GROWTH PERFORMANCE OF FOREST PLANTATIONS ON THE WESTERN MARGIN OF THEIR COMMERCIAL RANGE

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Title of Study: GROWTH PERFORMANCE OF FOREST PLANTATIONS ON THE WESTERN MARGIN OF THEIR COMMERCIAL RANGE

Major Field: NATURAL RESOURCE ECOLOGY AND MANAGEMENT

Abstract: The southern US contains some of the most productive plantation sites in the USA and Oklahoma is the western margin for several plantation species including sycamore (*Platanus occidentalis*), eastern cottonwood (*Populus deltoides*), loblolly pine (*Pinus taeda* L.), shortleaf pine (*P. echinata* Mill.), and pitch X loblolly pine hybrid (*P. rigida* X *P. taeda*). The long, hot summers and dry winters of Oklahoma provide an opportunity to compare the growth performance of these species at the edge of or outside of their natural range. The region is also prone to ice storms and glaze and pine plantations are negatively affected during such disturbances. Hence we carried out comparative studies on growth performance of different plantations in Oklahoma. One examined the growth performance and nutrient (nitrogen and phosphorus) uptake by sycamore and eastern cottonwood from a decommissioned swine lagoon in the north-central Oklahoma. The results showed that eastern cottonwood outperformed sycamore in both growth and nutrient uptake. The species showed the potential for removing a substantial amount of nutrients from the soil. In another comparative study between loblolly pine, shortleaf pine and pitch X loblolly pine hybrid in southeastern Oklahoma, loblolly pine outperformed both the other species, although shortleaf pine was native to the area. However, wood specific gravity was similar among the species. The final study examined simulated ice damage on loblolly pine stands which had previously undergone either thinning or thinning and pruning. Damaged trees had an average 2.4 m of the top removed. Four years after damage, the relative basal area decreased as the amount of live crown ratio loss increased. Thinned stands showed lower relative reduction in growth with the same level of crown damage than the non-thinned stands. Undamaged trees did not benefit from the opening caused by damaged trees. Unless the damage is severe, the stand can be allowed to recover after the thinning of the damaged trees.

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CHAPTER I

INTRODUCTION

The southern United States is the wood basket of the United States (Schultz 1997). Short-rotation woody crops (SRWC) promise high productivity under intensive management practices (Tuskan 1998) and the southeastern United States has been recognized as one of the primary potential regions for SRWC systems (Tuskan 1998). Southern pine forests are amongst the most productive forests in the United States (Guldin 2011). Extensive research on improved seedlings and intensive management practices including site preparation and fertilization has been the key to the development of successful pine plantation in the south in the last 60 years (Jokela et al. 2004; Fox et al. 2007).

Plantations of SRWC and southern pines are very likely to increase in the next few decades (Tuskan 1998; Ahn et al. 2000; Alig and Butler 2004). Part of the increase will be due to establishment of plantations beyond their current range. The potential future climate and the changes in temperature and precipitation may also cause species to shift their natural range, including changes in forest dynamics and composition (Iverson and Prasad 2001; Iverson and Prasad 2002; Walther et al. 2002; Parmesan 2006). However, information on potential growth performance of SRWC and southern pines under future conditions is limited. Growth performance of SRWC and southern pines in the new extended region is important to study the productivity and risk of plantation failure, as we are not certain of the tree response under novel altered climatic conditions.

Oklahoma is the western margin for two major southern pines, loblolly and shortleaf pine, and provides the potential for pine plantation expansion in the southern United States (Ahn et al. 2000, Alig and Butler 2004). On the other hand, SRWC plantations are not common this far west, but may increase due to interest in biofuels feedstock production. Having long, hot summers, and dry winters, the state provides for the potential expansion of both SRWC and southern pine plantations. The region also receives frequent ice storms which damage the pine plantations. Therefore, this region is an important location to study the growth performance of both SRWC and southern pines.

I studied the growth performance of several clones of eastern cottonwood (*Populus deltoides var deltoides*) and American sycamore (*Platanus occidentalis*) growing on a decommissioned swine lagoon located in north-central Oklahoma. Cottonwood and sycamore are among the species identified for SRWC systems in the United States (Graham et al. 1992) and growth performance of these species in the swine lagoon allows us to quantify nitrogen (N) and phosphorus (P) uptake. These nutrients can be pollutants if they move into nearby water resources via leaching and/or run off. As the number of concentrated animal feeding operations (CAFO), and the number of animals inside them have been increasing (Copeland, 2010), total N and P release from these facilities, and chances of polluting nearby water resources has also increased which could adversely affect the environment (Susarla et al., 2002; Gilchrist et al., 2007). Study of total biomass production and nutrient removal by these fast growing species from the swine lagoon will provide us detailed insights on the biomass and nutrient partitioning and potential of the species if planted at other similar sites.

My next study was on growth performance of some commercially important southern pines, loblolly pine (*Pinus taeda* L.), shortleaf pine (*P. echinata*), and pitch X loblolly pine hybrid (*P. rigida* Mill X *P. taeda* L.) in the southeastern Oklahoma, the western margin for commercial loblolly pine range. Southern pines cover about 30% of the 81 million hectares of land in southeastern United States, of which loblolly pine and shortleaf pine alone cover 21 million hectares (Schultz 1997; Groninger 2000; Zeide and Sharer 2002; McKeand et al. 2003; Guldin 2011). Pitch X loblolly pine hybrid has better form than pitch pine, is ice damage resistant, and can even outperform the parent species on poor sites or outside the natural range of loblolly pine (Little and Trew 1979; Kuser et al. 1987; Johnson et al. 1991). Studies on the growth performance of these pines in southeastern Oklahoma can provide information to help make decisions regarding a species selection for biomass production, considering the potential ice damage in the region.

My final study was on the growth and recovery of loblolly pine after different levels of ice simulated damage in southeastern Oklahoma. Loblolly pine plantations require high financial investments in the beginning as they require intensive management practices. Thinning and pruning are routine silvicultual practices in loblolly pine plantations and are meant to optimize resource utilzation resulting higher growth of the remaining trees and thus higher income. Loblolly pine are also susceptible to ice damage (Samuelson et al. 1992; Aubrey et al. 2007) and any severe ice events may cost the land owners a huge economic loss. Thus, information on the growth and recovery of intensively managed loblolly pine stands after ice damage would be important when making decisions regarding the productive utilzation of the damaged stand such that the loss is minimized (Aubrey et al. 2007).

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CHAPTER II

EVALUATING PERFORMANCE OF SHORT-ROTATION WOODY CROPS IN A DECOMMISSIONED SWINE LAGOON

Abstract

Decommissioned animal waste lagoons contain large quantities of nutrients including nitrogen (N) and phosphorus (P) and can cause pollution of nearby water resources. Using short-rotation woody crops (SRWC) for nutrient uptake and biomass production might be an inexpensive and eco-friendly method for the stabilization of decommissioned lagoons. We evaluated the annual growth performance and nutrient uptake by sycamore (*Platanus occidentalis*) for five growing seasons and several clones of eastern cottonwood (*Populus deltoides*) for four growing seasons in a soil backfilled, de-watered swine lagoon in north-central Oklahoma. Growth performance and nutrient uptake of cottonwood was higher than the sycamore in our study. At the end of the study, 5-year old sycamore reached an average height of 5.84 m [standard error (s.e.) = 0.39)] and had an average diameter at breast height (dbh) of 5.91 cm (s.e. = 0.20), compared to 4-year old cottonwood's 7.58 m (s.e. = 0.15) and 8.22 cm (s.e. = 0.34), respectively. Sycamore produced almost 30 Mg ha^{-1}of total biomass, whereas

cottonwood produced 53 Mg ha^{-1} by the end of the study. Total N and P uptake by sycamore was 327 (s.e. = 24) and 51 (s.e. = 4) kgs ha^{-1} respectively, whereas cottonwood N and P uptake was 699 (s.e. = 41) and 99 (s.e. = 6) kgs ha^{-1}, respectively, by the end of the study. We conclude that SRWC can use substantial amounts of nutrients from the decommissioned lagoons which can be removed from the site along with the harvest of the crops.

Introduction

In the United States, there are an estimated 238,000 animal feeding operations, 15% of which are CAFOs (concentrated animal feeding operations) (Dungan 2010). CAFOs are operations with larger number of animals that are confined in a small area before being sent for slaughter (US Environment Protection Agency). CAFOs can further be designated as large, medium, or small depending upon the nutrients they generate (EPA 2012). The data on livestock operations from 1982 to 1997 indicated an 88% increase in the number of animals in the larger CAFOs and more than 50% increase in the number of larger CAFOs in the United States (Copeland 2010). With the increase in population and increased demand for animal products, along with the cost effectiveness of CAFOs, these facilities are likely to increase in the future.

CAFOs have been accompanied by controversies as the lagoons for storing liquid manure also can be sources of infectious and resistant micro-organisms, greenhouse gases, odors, pesticides, and endocrine-disrupting chemicals, affecting both humans and the environment (Colborn et al. 1993, Fine et al. 1993, Pell 1997, Aneja et al. 2000, Johnson and Sumpter 2001, Schiffman et al. 2001, Susarla et al. 2002, Gilchrist et al. 2007, Vanotti et al. 2007). In addition, excess nitrogen (N) and phosphorus (P) present in theses lagoons might be hazardous to nearby water resources, even after their decommission, due to N and P run-off and/or leaching (Bicudo et al. 1999, Rabalais 2002, Jones et al. 2006). Although liquid manure can be used for irrigating crops, and some part of the manure gets digested, the sludge at the lagoon bottom remains inert and a potential source of pollutants.

