypotheses that the treatments resulted in greater tree growth per unit of canopy (more effective utilization of canopy) were tested using the LT metric. The Kolmogorov-Smirnov test revealed that the LT data were not normally distributed. Therefore, each of these hypotheses was tested using the Mann-Whitney U test to compare the LT values between the treatments ($\alpha = 0.05$). The comparisons between the control plots and each of the treatment plots were regarded as 3 independent comparisons (control vs. herbicide, control vs. fire, control vs. herbicide + fire). A similar strategy was implemented in the presence and absence of fertilizer at both the SU and CR sites.

RESULTS AND DISCUSSION

Physiology

Summer—Measurements for summer, 2000 were taken in July at the beginning of a series of dry months. Moisture stress compounded the severe drought experienced during 1999 in east Texas. Measurements taken at CR, the drier, sandier site, showed no significant difference between vegetation control treatments; however, a significant difference was shown for fertilizer treatments with unfertilized trees having greater photosynthetic rates, stomatal conductance, and transpiration (table 1). Kleiner and others (1992) found similar results in oak (*Quercus* spp.) seedlings in response to N additions and water stress. It was concluded that physiological performance is not improved by greater nutrition in the oak species used. This may be true for loblolly pine in dry conditions as well.

Higher photosynthetic and transpiration rates were also observed in unfertilized trees at SU for trees measured in the summer of 2000. This site, with its denser understory, had significantly lower photosynthesis in control plots than in fire-only and herbicide plus fire plots. Stomatal conductance and transpiration were significantly lower on control trees than in trees receiving herbicide only and herbicide plus fire (table 1).

The fertilizer trend was again detected in the 2001 growing season measurements. Unfertilized trees had higher photosynthesis, transpiration, and stomatal conductance at both sites (table 2). Fire-only plots had significantly greater photosynthesis, stomatal conductance, and transpiration than herbicide-only and control plots at CR. Because environmental conditions were drier on the day CR was burned, comparatively greater incidence of scorch was observed (table 3). Increased conductance and transpiration rates could be attributed to the scorch effect described in a study by Ryan (2000), in which defoliated ponderosa pine (*Pinus ponderosa* Engel.) had greater stomatal conductance and transpiration.

Winter—Measurements in winter 2001 showed stomatal conductance and transpiration to be significantly greater in fertilized trees at the CR site (table 4). There was higher than average rainfall for east Texas, which may have caused fertilized trees to have less stomatal limitation. Measurements from winter 2001 showed no significant differences in measured physiology at the SU site. SU had similar findings for fertilized plots, with unfertilized trees having greater photosynthetic, conductance and transpiration rates. Studies with *Zea mays* L. have reflected this finding. Wolfe and others (1988) found that rates of decline

Table 1—Means for treatments at the Cherokee Ridge and Sweet Union sites for summer, 2000

Treatment	Photosynthesis		Stomatal conductance		Transpiration	
	µmol CO_2 $m^{-2}s^{-1}$		*- - mol CO_2 $m^{-2}s^{-1}$ - -*		*mmol CO_2 $m^{-2}s^{-1}$*	
	CR	SU	CR	SU	CR	SU
Fertilizer	3.28a	5.92a	0.0352a	0.0634a	1.62a	2.63a
No fertilizer	4.18b	6.45b	0.0474b	0.0684a	2.15b	2.94b
Fire-herbicide	3.93a	6.51a	0.0441a	0.0727a	2.03a	3.13a
Herbicide	3.84a	6.27ab	0.0415a	0.0708a	1.89a	2.98a
Fire	3.64a	6.48a	0.0392a	0.0651ab	1.77a	2.75ab
Control	3.51a	5.48b	0.0415a	0.0551b	1.84a	2.29b

CR = Cherokee Ridge; SU = Sweet Union.

Table 2—Means for treatments at the Cherokee Ridge and Sweet Union sites for summer, 2001

Treatment	Photosynthesis		Stomatal conductance		Transpiration	
	µmol CO_2 $m^{-2}s^{-1}$		*- - - mol CO_2 $m^{-2}s^{-1}$ - - -*		*- mmol CO_2 $m^{-2}s^{-1}$ -*	
	CR	SU	CR	SU	CR	SU
Fertilizer	3.78a	2.78a	0.0351a	0.0232a	1.26a	0.70a
No fertilizer	4.42b	3.37b	0.0473b	0.0347b	1.79b	1.08b
Fire-herbicide	4.14ab	2.92a	0.0398ab	0.0272a	1.53ab	0.83a
Herbicide	3.65b	3.19a	0.0362b	0.0329a	1.24b	1.01a
Fire	4.59a	3.15a	0.0478a	0.0273a	1.81a	0.85a
Control	4.00ab	3.03a	0.0408ab	0.0283a	1.52ab	0.86a
Current flush	5.11a	2.74a	0.0565a	0.0375a	2.08a	1.14a
1-year old flush	3.08b	2.38b	0.0258b	0.0199b	0.97b	0.63b

CR = Cherokee Ridge; SU = Sweet Union.

