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Relationships between climate, radial growth and wood properties of mature loblolly pine in Hawaii and a northern and southern site in the southeastern United States

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ABSTRACT

Production rates of loblolly pine (*Pinus taeda* L.) in favorable exotic environments indicate that full biological expression of growth potential in loblolly pine has not yet been attained in its native range. In previous work, high productivity in a loblolly pine plantation in Hawaii (HI) was hypothesized to be related to a more favorable climate conducive to year round carbon gain. To better understand the role of climate in limiting loblolly pine growth, relationships between radial growth and climate were examined in mature loblolly pine grown on two sites representing the opposite latitudinal ends of its ecological niche, Mississippi (MS) and North Carolina (NC), and on a third site in Hawaii (HI) representing a more favorable exotic environment. Raw ring widths were detrended and chronologies built for each site. At the northernmost site, ring width index (RWI) was positively correlated to February, April and July temperatures, annual mean temperature of the current and previous year, and annual maximum temperature. In MS trees, the only significant correlation between growth and climate was a positive correlation between RWI and November temperature. Growth at the MS site was likely more impacted by frequent hurricanes. In HI trees, no significant correlations between growth and temperature were observed but RWI was significantly related to precipitation during the dry season, which occurred from May–September. Potential anatomical alterations in the earlywood and latewood transition zones and timing of earlywood and latewood formation were indicated and may account for low ring specific gravity and percent latewood in HI trees. The moderate temperatures at the HI site likely supported high productivity but sensitivity to precipitation in HI trees indicates that reductions in water availability may effect loblolly pine growth even under more moderate temperatures when evaporative demand is low.

1. Introduction

Loblolly pine (*Pinus taeda* L.) is the dominant plantation species in the southern United States (U.S.) (Schultz, 1999) and over the last 50 years a tripling of productivity has been achieved through improvements in genetics, seedling culture and management of resource availability (Fox et al., 2007). However, production rates of loblolly pine outside its native range in favorable exotic environments indicate that full biological expression of growth potential in loblolly pine in its native range has not yet been attained (Jokela et al., 2004). For example, growth rates of loblolly pine plantations in Brazil and Argentina can be three times that for similar stands on the U.S. mainland (Schultz, 1999). Maximum carrying capacity for closed canopy loblolly pine stands is between 45 and 50 $m^2\ ha^{-1}$ (Jokela et al., 2004), but basal area in a loblolly pine study in Hawaii (HI), known as the Olinda Study (Debell et al., 1989; Harms et al., 1994, 2000), was 93 $m^2\ ha^{-1}$ at 48 years of age (Samuelson et al., 2010). Higher carrying capacity in the Olinda Study and other favorable exotic environments appears to be related to climate, specifically low evaporative demand, mild year-long temperatures, and longer day lengths (Lanner, 1966) that promote year round carbon gain (Samuelson et al., 2010), support high leaf area (Harms et al., 1994) and reduce competition-related mortality (DeBell et al., 1989). Wallinger (2002) also suggested a longer growing season may explain a tripling of productivity in loblolly pine plantations in Brazil. In contrast, on the mainland in its native range, stem growth and latewood production are dominated by a surge of growth in the spring and slowing of growth in the fall related to temperature and water availability. The more moderate climate of HI may serve as a model of climate conditions supporting optimum productivity in loblolly pine (Samuelson et al., 2010)

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and growth under those climate conditions may provide insight into the potential impact of climate change on loblolly pine productivity.

Continued increases in the rate of warming are predicted to occur in the southeastern U.S. with the greatest projected increases in temperature and evaporative demand during summer months (Karl et al., 2009). In the future, the duration and intensity of summer droughts may increase (Seager et al., 2009) and impact loblolly pine forest productivity (Schmidtling, 1994; Noormets et al., 2010). For example, simulations from a process based ecosystem model indicated reductions in net primary productivity as high as 40% in southern forests in response to drought over the period of 1895–2007 (Chen et al., 2012). Changes in current climate envelopes (Ibáñez et al., 2006) may result in shifts in range limits so that species remain in their ecological or "requirement" niches (Leibold, 1995; Holt, 2009), which will impact forest planation management (Huan et al., 2011). To better understand how changes in climate may influence loblolly pine growth, we explored relationships between climate and stem radial growth in mature loblolly pine grown on two sites representing the opposite latitudinal ends of its ecological niche, Mississippi (MS) and North Carolina (NC), and on a third site representing a more favorable exotic environment in HI (the Olinda Study). We tested the hypotheses that: (1) the relationships between climate and tree ring indicators are of opposite sign in northern and southern sites on the mainland, and (2) because of low intra and inter-annual variation in temperature, there will be no relationship between climate and radial growth of HI trees.