Conventional methods such as removal and transportation of the sludge or pumping and treating by advanced technologies are expensive and may have negative impacts on the public and workers (Susarla et al. 2002, Jones et al. 2006). Therefore, phytoremediation, which uses plants to remove, degrade, or contain soil and water pollutants from a wide range of soil environments can be a good option (Lasat 2002, Eapen and D'souza 2005, Doty et al. 2007). Plants remediate polluted sites through a combination of processes, e.g., phytoextraction, phytostabilization, phytofiltration and phytovolatilization (Kumar et al. 1995, Ghosh and Singh 2005). Larger plant rooting volume or surface area increases the uptake of pollutants from a larger soil volume. Likewise, larger plants have the ability to phytoaccumulate more contaminants. The other benefits of phytoremediation include lower cost, carbon sequestration, soil stabilization, and biomass production (Paulson et al. 2003, Rockwood et al. 2004, Eapen and D'souza 2005).

Selecting the right species for specific tasks is important. Short-rotation woody crops (SRWC) could be an excellent choice to remove excess nutrients from the soil because they are fast growing, have high productivity (Dipesh et al. 2012) and have deep and extensive root systems (Tuskan 1998, Isebrands and Karnosky 2001, Licht and Isebrands 2005). As a result, SRWC use large amounts of available nutrients and water for their growth (Rockwood et al. 2004). Soil macro nutrients, especially N and P uptake is high in SRWC plantations under nutrient rich conditions. For example, a *Populus deltoides* plantation treated with N fertilizer extracted up to 125 kg N ha^{-1} yr^{-1} (Coleman et al. 2004), whereas annual P uptake by the species may be 15 kg ha^{-1} or more (Lodhiyal et al. 1994, Dipesh et al. 2012). Trees may use 450 kg of water per kg of net biomass production, however, water uptake by an individual tree depends upon its size including leaf area (Licht and Isebrands 2005). A 4-year old hybrid *Populus* stand (height range 11.0 to 15.1 and dbh range 8.3 to 15.1 cm) with a basal area of 21.4 m^2 ha^{-1} transpired 113 mm $month^{-1}$ (Hinckley et al. 1994). In addition, SRWC can produce between 5-20 Mg ha^{-1} yr^{-1} dry biomass (Stolarski et al. 2008, Stolarski et al. 2011, Dipesh et al. 2012). Because SRWC are intensively managed, they have a rotation cycle of 10 years or less (Rockwood et al. 2004) and some SRWC such as *Salix* spp. can be harvested in 3-4 years (Heller et al. 2003). Biomass from SRWC may also be a significant contributor to the energy feedstock. Thus, SRWC have the potential for supplementing several societal needs including renewable energy and extraction of nutrients from the sludge which might otherwise enter nearby water resources. The majority of the studies on performance of plants on contaminated soils are usually conducted in controlled conditions, and a better understanding of various aspects of growth performance and biomass/nutrient partitioning requires more extensive research under field conditions.

Sycamore is one of the model species of SRWC (Tuskan 1998) and can even tolerate metal contaminated sites (Pulford and Watson 2003). Sycamore can produce woody biomass greater than 14 Mg ha^{-1} y^{-1} (van Miegroet et al. 1994). *Populus* spp. can produce in excess of 20 Mg ha^{-1} y^{-1} woody biomass (Heilman and Fu-Guang 1993, Zsuffa et al. 1996). *Populus deltoides* has high nutrient requirements and exhibits rapid growth rate along rivers, swamps or standing waters (Gochis and Cuenca 2000, Robinson et al. 2000, Vose et al. 2000, Doty et al. 2007). We planted American sycamore (*Platanus occidentalis*) and eastern cottonwood (*Populus deltoides* var. *deltoides*), the two species identified in the SRWC in the United States (Graham et al.

1992) on a decommissioned swine lagoon in north-central Oklahoma. Our primary objective was to test the feasibility of cottonwood and sycamore stands to stabilize a decommissioned lagoon with a focus on N and P uptake. We also measured biomass production and biomass partitioning to stem, branch, and leaf. In addition, we compared the growth performance of 25 cottonwood clones. Such studies provide a detailed understanding of the growth and nutrient uptake potential on decommissioned lagoon site and may serve as a model for phytoremediation using SRWC on similar other sites.

Materials and methods

Site description

The site, located in Stillwater, OK, USA (36^{o}06’48”N, 97^{o}05’43”W), is a 0.8 ha decommissioned swine lagoon that had been operated for more than 50 years by Oklahoma State University. The average annual temperature of the site between 1998 and 2012 was 15.8^{o}C and annual precipitation was 85 cm. The last two years, 2011 and 2012, were hotter (16.4^{o}C and 17.3^{o}C, respectively) and drier (precipitation 43 and 57 cm, respectively) than other years in this time period (Oklahoma Climatological Survey 2013).

In November 2007, the liquid was pumped out from the lagoon until the sludge was exposed. The sludge had a pH of 7.3 and contained total N and P concentrations of 18.5 g kg^{-1} and 21.8 g kg^{-1}, respectively (Penn et al. 2013). Detailed chemical properties of the sludge can be found in Penn et al. (2013). When the sludge was exposed, a 10-30 cm soil cap of the existing earthen berm of the lagoon was compacted on the top of the exposed sludge and then contoured to maintain positive surface drainage from the site.

The soils were Easpur (Fine-loamy, mixed, superactive, thermic Fluventic Haplustoll) and Teller (Fine-loamy, mixed, active, thermic Udic Argiustoll) series, both of which belong to the same parent material, loamy alluvium. Both series consist of very deep, well drained, loamy to sandy clay loam soil with high water holding capacity. pH of the soil ranges from 6.6 to 7.2. When the work was complete, careful study of the site showed a lot of variability on soil and sludge depth but on average, the top ~60 cm was pure soil and the 61-120 cm was a mixture of sludge and soil. Below 120 cm there was a layer of pure sludge that varied in depth on top of a clay liner.

Stand establishment

In March 2008, unimproved sycamore seedlings and a mix of 25 different cottonwood clones were hand planted. Sycamore were 1-0 bare-root seedlings purchased from George O. White Nursery (Licking, MO). The 50 cm long cottonwood cuttings were originally selected from eight different states with the nine of the clones from southeastern Oklahoma (Table II-1). Clones were obtained from the Kiamichi Forest Research Center, Idabel, OK. Each species was planted in 4 separate randomly assigned plots (replications) at a 1.8 m X 2.4 m spacing (2316 trees ha^{-1}). Each sycamore plot was approximately 0.10 ha in size, and was fractionally larger than cottonwood plots, which had an area of 0.09 ha. Immediately after planting, oxyfluorofen [2-chloro-1-(3-ethoxy-4-nitrophenoxy)-4-(trifluoromethyl) benzene] (trade name: Goal, company: Dow AgroSciences) was sprayed to reduce competition. Cottonwood cuttings suffered deer herbivory during the first year and a deer fence was subsequently installed around the study site and cottonwood cuttings were replanted in March 2009. Of the four cottonwood replications, two received a random mixture of cottonwood clones and their identity was not tracked during the study. The clones in the other two replications were tracked throughout the study to compare clonal differences. The stands received glyphosphate as needed to reduce interspecific competition. Drip irrigation was provided as needed during the growing seasons from 2008 – 2011. In 2012 irrigation was provided by aboveground sprinklers.

Data collection

We measured height (h) and diameter at breast height (dbh) of all trees after each growing season. Every year, in October and/or early November from 2010 forward, when the leaves were still on the trees, we harvested several trees of varying sizes to ensure adequate representation of all size classes. Height and dbh were recorded before felling. We harvested 8, 4, and 2 trees of each species 2010, 2011, and 2012 respectively. We separated branches, leaves, and stem (with bark) from the harvested trees and oven dried the samples until constant weight. We combined the three years of data and developed different allometric equations for stem (wood + bark), branch, and leaf. The independent variable dbh^2*h was the best predictor for each individual biomass component (Eq. 1). For nutrient content data, we assumed bark biomass to be 10% of total stem biomass for sycamore (Cobb et al., 2008) and 20% of total stem biomass for cottonwood (Guidi et al., 2008).

$$y = a\,(\mathrm{dbh}^2 * \mathrm{h}) + b, \qquad \text{(Eq. 1)}$$

where y, the dependent variable, was component or total dry weight, a and b were regression coefficients (Table II-2), and dbh^2*h, the independent variable.

We accounted for leaf abscission before harvest using leaf litter collected from litter traps. Each plot had five rectangular or circular litter traps positioned under randomly selected trees. The rectangular traps had an approximate surface area of 0.16 m^2, whereas the circular ones had 0.11 m^2. Each year, leaf litter was collected throughout the growing season, either on a monthly basis or bi-weekly basis depending upon the rate of leaf fall. We found that 33% and 32% of the total leaf biomass was collected in the litter traps before the harvest for sycamore and cottonwood, respectively. Thus, the standing foliage of sycamore and cottonwood at the time of harvest was multiplied by 1.5 and 1.47 to calculate total leaf biomass.