Table 3—Scorch Index for burned plots at the Sweet Union and Cherokee Ridge sites[a]

Site	Treatment	Scorch index
CR	Fire	82.9
	Fire + herbicide	263.2
	Fertilizer + fire	256.3
	Fertilizer + fire + herbicide	283.4
SU	Fire	1.0
	Fire + herbicide	80.8
	Fertilizer + fire	105.3
	Fertilizer + fire + herbicide	160.2

CR = Cherokee Ridge; SU = Sweet Union; E = fertilizer; F = fire; H = herbicide.

[a] The Scorch Index was computed as the sum of the products of percent treatment scorch (percent) and mean scorch height (m) of the treatment plots.

in photosynthetic capacity were greatest in leaves with N additions than those without during a drydown period. It was suggested that early-season expansion caused greater water demands, which lowered gas exchange during the dry period. Walters and Reich (1989) found similar results using American elm (*Ulmus americana*), where high N concentrations increased photosynthetic rates when trees were provided with irrigation but decreased photosynthetic rates when trees were exposed to water stress.

Tree Growth

At CR, no significant increases in diameter growth per unit crown area (LT) were observed (fig. 1). This was unexpected given that increased photosynthetic rate was observed for unfertilized trees at the same site. In addition, the growth increase for trees receiving fire and fertilizer was significantly less than that of controls. This observation is partially supported by the scorch effect theory (Ryan 2000); it is possible that increased transpiration and conductance rates served as a compensatory mechanism for decreased foliar surface area. However, for this theory to be further supported, similar results on herbicide plus fire plots would be expected.

At SU, all combinations of vegetation control produced significantly greater LT values on unfertilized plots, compared to controls (fig. 2). However, no significant differences were observed in fertilized plots. Photosynthesis was higher in unfertilized plots receiving vegetation control than in unfertilized controls. This corresponded to an increase in LT for the same plots at SU. This result supports the conclusion that reduction of the thick understory present at SU (through use of herbicide competition control) could have contributed to increased photosynthetic rate in crop trees. Increased photosynthetic rate may have in turn contributed to the increased diameter growth per unit crown area. Increased photosynthetic rate of crop trees due to reduction in competitors as a result of herbicide use has not been previously reported, although one study reported the opposite effect (Samuelson 1998).

The increased tree growth observed in plots receiving fire can be understood in terms of an increased LT at SU, but not at CR. One explanation relates to overall vertical crown length. No vertical measurements of the crown were made. However, because the CR site was thinned more heavily than SU, the vertical distribution of foliage on trees at CR was generally greater. It is possible that the lower branches of trees at the CR site did not act as the carbon sink that is normally associated with lower pine tree branches. According to Stephens and Finney (2001), photosynthate production varies throughout the crown. It is generally thought that loss of the less efficient lower crown by scorching (which occurred at CR) will reduce the transpiration demand but not photosynthate production because the more-efficient foliage will remain. It was possible that physiological activity occurring in the lower branches of trees at CR significantly contributed to overall growth. A loss of foliage on lower branches as a result of scorch at CR would have been more detrimental to trees. Therefore, when lower branches were defoliated by scorch, growth was significantly reduced at CR but not at SU. Such an effect could not be determined, because samples removed from crop trees for physiological analysis were taken from the upper third of the crown.

Table 4—Means for treatments at the Cherokee Ridge and Sweet Union sites for winter, 2001

Treatment	Photosynthesis		Stomatal conductance		Transpiration	
	- μmol CO$_2$ m^{-2}s^{-1} -		- - - mol CO$_2$ m^{-2}s^{-1} - - -		- mmol CO$_2$ m^{-2}s^{-1} -	
	CR	SU	CR	SU	CR	SU
Fertilizer	4.41a	5.81a	0.0475a	0.0448a	1.03a	0.86a
No fertilizer	4.25a	5.72a	0.0441b	0.0496a	0.96b	0.96a
Fire-herbicide	4.49a	5.91a	0.0473a	0.0466a	1.01a	0.93a
Herbicide	4.29a	5.85a	0.0455a	0.0465a	0.99a	0.91a
Fire	4.16a	5.44a	0.0439a	0.0415a	0.97a	0.81a
Control	4.41a	5.85a	0.0466a	0.0541a	1.01a	0.99a

CR = Cherokee Ridge; SU = Sweet Union.