In addition to growth, wood specific gravity (SG) measurements have been correlated with regional climate parameters of precipitation and temperature for both angiosperms (Wiemann and Williamson, 2002) and gymnosperms (Briffa et al., 2002). For example, within a given region, cultivation of *Pinus sylvestris* L. at an elevated temperature impacted earlywood SG (Kilpeläinen et al., 2003) while *Picea abies* (L.) Karst latewood SG showed a greater response to summer temperature (Franceschini et al. 2012) and drought (Bouriaud et al., 2005). Regional variation in wood properties for loblolly pine has been shown (Jordan et al., 2008), with the extended growing seasons in the southernmost latitudes affording greater ring SG as a function of greater latewood formation (Jokela et al., 2004). Antony et al. (2010) determined that stands in the southern Atlantic Plain and Gulf Coastal Plan have the highest SG within the loblolly pine range because of higher summer precipitation, higher mean annual temperature and a longer growing season. In the present study, the HI loblolly pine provided an opportunity to examine trends in ring, earlywood and latewood SG, and percent latewood of mature wood under climate conditions atypical of those found on the mainland.

2. Materials and methods

2.1. Hawaii (HI) site

The 1.6 ha spacing trial was located on Maui at an elevation of 1120 m on the northwest slope of Haleakala (Table 1). The study was established in January 1961 by the USDA Forest Service and Hawaii State Division of Forestry and Wildlife (Whitesell, 1970) and designed using a Latin Square Design with four replications. Each treatment plot was 0.11 ha with the central square 25 tree plot forming the measurement plot. The square spacing treatments were 1.8 m, 2.4 m, 3.0 m, and 3.7 m. One-year-old seedlings were purchased commercially and the seed source is unknown. Growth has been monitored over the life of the study (Whitesell, 1970; Debell et al., 1989; Harms et al., 1994, 2000; Samuelson et al., 2010). No thinnings were conducted.

A core 12 mm in diameter was removed at breast height (1.37 m) from three randomly selected trees, dominant in the canopy and within 1 standard deviation of average plot DBH, from each plot for a total of 48 cores in January 2009 when trees were 48 years of age. Eight cores were deleted from the data set due to core breakage or absence of pith. At the time of sampling, basal area and volume were similar among spacing treatments and averaged 93 m^2 ha^{-1} and 1076 m^3 ha^{-1}, respectively (Table 1) (Samuelson et al., 2010). Cores were pooled across treatments to increase the sample size in chronology development.

Monthly precipitation data were obtained from a weather station in Olinda located 1.8 km from the study site (http://www1.ncdc.noaa.gov/pub/data/, Olinda #1 332, Coop ID: 517041). The 12 month Standard Precipitation Index (SPI) values for the Olinda station were provided by the state Climatologist (Dr. Pao-Shin Chu, State Climatologist, Dept. of Meteorology, University of HI at Manoa). The SPI is a probability index with an index of zero indicating the median precipitation amount and positive values indicating greater and negative values indicating less than median precipitation (Guttman, 1999). Temperature data were obtained from a station located 3.6 miles from the study site in Kula, HI (http://www1.ncdc.noaa.gov/pub/data/, Kula Branch Station 324.5, Coop ID: 515000) beginning in 1979. No data on the Palmer Drought Severity Index (PDSI) were available for the Olinda area. The PDSI includes precipitation, evaporation, runoff and soil moisture in determining drought severity, with negative values indicating greater severity (Guttman, 1999).

2.2. Mississippi (MS) site

The research site was located in the USDA Forest Service Harrison Experimental Forest near Saucier, MS within the DeSoto National Forest 32 km north of Gulfport, MS (elevation 50 m) (Schmidtling, 1973). The experiment was designed as a randomized complete block with five cultivation-fertilization treatments and four blocks (see Johnsen et al., 2009 for a complete description). Five treatments were applied: (1) no cultivation or fertilization, (2) cultivated with no fertilization, (3) cultivated with a single application of 112 kg ha^{-1} of NPK fertilizer, (4) cultivated with a single application of 224 kg ha^{-1} of NPK fertilizer, and (5) cultivated with a single application of 448 kg ha^{-1} NPK fertilizer. Cultivated plots were disked prior to planting, disked three times each season for the next 3 years, and mowed in years 4 and 5 to reduce competition. Fertilizer was applied 1 year after planting. One-year-old bare root seedlings were from local seed were planted with on a 3.05 × 3.05 m spacing in February 1961. No thinnings were

Table 1
Description of loblolly pine stands located in Hawaii (HI), Mississippi (MS) and North Carolina (NC) including mean plot-level diameter at breast height (DBH), height (HT) and basal area (BA), and chronology descriptive statistics including mean sensitivity (ms), expressed population signal (EPS), and between tree correlation (r_{bt}). For the MS site, HT was last measured in 2000 and DBH and BA were measured in 2006. The other sites were measured at the time of coring. The number of tree rings in the NC stand ranged from 49 to 62.

Site	Location	Elevation (m)	Planted	Thinnings	DBH (cm)	HT (m)	BA (m^2 ha^{-1})	# Cores	ms	r_{bt}	EPS
HI	20.49°N, 156.17°W	1120	1961	None	36.7	30.6	93	38	0.33	0.17	0.88
MS	30.65°N, 89.04°W	50	1961	None	28.8	19.8	18	13	0.43	0.27	0.82
NC	36.00°N, 78.97°W	90	Natural	1980	34.2	31.7	50	30	0.26	0.16	0.85