Harvested trees were used for most of the nutrient sampling. We collected leaf, stem wood, stem bark and branch samples from the oven dried materials for nutrient analyses. The samples were analyzed by SWFAL (Soil, Water and Forage Analytical Laboratory), Oklahoma State University, to determine N and P concentrations. Nitrogen concentration was determined using the Combustion Nitrogen Analysis (CNA, LECO CN628, LECO Corporation, St. Joseph, MI, USA), whereas P concentration was determined using the total digestion process (Inductively Coupled Plasma spectrometry technique-ICP, Spectro Ciros, Spectro A.I. Inc., MA, USA). Both N and P were scaled to total N and P content per tree and then per hectare using the biomass of each aboveground component.

Data Analysis

Trees along the outside rows of all plots served as buffer trees and were not included in analyses. Data were analyzed using a single factor ANOVA to determine if the species differ in their aboveground biomass following the 2012 growing season. In addition, biomass and nutrient concentrations were compared between the species. Clonal performance of the cottonwood selections was tested based on aboveground biomass of the clones from two replications where clonal identity was tracked. Given the small sample size and the random distribution of clones within plots, buffer trees were included in this analysis. A single factor ANOVA was used to detect the differences in nutrient (N and P) uptake among the years by individual biomass components. A factorial ANOVA that included species and above ground component as main effects was performed to see if ranking of biomass components based on nutrient concentrations were consistent in both species based on 2012 data. Fisher's protected least significant difference (LSD) was performed for mean separation when appropriate. Tests were performed at 0.05 level of significance.

Results

Species growth and biomass partitioning

At the end of four (cottonwood) and five (sycamore) growing seasons, survival was 81 % and 96 % respectively. Five percent of the sycamore exhibited forking below breast height whereas the percentage was 14% in cottonwood. Although more sycamore trees survived, cottonwood growth outperformed sycamore throughout stand development (Figure II-1). At age 2, both dbh and height of cottonwood were more than twice those of sycamore at the same age. This absolute difference in tree size was maintained through age 4 at which time heights were 7.58 and 5.10 m and dbh were 8.22 and 5.43 cm in cottonwood and sycamore, respectively (Figure II-1).

Standing aboveground biomass was higher in cottonwood throughout the study (Figure II-2). In 2012, the four-year-old cottonwood contained 42 Mg ha^{-1} of total aboveground standing biomass which was significantly greater than the five-year-old sycamore biomass of 22 Mg ha^{-1} ($P < 0.0001$). For sycamore, total biomass accumulation increased 51% between age 2 and 3, 38% between age 3 and 4 and 19% between age 4 and 5. For cottonwood, total biomass accumulation increased by 92 % between age 2 and 3 and 40 % between age 3 and 4. The species differed in biomass partitioning during the study period. Sycamore distributed biomass in the different components in the order of stems>branches>foliage throughout the study period. In contrast, cottonwood had greater foliage biomass than branch biomass during the first year. Comparing both species at age four, the proportion of biomass components were 47%, 30%, and 23% for stem, branch, and foliage in sycamore and 60%, 22%, and 18% in cottonwood.

When leaf production from previous years (except first year) were added to the standing biomass from 2012 to estimate total biomass production throughout the study, cottonwood stands produced over 53 Mg ha^{-1} total biomass with a mean annual biomass production of 13.3 Mg ha^{-1} yr^{-1} through age 4. In contrast, 5-year old sycamore produced 30 Mg ha^{-1} total biomass at the rate of 6 Mg ha^{-1} yr^{-1} through age 5. Of the total sycamore biomass production (including cumulative leaf production), leaves accounted for 45% biomass, followed by stem plus bark biomass (34%) and branch biomass (21%). Cottonwood stems contained 48% of the total biomass production by age 4, followed by leaf (35%) and branches (17%).

Cottonwood clones growth performance

Cottonwood clones varied in height ($P = 0.002$), dbh ($P < 0.0001$), and standing aboveground biomass ($P < 0.0001$, Table II-1**).** Each tree of clone S7C7 from Texas had almost 1.5 times the height and 2.3 times the dbh of the clone 4 from Kentucky resulting in 450% more biomass difference between the best and worst performing clone. Clones, from Oklahoma and Texas generally exhibited greater standing biomass than clones from more northern sources when measured at age 4.

Nutrients

Each harvested plant component had similar nutrient concentrations among years except for the N in cottonwood stem, which was higher in the final year of study than the previous years ($P = 0.05$) (Table II-3). Hence we averaged the three years of nutrient concentrations for each biomass component for further analyses and scaling. We found that both N and P concentrations were inconsistent among the biomass components of the species ($P < 0.0001$ for species x component interaction) (Table II-4). Both species had higher concentration of N and P in their leaves than other biomass components ($P < 0.0001$). Stem and branch N concentration in sycamore were statistically similar to one another but lower than bark or leaf. In comparison, stem N concentration was lower than branch concentration for cottonwood. Cottonwood N concentration of the foliage ($P < 0.0001$) and bark ($P < 0.05$) was greater than for sycamore. Sycamore and cottonwood P concentrations did not differ ($P = 0.08$). For sycamore, P concentration varied among the biomass components (P < 0.0001) and was highest in foliage and lowest in the bark. For cottonwood, P concentrations were ranked foliage>branch>bark>stem and each component was different from one another (P < 0.0001).

After the 2012 growing season, including nutrient uptake by the leaves in previous years, 4-year old cottonwood stands had extracted 699 kg ha^{-1} N and 99 kg ha^{-1} P, whereas, 5-year old sycamore had extracted 327 kg ha^{-1} and 51 kg ha^{-1} of N and P, respectively (Figure II-3a, II-3b). The majority of nutrient uptake was by the foliage.

Nitrogen uptake by sycamore and cottonwood foliage was 76% and 68%, respectively, while P uptake by foliage was over 50% in both species.

Discussion

Species growth and biomass partitioning

Concentrations of N and P in the decommissioned swine lagoon solids in our study were similar to previous studies (see Penn et al. 2013). These high nutrient levels have the potential to pollute water sources if improperly handled (Cressie and Majure 1997, Steeves 2002, Jones et al. 2006, Vanotti et al. 2007). In our study, a total of 699 kg ha^{-1} N and 99 kg ha^{-1} P was removed from the soil through four years using cottonwood grown as SRWC. While this is only a very small fraction of the total N and P in the soil, the goal in our study is to capture as much available N and P. To this end, we have not measured any elevated levels of these nutrients in testing wells adjacent to the stands (data not shown). While we cannot guarantee that the plants have stopped the nutrients from moving into the water resouces because the nutrients were not mobile before the study, we surely can assert that using SRWC to stabilize the decommissioned lagoon was not only more cost effective than removal and transportation but also resulted in a beneficial use of the manure as it provided over 13 Mg ha^{-1} yr^{-1} of biomass which can be used to produce fiber or a cellulosic biofuel feedstock.

Cottonwood outgrew sycamore throughout the study period. At the end of the study, 4-year old cottonwood had greater height and diameter and contained almost twice the standing biomass as compared to the 5-year old sycamore. Other species that might have been tested include black willow (*Salix nigra*) and boxelder (*Acer negundo*) as they were both naturally invading the study site. In particular, black willow seemed well adapted to the site and is a species commonly grown in SRWC systems (Rockwood et al. 2004, Dimitriou et al. 2006).

Growth performances in our study were inconsistent with some previous comparative studies between sycamore and cottonwood. For example, Coyle and Coleman (2005) reported greater sycamore height and dbh, and ultimately greater aboveground biomass than cottonwood in control as well as treatment plots at age 3 in an irrigation and fertilization study conducted in South Carolina. Similarly, Lockaby et al. (1997) also reported better growth and survival of sycamore than cottonwood in an irrigation and fertilizer treatment study in upper Coastal Plain of Alabama. We used unimproved sycamore seedlings in contrast to cottonwood clones selected for fast growth. We also noticed that sycamore started producing leaves 2-3 weeks later than cottonwood during each year of study indicating a shorter growing season for sycamore than the cottonwood. In the final year of study, sycamore trees suffered more leaf abscission than the cottonwood from drought stress before trees were irrigated beginning in early July.

Both sycamore and cottonwood growth performance and biomass production in our study were lower than most previous SRWC studies. For example, sycamore height ranged from 8 m to 9.9 m while dbh ranged from 7.1 cm to 8.8 cm in 5-year old sycamore studies (Davis and Trettin 2006, Devine et al. 2006). A study by Cobb et al. (2008) in a fertilization and irrigation study on sycamore measured greater height, diameter, and biomass after six growing seasons than our 5-year old sycamore. Although the results came from stands one year older than ours, the differences were much greater what could be attributed to one year's age difference. Davis and Trettin (2006) also reported aboveground biomass of 29 Mg ha^{-1} after five growing seasons in a sycamore stand planted at 1385 trees ha^{-1}, a result of much greater height and diameter than our study. Similarly, van Miegroet et al. (1994) reported aboveground biomass ranging from 28 to 43 Mg ha^{-1} in an N fertilizer application study on sycamore after three years. The higher yield was the result of high density plantations (3333 trees ha^{-1}) compared to ours (2316 trees ha^{-1}). Coyle and Coleman (2005) reported similar annual sycamore aboveground biomass production as ours but in the less dense stand (1313 trees ha^{-1}) than ours.