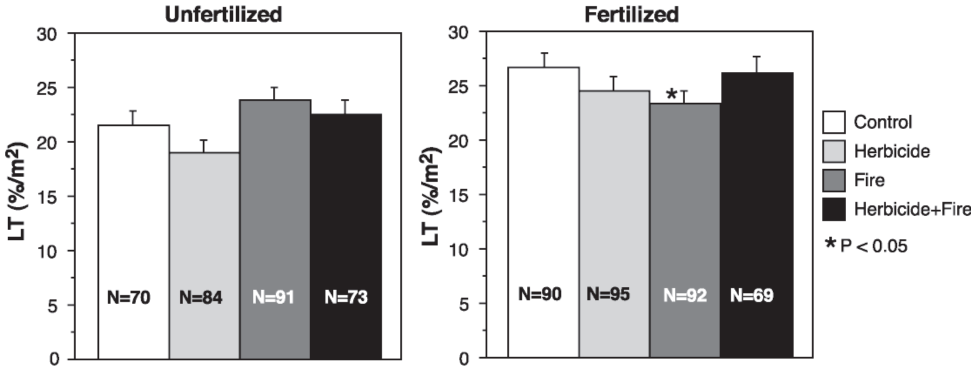

Figure 1—Effect of treatment on loblolly pine tree growth at the Cherokee Ridge site, assessed using LT (reported as mean ± standard error). LT was calculated as the percent ratio of the tree's DBH^2 to its baseline value (%T, measured in December 2001 and December 1999) per unit crown area (measured in July 2000). All comparisons made were between the respective vegetation control treatment and the control.

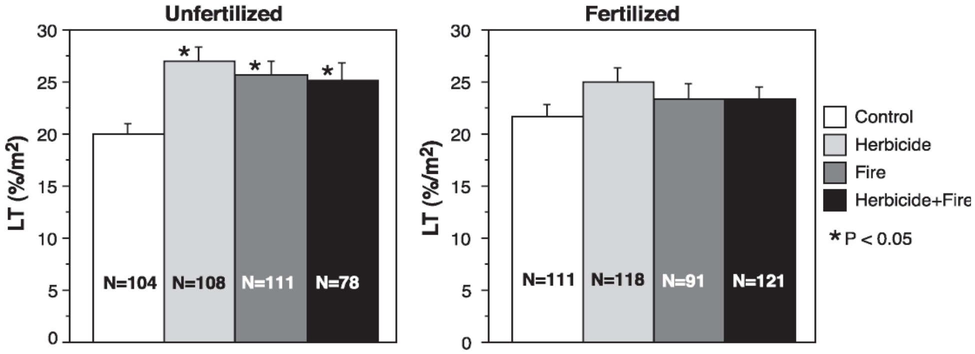

Figure 2—Effect of treatment on loblolly pine tree growth at the Sweet Union site, assessed using LT (reported as mean ± standard error). LT was calculated as the percent ratio of the tree's DBH^2 to its baseline value (%T, measured in December 2001 and December 1999) per unit crown area (measured in July 2000). All comparisons made were between the vegetation control treatment and the control.

Another possible explanation for the inability of LT to account for growth increases at the CR site could be due to initial crown size. The crown areas of trees at CR were generally larger than those at SU, due to prior thinning operations. It is reasonable to expect that it may take longer to detect differences in larger crowns than in smaller crowns, yet physiological differences were much more readily apparent (i.e. greater photosynthetic rate on unfertilized trees). Because the crowns were measured over a period of 2 years, it is possible that it was too early to observe changes in crown area in trees at CR with larger crowns.

CONCLUSION

Fertilizer failed to significantly increase rates of photosynthesis, transpiration, and stomatal conductance in mature loblolly pine trees at two sites in east Texas. Trees receiving vegetation control in the form of herbicide, fire, or herbicide plus fire exhibited variable physiological responses across the two sites. In terms of tree growth per unit crown area, unfertilized trees receiving herbicide treatment exhibited significantly greater growth increases than control trees. All results were likely impacted by the presence of drought throughout the study.

In situations where water is a limiting resource, fertilizer may cause increased physiological stress in pine trees. This result has been observed in studies involving American elm, oak species, and maize. However, the physiological stressor responsible for the observed responses is yet to be determined.

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