Despite growing faster than sycamore in our study, cottonwood growth performance was slower than cottonwood or hybrid poplar in some previous studies. For example, 4-year-old cottonwood plantations had dbh greater than 14 cm and height above 9.6 m (Francis and Baker 1981, Robison et al. 2006), much greater than our study. Similarly, in a 4-year hybrid poplar (*Populus trichocarpa* X *Populus deltoides*) stands with N applications, Heilman and Fu-Guang (1993) reported height above 11 m and dbh greater than 8.5 cm, even in control plots. In a study by Labrecque and Teodorescu (2005), 4-year old hybrid poplar (*P. mxaximowiczii* X *P. nigra*) reached similar height as in ours, however, produced 66 to 72 Mg ha^{-1} of standing aboveground biomass, due to planting at high density (18,000 ha^{-1}). However, annual aboveground biomass production by cottonwood in our study was greater than some studies (e.g. Coyle and Coleman 2005).

Slower growth and relatively low biomass production of both species in our study despite growing in nutrient rich soils might be attributed to hot and dry conditions that occurred in central Oklahoma during 2011 and 2012. The maximum average temperatures during summer (June + July + August) were 38^{o}C and 35^{o}C in 2011 and 2012, respectively (average is 27^{o}C between 1998 and 2010). This was accompanied by abnormally low rainfall during these three months in 2011 and 2012 which were only 6.5 cm and 12.4 cm, respectively (average is 30 cm between 1998 and 2010). In 2012 we started irrigating in early July and the trees had already started exhibiting leaf abscission which may have reduced growth during that year. Additionally, part of the reason for slower growth might be attributed to the compacted soil cap which was not ideal soil conditions for the plantation establishment and tree growth.

Of the standing aboveground biomass at the end of the study, stem biomass including bark accounted for the greatest percentage of biomass in both sycamore and cottonwood similar to previous studies (Lodhiyal and Lodhiyal 1997, Puri et al. 2002, Ares and Brauer 2005, Cobb et al. 2008). As stem biomass continues to accumulate over time while both leaves (annually) and branches abscise, the percentage of biomass in the stem will continue to increase over time. When the previous three years of foliage was included to calculate total biomass production, sycamore foliage accounted for the greatest percentage of the biomass, whereas in cottonwood, stem biomass still contained the highest percent biomass. This would imply that cottonwood exhibited greater growth efficiency, i.e., stemwood production per unit of leaf biomass, than sycamore.

Cottonwood clones growth performance

Out of top ten best performing clones, seven were from Oklahoma, the other three were S7C7 from Texas and ST-124 and ST-66 from Mississippi. The only poor performing clones from Oklahoma source were 2-8 and 20-1. Cuttings imported from other locations did not perform as well confirming the importance of using locally adapted sources (Savolainen et al. 2007). Oklahoma is on the western edge of the eastern cottonwood range and as such it may be more critical to use locally adapted stock than further east. The variation in performance points out the ability to further select for fast-growing and site-specific clones.

Nutrients

Nutrient uptake by the trees depend upon plant demand, soil availability, and internal mobilization within the plant, and thus varies among the species. Nitrogen is taken up as NH_4^+ and NO_3^-, the former usually being taken up in greater amounts (Templer and Dawson 2004). Nitrate not taken up by the trees may be either lost or re-mineralized by the microbes to the available NH_4^+ form for uptake (Templer and Dawson 2004). Most of the soil P, on the other hand, is in the unavailable form and the available P is taken up in the form of Pi (orthophosphate). Mycorrhizae play an important role in P uptake as they increase the surface area of the roots for more P absorption.

Except for cottonwood stem N, N and P concentrations were fairly stable throughout a very active early stage of stand development. Among the tree components, foliage has the highest and stem wood tends to have the lowest N and P concentrations (Van Lear et al. 1984, Lodhiyal et al. 1995, Singh 1998, Ponette et al. 2001, Rockwood et al. 2004, Swamy et al. 2006, Cobb et al. 2008). This was true in our study, except for stem P which was higher than P concentration in the bark and branch. Nitrogen concentrations in most of the tree components in our study were similar or higher than those reported by previous studies (van Miegroet et al. 1994, Singh 1998, Casselman et al. 2006, Swamy et al. 2006, Cobb et al. 2008, Brinks et al. 2011). Similarly, P concentrations in the biomass components in our study were mostly higher than other studies (Ponette et al. 2001, Swamy et al. 2006). Although P uptake is highest in soil with pH 5.0 and 6.0 (Schachtman et al. 1998), the sludge in our study had a pH of 7.3. Therefore the, higher P concentration in the trees in our study might result from the extremely high P content of the soils at the site. Because of higher P concentration in the aboveground biomass components than reported by most previous studies, total P uptake by both species in our study was higher than those previously reported (Lodhiyal et al. 1994, Heilman and Norby 1998, Adegbidi et al. 2001). From the perspective of phytoremediation, the relatively high tissue N and P concentrations are a desirable because extraction is a function of biomass multiplied by concentration.

Nutrient uptake was almost consistent among the biomass components in both species, cottonwood always being larger than sycamore. Accompanied by higher aboveground biomass, cottonwood contained higher N and P than sycamore. Annual N uptake by sycamore in our study was within the range suggested for SRWC by previous studies (Adegbidi et al. 2001, Devine et al. 2006). However, total N uptake by cottonwood was higher than Swamy et al. (2006), because both aboveground biomass and N concentration were higher in our study. Total biomass yield and total N uptake can still be higher than our study if trees are planted in a high density and N fertilizer is applied (van Miegroet et al. 1994).

Conclusion

Decommissioned lagoons contain high levels of nutrients that are a potential threat to nearby water sources if not properly managed. Short- rotation woody crops provide an inexpensive and viable option to extract valuable nutrients from the soil/sludge mixture in decommissioned lagoons, produce biomass, and prevent nutrients from reaching water sources. Both sycamore and eastern cottonwood, growing at the edge of their natural range under several years of record high summer temperature, underperformed relative to other published studies east of Oklahoma despite being planted in the nutrient rich soils. Both species were able to extract a significant amount of N and P within a few years. However, cottonwood outperformed sycamore and took up almost 700 and 100 kg ha^{-1} of N and P, respectively, within four years, much greater than the 5-year old sycamore. Among the cottonwood clones, local clones were better than clones from more northern locations and produced higher biomass and higher nutrient uptake. The results from the study suggest that nutrients contained in sludge of a decommissioned lagoon can be beneficially reused and removed by SRWC which can potentially reduce off-site movement of nutrients and reduce the risk of water pollution.

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Tables

Table II- 1 Ranking of cottonwood clones based on aboveground biomass

Rank	Clone	Source	Height (m)	dbh (cm)	Aboveground biomass (kg tree^{-1})
1	S7C7	TX	8.41	11.92	34.61 a
2	I-8	OK	8.12	10.25	27.66 ab
3	104	OK	8.30	10.33	26.75 abc
4	113	OK	8.12	10.83	26.69 abc
5	20-8	OK	7.48	10.83	24.93 abcd
6	11-3	OK	7.91	9.90	23.69 abcde
7	117	OK	7.43	9.15	21.37 bcdef
8	84-11-5	OK	7.34	9.39	20.75 bcdef
9	ST-124	MS	7.47	9.34	19.78 bcdefg
10	ST-66	MS	7.57	8.80	18.53 bcdefgh
11	2-8	OK	7.47	7.98	16.22 bcdefgh
12	77-J01-00	IL	6.52	8.17	15.87 bcdefgh
13	ST-72	TN	7.30	7.90	14.99 cdefgh
14	20-1	OK	7.60	7.76	14.40 defgh
15	721005	TN	6.60	7.09	13.82 defgh
16	64-312-2	IL	6.64	6.66	13.54 defgh
17	ST-163	MS	7.49	7.42	13.11 defgh
18	ST-148	MS	6.97	7.06	13.05 defgh
19	D-19	IL	6.81	6.80	11.64 efgh
20	721704	TN	6.46	6.96	10.43 fgh
21	64-243-03	MO	6.88	6.34	10.41 fgh
22	2433	AL	6.95	6.50	10.19 fgh
23	111438	MS	6.97	5.72	8.90 fgh
24	64-251-3	MO	6.64	5.70	7.90 gh
25	4	KY	5.80	5.19	6.44 h

Clone identifiers and state of origin are listed. Aboveground biomass values that share the same letter indicate no significant difference ($P < 0.05$). (n=9).

Table II- 2 Regression coefficients for various biomass components of the harvested sycamore and cottonwood trees

Species	Stem		Branch		Foliage	
	a	b	a	b	a	b
Sycamore	114.3	1.77	56.5	1.37	54.3	0.31
Cottonwood	178.5	0.25	58.6	0.43	22.8	0.92

Fourteen different sized trees of each species were harvested 2010-2012. (n = 14).

Table II- 3 Nutrient concentrations in each tree component over three growing seasons for sycamore and cottonwood

		Nitrogen (g kg^{-1})				Phosphorus (g kg^{-1})			
Species	Age	Foliage	Branch	Bark	Stem	Foliage	Branch	Bark	Stem
Sycamore	3	18.6a	5.7a	7.9a	4.9a	2.0a	1.4a	1.3a	1.6a
	4	17.3a	4.6a	6.0a	2.4a	1.8a	1.4a	0.8a	1.2a
	5	19.6a	ψ	7.0a	3.8a	2.5a	ψ	1.1a	2.0a
Cottonwood	2	25.0A	8.2A	10.8A	3.4B	2.9A	2.3A	1.8A	1.1A
	3	25.3A	6.0A	9.1A	3.1B	2.3A	1.7A	1.4A	1.1A
	4	29.0A	ψ	14.0A	5.0A	3.0A	ψ	1.0A	1.0A

Each harvested tree was an experimental unit (n=8, 4, and 2 for the three successively older stand ages). Values with same letter in the columns indicate no significant difference within the species (lowercase for sycamore, uppercase for cottonwood) ($P < 0.05$). ψ indicates no data.

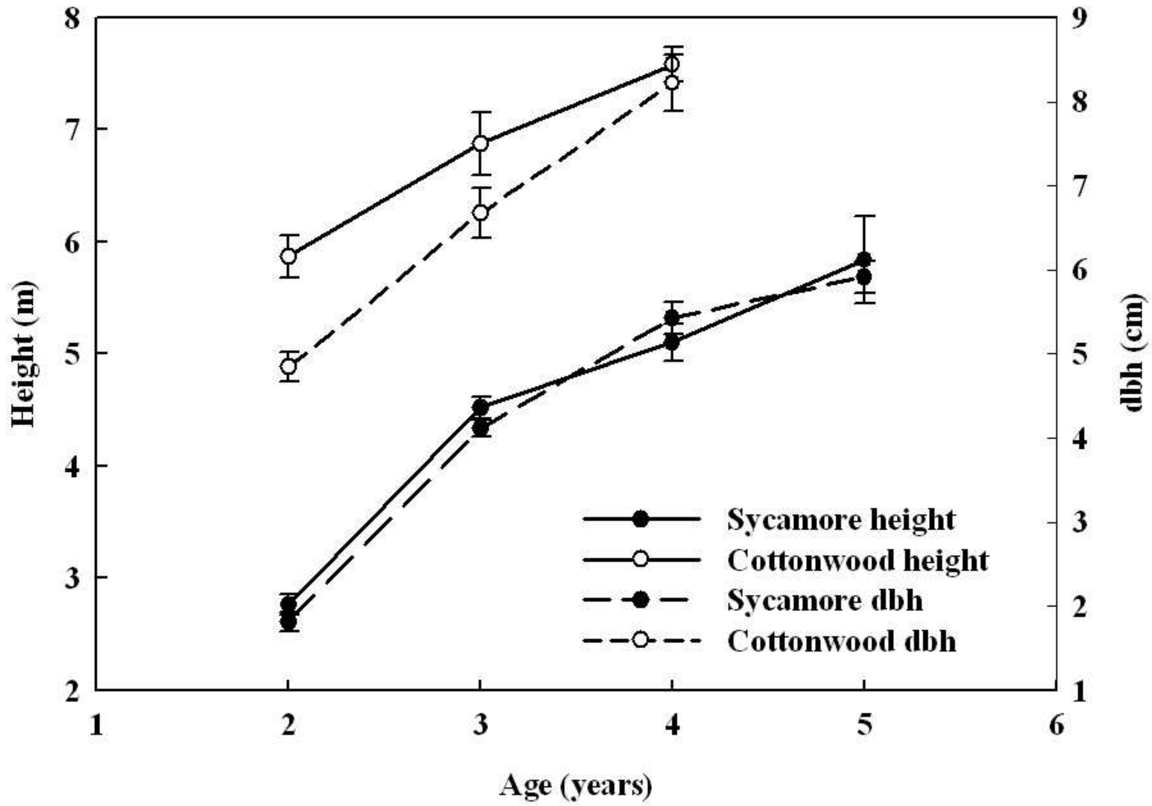
Table II- 4 Nutrient concentrations in each tree components for sycamore and cottonwood

	Nitrogen ($g\ kg^{-1}$)				Phosphorus ($g\ kg^{-1}$)			
Species	Foliage	Branch	Bark	Stem	Foliage	Branch	Bark	Stem
Sycamore	18.5Ab	5.1Ca	7.0Bb	4.9Ca	2.1Aa	1.4BCa	1.0Ca	1.6Ba
Cottonwood	25.8Aa	7.1Ca	11.3Ba	3.8Da	2.7Aa	2.0Ba	1.4Ca	1.0Da

Values with the same letter indicate no significant difference in either N or P concentration (upper case indicates comparisons among the biomass components and lower case indicates comparisons between the species). (n=14).

Figures

Figure II- 1 Growth of sycamore and cottonwood during the study period



*The solid lines depict tree height plotted using the primary y-axis on the left and dashed lines depict tree dbh plotted using the secondary y-axis on the right. Vertical bars represent standard errors. (n=4).

Figure II- 2 Yearly biomass partitioning in sycamore and cottonwood

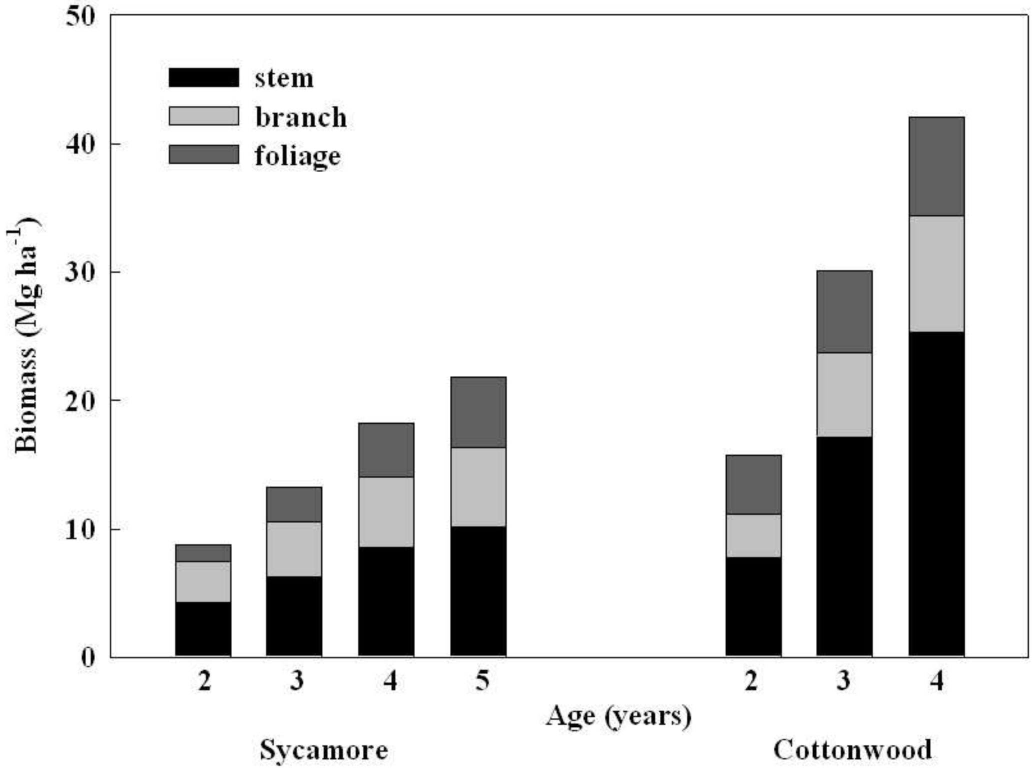
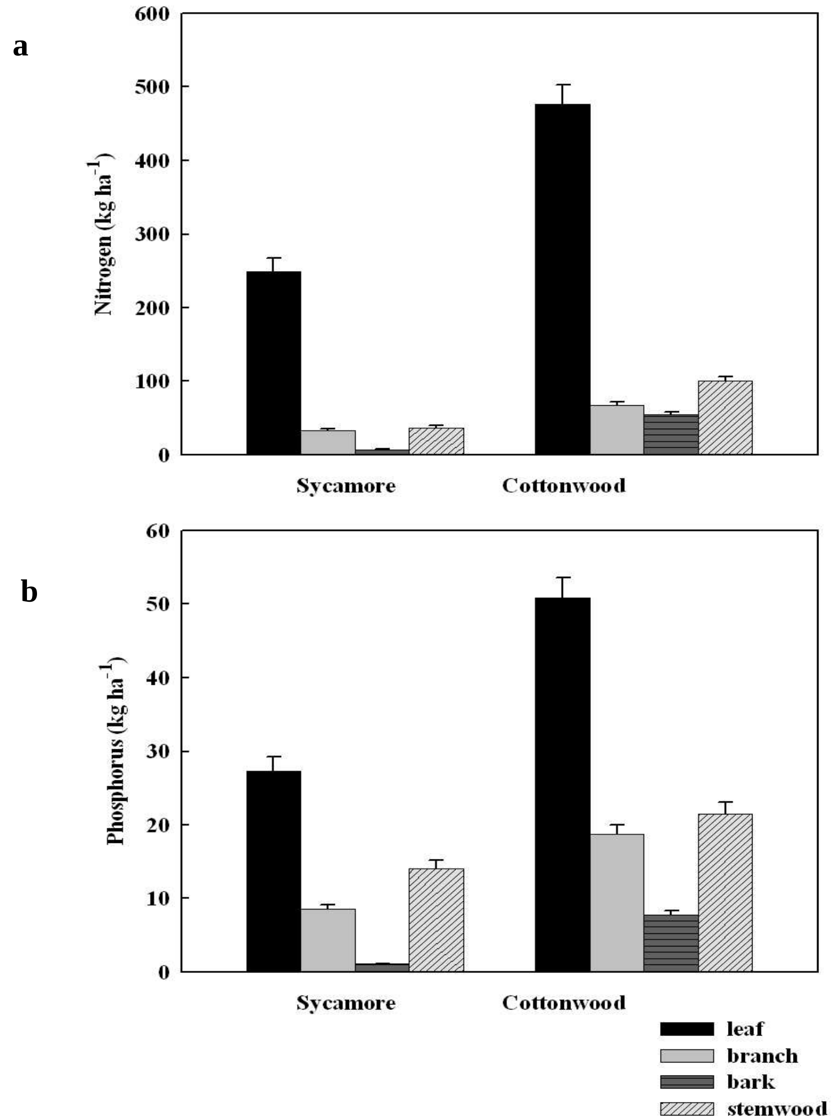


Figure II- 3 Total N (a) and P (b) uptake by sycamore and cottonwood during the study period



* Foliage nutrients are cumulative beginning with age 2.

CHAPTER III

COMPARISON OF LOBLOLLY, SHORTLEAF, AND PITCH X LOBLOLLY PINE PLANTATIONS GROWING IN OKLAHOMA

Abstract

We studied survival, growth, stem volume, bark, crown, and stem characteristics of 10-year old loblolly pine (*Pinus taeda* L.), shortleaf pine (*P. echinata* Mill.), and pitch X loblolly pine hybrid (*P. rigida* X *P. taeda*) stands planted at four sites in 2002 in southeastern Oklahoma to determine the genotype best suited for expanding the commercial range of pine plantations. Loblolly pine and pitch X loblolly pine hybrid plantations had a survival of 70% and above, higher than shortleaf pine (59%). Loblolly pine reached an average height of 9.42 m and dbh of 16.50 cm, outgrowing both the shortleaf pine (6.85 m and 11.78 cm, height and dbh, respectively) and pitch X loblolly pine hybrid (8.27 m and 14.18 cm, height and dbh, respectively). We did not observe any statistical differences in wood specific gravity (overall mean of 0.51). Although, tree size affected tree crown area and bark thickness, the genotypes did not differ when compared at the same dbh. Shortleaf pine trees were least cylindrical of the genotypes based on Girard form class. We conclude that planting loblolly pine was the best choice for extending pine range if productivity is the top priority assuming no ice damage.

Introduction

The area of pine plantation in the southeastern USA has increased since the 1950's and will likely further increase over the next several decades (Alig and Butler 2004, Fox et al. 2007, Wear and Greis 2012). Part of this change is due to the expanded range of commercial pine which helps counterbalance the decline in forest cover caused by timber harvesting for agriculture and urban expansion (Borders and Bailey 2001, Wear and Greis 2002). The south-central subregion has the most potential for pine plantation expansion in the southern USA (Ahn et al. 2000, Alig and Butler 2004). For instance, loblolly pine (*Pinus taeda* L.) plantations have been established beyond the periphery of its natural range in southeastern Oklahoma and eastern Texas (Baker and Balmer 1983, Sampson and Allen 1999).

Southern pine forests are among the most productive in the United States, with loblolly pine and shortleaf pine (*P. echinata* Mill.) being major species (Lawson 1990, Schultz 1999, Guldin 2011, Stewart et al. 2012). Together, loblolly pine and shortleaf pine forests cover 21 million hectares, more than 75% of total pine forest in the Southeast (Smith et al. 2009, Guldin 2011). Because of its fast growth and versatility, loblolly pine is the most important commercial timber species in the southeastern USA (Schultz 1999, McKeand et al. 2003). Loblolly pine has the second widest range among the pines and composes more than half of the total southern yellow pine volume (Schultz 1999, Cain and Shelton 2000, Studyvin and Gwaze 2012). It ranges from Delaware and New Jersey to central Florida and westwards to eastern Texas and southeast Oklahoma (Schultz 1999). Shortleaf pine, the pine with most extensive natural range, is the second most important pine species in the Southeast (Gwaze 2009, Guldin 2011). Shortleaf pine is native to 22 states, ranging from New York and New Jersey to Florida and Oklahoma and Texas to the west (Lawson 1990). Compared to loblolly pine, shortleaf pine is slower growing, but more fire tolerant, cold tolerant, ice tolerant, and drought tolerant (Lawson 1990, Schultz 1997).

A possible limitation to northward expansion of loblolly pine plantations is ice storms which have the potential to destroy young loblolly pine stands (Schultz 1997). For instance, an ice storm in southeastern Oklahoma and western Arkansas in the winter of 2000 caused substantial damage to sapling-sized loblolly pine plantations (Burner and Ares 2003). While susceptible, shortleaf pine is better able to withstand ice storms. In adjacent plantings of loblolly pine and shortleaf pine, shortleaf pine suffered 30% damage while loblolly pine suffered 60% damage and shortleaf pine exhibited a greater likelihood of stem bending rather than breaking (Boggess and McMillan 1954).

Pitch X loblolly pine hybrids incorporate the better growth rate of loblolly pine and cold hardiness of pitch pine (*Pinus rigida* Mill) and can be planted north of the loblolly pine range (Kuser et al. 1987). Pitch X loblolly pine hybrids may outperform the parent species on poor sites or outside of the natural loblolly pine range (Little and Trew 1979, Kuser et al. 1987, Johnson et al. 1991). In addition to greater cold tolerance, pitch X loblolly pine hybrids are presumably more tolerant of ice and snow which may permit expansion of pine plantations further north or in the face of a more variable climate (Baker and Langdon 1990, Johnson et al. 1991).

An uncertainty regarding the future of southern forests is potential climate change and the associated changes in temperature and precipitation (Wear and Greis 2012). Climate change may cause shifts in species geographic range as well as changes in forest structure and composition (Iverson and Prasad 2001, Iverson and Prasad 2002, Walther et al. 2002, Parmesan 2006). The potential effects of climate change on future pine geographic ranges, productivity, survival, and phenology are not clear (Hughes 2000, Wear and Greis 2002, Wear and Greis 2012). Details on growth patterns and climate influences on pine productivity are helpful to forecast the future range of commercial plantations and to improve intensive pine management strategies to increase future yields.

Identifying the most appropriate plantation species to balance productivity and risk of plantation failure will facilitate the expansion of the commercial pine range in the southeastern USA. Loblolly pine, shortleaf pine, and pitch X loblolly pine hybrids growing along the periphery of the commercial range of southern pine present the opportunity to assess these three potential genotypes. To address the questions of stand establishment and productivity, we compared the growth performance of loblolly pine, shortleaf pine, and pitch X loblolly pine hybrid plantations established in 2002 in southeastern Oklahoma, within the natural range of shortleaf pine, but within, west and north of the loblolly pine natural range. The specific objectives of this study were to compare survival, growth [height and diameter at breast height (dbh)], stem volume, wood specific gravity (SG), crown area, form class, and bark thickness among the pine genotypes through age 10.

Materials and methods

Site description

The study was conducted at four sites, Antlers, Cavanal, Idabel, and Shinewell, in southeastern Oklahoma that encompassed a wide range of characteristics (Table III-1). These sites are within the natural range of shortleaf pine. Antlers and Cavanal are west and north of the natural range of loblolly pine, but within its potential commercial range (Figure III-1). The climate is characterized by long, hot summers, and dry winters. All sites have approximately 210 frost free days. Between 1971 and 2000, Cavanal had 14.7 cm of annual frozen and freezing precipitation (snowfall, sleet, freezing rain, and hail), the highest among the sites. The other sites had less than 6 cm with Idabel having only 1 cm (Oklahoma Climatological Survey 2013). Soil pH values at Antlers and Cavanal were lower than Idabel and Shinewell. Soils at Idabel and Shinewell were poorly to well drained, whereas soils at Antlers and Cavanal were mostly well drained.

Study design

The study was a generalized random complete block design, i.e., a randomized complete block study was installed at each site. No mechanical site preparation was conducted. Herbaceous weed control was carried out using Oust® (Sulfometuron methyl, DuPont Agricultural products, Wilmington, DE) at Shinewell only. Loblolly pine, shortleaf pine, and pitch X loblolly pine (F1 hybrids) plantations were established between February and April 2002 using 1-0 bare-root seedlings. Loblolly and shortleaf pine were improved seedlings from Western Gulf Tree Improvement Program grown at the Oklahoma Forestry Services nursery in Goldsby, OK from seed collected at the Oklahoma Forestry Services seed orchard in Idabel, OK. Pitch X loblolly pine hybrids were a mix of F1 genotypes from crosses between pitch pine parents from the northeast and mid-Atlantic states and loblolly parents from the Maryland shore, Delaware, the Virginia Piedmont, and coastal South Carolina (MeadWestvaco, Richmond, VA). Shinewell was planted first, on February 25, 2002, and Idabel was planted last, on April 4, 2002. Shinewell and Idabel had four blocks, whereas Antlers and Cavanal had three.

Trees were planted at a spacing of 2.44 m x 3.05 m (1343 tree ha^{-1}). The individual plot areas ranged from 0.06 to 0.07 ha depending upon the available space and contained 72-90 trees and an additional strip of buffer trees on each side. Prior to the ninth growing season (2010), approximately every other tree was selected in the loblolly and pitch X loblolly pine stands at Idabel for thinning.

Measurements

Height was measured annually following the first through fifth growing seasons on every live tree. We measured tree diameter at breast height (dbh; 1.37 m above ground level) after the fourth and fifth growing seasons. We resumed measurements in March 2011 (after ninth growing season) and conducted them again the following year (the tenth growing season) except in Idabel, where measurements were also taken prior to the thinning (after eighth growing season in February 2010). We used Haglöf Vertex IV Hypsometer with Transponder T3 (Haglöf, Längsele, Sweden) to measure the height to the nearest tenth of a meter. Diameter at breast height was measured to the nearest tenth of a cm using a diameter tape. We also measured crown diameters to the nearest tenth of a meter in two perpendicular directions for every third tree during final measurements period.

Following the tenth growing season, two randomly selected buffer trees of each plot were harvested approximately 10 cm above the ground. The harvested trees were measured for diameter and bark thickness to the nearest 0.1 cm with Haglöf Barktax Bark gauge (Haglöf, Längsele, Sweden) every meter along the stem from the base to the top. An approximately 3 cm thick disc was cut out from the base of all harvested trees. After bringing them to the laboratory, discs were debarked and kept immersed in water until saturated. The wet volume of each saturated disc was determined by water displacement. The discs were then oven dried at 65^{o}C to constant weight and their final weight recorded.

Calculations

Percent tree survival for each plot was calculated based on the initial number planted. For loblolly pine and shortleaf pine, site indices (SI) of individual sites were calculated using equations from Smalley and Bower (1971).

To calculate total stem volume (outside bark) of the harvested trees, the volume of each 1 m long section was calculated using Smalian's formula (Eq. 1), except the top most section which was calculated as a cone. The volume of each section was summed to calculate total volume.

$$V_i = \pi l\{(d_{i-1}^2 + d_i^2)/80000\} \qquad \text{(Eq. 1)}$$

where, V_i is the volume in m^3 of any 1-m log, l is length of the log, which was always 1 m, and d_{i-1} and d_i are the outside bark diameters (cm) of the log at the lower end and upper end measured in cm, respectively.

From the harvested trees, linear regression equations were developed to predict stem volume (m^3) from dbh^2 x height for each pine species and site combination. However, the relationship did not statistically differ among pine genotypes (P = 0.49) or sites (P = 0.80). As a result, we used one equation (Eq. 2, R^2 = 0.97) for calculating standing volume of trees.

$$\text{Stem volume} = 0.000038 \times dbh^2 \times height + 0.0054, \qquad \text{(Eq. 2)}$$

Specific gravity of the disc was calculated by dividing the oven dry weight by the disc volume. Crown area was calculated as an ellipse using two perpendicular crown widths. Girard form class was calculated as the ratio of inside bark diameter 5 m aboveground to outside bark dbh.

Statistical Analysis

Statistical analyses were conducted on the data after tenth growing season only. The exception to this was tree survival where data from the Idabel site were from pre-thinning after the eighth growing season and data from the other sites were from after the ninth growing season. Survival, height, dbh, stem volume, and crown area data were averaged within plots or scaled to the hectare level such that the plot was the experimental unit, i.e., n=3 or 4, depending upon the site. Height, dbh, and stand-level volume were analyzed using PROC GLM procedure of SAS 9.3 (SAS Institute Inc. 2011). Data from the harvested trees, i.e., SG, bark thickness (at breast height), and form class were analyzed using individual trees as experimental units (total = 84 samples). Because variables such as SG, crown area, bark thickness, and Girard from class might be influenced by tree size, we analyzed these using Analysis of Covariance (ANCOVA) with dbh as a covariate. When appropriate, we used Fisher's protected least significant difference (LSD) with $\alpha = 0.05$.

Results

Most mortality occurred the year of establishment. At the end of the first growing season, survival of pitch X loblolly pine hybrid, loblolly pine and shortleaf pine were 80, 76, and 66%, respectively. Between ages 1 and 8 at the Idabel site and 1 and 9 at the rest of the sites, survival only decreased by additional 9, 6 and 7% respectively for pitch X loblolly pine, loblolly pine, and shortleaf pine (Figure III-2). When analyzed at age 9 (and age 8 for Idabel stands), survival of pitch X loblolly pine hybrid and loblolly pine was higher than shortleaf pine ($P = 0.02$) (Figure III-2). At all sites, loblolly pine survival was greater than shortleaf pine survival, although not significantly so when tested at each site separately. However, there was an interaction between site and pine genotypes ($P = 0.01$) because the ranking of pitch X loblolly pine hybrid survival varied across sites (Figure III-3). Survival of pitch loblolly pine hybrid was statistically similar to loblolly pine and shortleaf pine at Antlers ($P = 0.35$), Cavanal ($P = 0.09$), and Shinewell ($P = 0.07$), but greatest of any genotype at Idabel ($P = 0.02$).

Differences in tree size (height and dbh) were consistent across stand development with loblolly pine the largest, pitch X loblolly pine hybrid intermediate, and shortleaf pine the smallest (Figure III-4a, 4b). At age 10, average heights of loblolly pine (9.42 m), pitch X loblolly pine hybrid (8.27 m) and shortleaf pine (6.85 m) varied among the genotypes ($P < 0.0001$) and sites ($P < 0.0001$), but differences among genotypes were consistent across the sites (genotype X site interaction, $P = 0.10$). Trees at the Idabel site were tallest (9.21 m) followed by trees at Shinewell (8.36) and Antlers (7.93), which were statistically similar to one another. Trees at Cavanal were the shortest (6.8 m). Similar to height, average dbh of loblolly pine (16.5 cm), pitch X loblolly pine hybrid (14.2 cm), and shortleaf pine (11. 8 cm) differed ($P < 0.0001$). These differences also were consistent across the sites (genotype X site interaction, $P = 0.19$) (Table III-2). Trees at Cavanal had the smallest dbh (12.69 cm), whereas trees at Idabel (14.66 cm), Shinewell (14.53 cm), and Antlers (14.45 cm) were statistically similar. For loblolly pine, at base age 25, site index at Idabel was highest (23.5 m), followed by Shinewell (20.7 m), whereas Antlers and Cavanal had same site index (19.9 m). Site index for shortleaf pine was highest at Idabel (20.4 m) followed by Shinewell (18.5 m), Antlers (17.5 m), and Cavanal (16.4 m).

Standing stem volume per hectare followed the trend of tree sizes when measured after 10 growing seasons. Stem volume per hectare was different among the genotypes ($P < 0.0001$) and sites ($P = 0.009$), and these differences were again consistent among the sites (genotype X site interaction, $P = 0.17$) (Figure III-5). Loblolly pine had the greatest stem volume (91.1 m^3 ha^{-1}) followed by pitch X loblolly pine hybrid (55.0 m^3 ha^{-1}) and shortleaf pine (36.5 m^3 ha^{-1}). Standing stem volume at Cavanal was significantly lower (44.0 m^3 ha^{-1}) than Antlers (72.6 m^3 ha^{-1}) and Shinewell (68.3 m^3 ha^{-1}), which were similar to one another and Idabel (58.3 m^3 ha^{-1}).

When tested using ANCOVA, the relationship between dbh and SG was not significant ($P = 0.25$). The overall average SG was 0.5 (s.e.= 0.005) and it was not significantly affected by genotype ($P = 0.79$). However, trees of Shinewell had the lowest SG of 0.48, which was statistically different than trees from the other sites, which had SG of 0.50 and above ($P = 0.0009$) (Table III-2). We did not observe any significant genotype-by-site interaction for SG ($P = 0.70$).

Crown area (m^2) exhibited a significant relation with dbh (cm) ($P = 0.06$, crown area = 0.7573*dbh - 3.1010, Figure III-6a). After accounting for tree size using ANCOVA, we did not observe any genotype effect ($P = 0.51$) or site effect ($P = 0.97$) (genotype X site interaction, $P = 0.49$) on crown area. Among the genotypes, pitch X loblolly pine hybrid, loblolly pine, and shortleaf pine had crown areas of 9.0 (s.e.= 1.23) m^2, 6.16 (s.e.= 1.52) m^2, and 6.41(s.e.= 1.12) m^2, respectively. Among the sites, Cavanal, Idabel, Antlers, and Shinewell had crowns area of 7.86 (s.e.= 2.46), 7.27 (s.e.= 0.57), 7.19 (s.e.= 0.74), and 6.42 (s.e.= 1.46) m^2, respectively.

Bark thickness increased with dbh ($P < 0.0001$, bark thickness = 0.0532*dbh + 0.5627; Figure III-6b). After accounting for tree dbh, we found that differences in bark thickness were not significant among the genotypes ($P = 0.97$) and sites ($P = 0.65$) (site X genotype, $P = 0.61$). Loblolly pine had a bark thickness of 1.38 (s.e.= 0.05) cm and shortleaf pine and pitch X loblolly pine hybrid had a bark thickness of 1.22 (s.e.= 0.06) and 1.19 (s.e.= 0.05) cm respectively, but these differences were a function of tree dbh. Shinewell, Antlers, Cavanal, and Idabel had a bark thickness of 1.38 (s.e.= 0.07) cm, 1.31 (s.e.= 0.06) cm, 1.21 (0.07) cm, and 1.14 (s.e.= 0.06) cm, respectively.

The relationship between Girard form class and tree dbh was significant ($P = 0.0002$, Girard form class = 0.0343*dbh - 0.0101, Figure III-6c). After accounting for tree dbh using ANCOVA, we still detected the genotype effects on form class ($P = 0.004$). Loblolly pine and pitch X loblolly pine hybrid had similar form class of 0.50 (s.e.= 0.02) and 0.48 (s.e.= 0.03), and were significantly greater than shortleaf pine which had a form class of 0.36 (s.e.= 0.04). Form class was not affected by site ($P = 0.16$). Form class values at Idabel, Shinewell, Antlers, and Cavanal were 0.58 (s.e.= 0.02), 0.43 (s.e.= 0.03), 0.38 (s.e.= 0.04), and 0.33 (s.e.= 0.04) respectively. Again, the genotype differences were consistent across the sites ($P = 0.29$).

Discussion

Planted beyond its natural range, loblolly pine outperformed both shortleaf pine and pitch X loblolly pine hybrids indicating that planting loblolly pine in the southeastern Oklahoma appears to be the best option for expanding the commercial pine range within the conditions under which this study was conducted and there is no ice damage. In several previous comparisons, loblolly pine was the fastest growing. In a study carried out in southern Arkansas, loblolly pine exhibited better growth than shortleaf pine from age 8 to 12 (Cain 1990). Similarly, Groninger et al. (2000) reported greater growth performance by loblolly pine than pitch X loblolly pine (F2) hybrids in a competition control study on the Virginia Piedmont after 9 growing seasons. The level of genetic improvement may contribute to genotype differences. While both loblolly pine and shortleaf pine were improved selections from the Western Gulf Tree Improvement Cooperative, the extent of improvement within loblolly pine was greater, i.e., shortleaf pine were first generation selections while loblolly pine was a second generation. The pitch X loblolly pine hybrids selections were based on cold hardiness and fast growth, but these were F1 crosses and had not yet undergone additional screening in progeny tests. Even though genetic improvement plays a role, our results indicate the potential growth of the genotypes using the best available genetics at the time of planting. The advantage of loblolly pine plantations established currently can be expected to be larger given additional tree improvement efforts in that species.

During the study period, the research sites did not experience any substantial ice storms. Loblolly pine is more susceptible to ice damage than shortleaf pine (Lawson 1990, Schultz 1997) or pitch X loblolly pine hybrids (Little and Trew 1979, Kuser et al. 1987). Planting shortleaf pine or pitch X loblolly pine hybrids may reduce the risk of ice damage, especially during the sapling and pole stage, at the expense of potential productivity. Native shortleaf pine might be an option for landowners with multiple objectives who would like to reduce risk of plantation failure because of wildfire and drought as well as ice storms.

As was the case in our study, other researchers have found that the majority of mortality occurs during the first year after planting (Ponder Jr 2004, Rahman et al. 2006). However, percent survival of individual pine genotypes at the end of the study period in our study was lower when compared with other studies (Little and Trew 1979, Kuser et al. 1987, Yeiser and Barnett 1991, Cain 1999, Cain and Shelton 2000, Borders and Bailey 2001, Barnett and Brissette 2004, Studyvin and Gwaze 2012). Half the sites in our study were beyond the natural range of loblolly pine and all were along the western margin of the commercial pine range. Although the seedlings received approximately 130 cm of precipitation in 2002, which is above average (see table III-1), precipitation was much less in year 2003 and 2005 at the study sites. For instance, Cavanal received only 86 cm and 74 cm in 2003 and 2005, respectively, compared to the average precipitation (113 cm). Another possible contributing factor to the relatively low survival was the lack of mechanical site preparation and limited chemical weed control, both of which are important to improve plantation establishment (Nilsson and Allen 2003).

Loblolly pine and shortleaf pine survival was fairly consistent across sites (loblolly pine > shortleaf pine). However, survival of pitch X loblolly pine hybrids varied. Our study sites were all within the natural range of shortleaf pine. As such, shortleaf pine might be expected to have higher survival than pitch X loblolly pine hybrid and loblolly pine, the non-native genotypes. However, shortleaf pine survival was lowest among the planted genotypes on three of four sites. The loblolly pine and shortleaf pine seedlings were from the same nursery and treated similarly before planting. While the pitch X loblolly pine hybrid seedlings were from a different source, the seedlings were of high quality and carefully handled and planted. Survival of pitch X loblolly pine hybrids was relatively high at three of four sites, but the lowest of all three genotypes at Shinewell. Survival of pitch pine is lower in flooded conditions than normal conditions (Craine and Orians 2006) and seasonal excess water at Shinewell might have contributed to the lower survival of pitch X loblolly pine hybrid.

Growth results in our study were similar to other studies. For example, Hennessey et al. (2004) reported an average height of 9.2 m, similar to our finding, in a 9-year old loblolly pine planted in southeastern Oklahoma. Similarly, in a study across Ouachita and Ozark National Forests in Arkansas and Missouri, 10-year old shortleaf pine had an average height of 5.95 m (Studyvin and Gwaze 2012), comparable to ours. Even though growth in our study was comparable to other plantation studies in the region, growth can be accelerated due to more intensive silviculture. For instance, Borders and Bailey (2001) reported an average height of 11.7 m and volume of 115 m^3 ha^{-1} in a 10-year old loblolly pine stand with intensive mechanical site preparation, fertilization, and competition control.

Sitewise, loblolly pine and pitch X loblolly pine hybrid trees at Idabel were bigger than the other sites. Loblolly pine and pitch X loblolly pine hybrid stands at Idabel were thinned which removed the smaller trees leaving the larger ones behind. Cavanal, on the other hand, is located at the northern most side of the study area and is probably lesser suited site than others for the pines studied.

Stemwood SG is an important indicator of tree wood quality for wood and pulp production and is important for ecosystem studies and carbon storage (King et al. 2006, Jordan et al. 2008). We did not find any significant differences when comparing SG among the genotypes planted at the same sites. This finding is consistent with another study (Gibson et al. 1986). This suggests that stemwood SG of even-aged pine stands is fairly constant when planted at same site with same level of management. However, Shinewell trees had lower SG than trees from other sites. Trees in soils with higher moisture have lower stemwood SG than trees at drier soils (Gibson et al. 1986, Miles and Smith 2009) and Shinewell probably had the highest soil moisture level among the sites because of higher average annual rainfall and higher water table. Average SG in our study was 0.51, and was similar to results from previous pine studies (Jordan et al. 2008, Ledig et al. 1975) but slightly higher than most other studies (Cregg et al. 1988 Jayawickrama et al. 1997, Naidu et al. 1998). One of the many factors SG depends upon is the sampling position (Miles and Smith 2009) and most of these studies measured SG at breast height, whereas samples in our study were taken from stump height. Since, wood SG decreases along the height of the tree (Clark III et al. 2008), SG in our study might have been slightly higher than other studies. However, the comparison among genotypes accurately reflects species differences. We did not find an effect of tree size on stemwood SG, because for even-aged plantations, stemwood SG is age dependent rather than size dependent (de Castro et al. 1992).

Crown dimensions play an important role in determining forest health and productivity (Cole and Lorimer 1994, Larocque and Marshall 1994, Zarnoch et al. 2004). While crown area and tree size are positively correlated (Zarnoch et al. 2004), species difference may shift the relationship. For instance, loblolly pine trees were larger than pitch X loblolly pine hybrid despite the similar crown areas.

Larger trees have thicker bark (Bragg 2004, Laasasenaho et al. 2005). In our study, loblolly pine trees were larger and had thicker bark, whereas shortleaf pine trees were smaller than other pines and had thinner bark, but the relationship between tree size and bark thickness was consistent among genotypes. Bark thickness in our study was slightly higher than what Tiarks and Haywood (1992) reported on 11 year old loblolly pine stands in Louisiana, but within the range Bragg (2004) reported for loblolly pine and shortleaf pine.

After correcting for tree dbh, we found that shortleaf pine had less cylindrical stems than other two genotypes. Shortleaf pine had less cylindrical stems possibly because lower survival and lower stand density causes less cylindrical stems (Maker and Boyd 2008). Although, all genotypes had the same relationship between dbh^2h and volume, shortleaf pine were shorter and difference in dbh and inside bark diameter at approximately 5 m tree height was relatively greater in shortleaf pines than the other genotypes, thus making shortleaf pine less cylindrical than loblolly pine and pitch X loblolly pine hybrids. Our results of form class value of loblolly and pitch X loblolly pine hybrid were within the range reported by Maker and Boyd (2008) in 12-18 year old loblolly pines in North Carolina Piedmont.

Conclusion

Southeastern Oklahoma is the northern and western extent of natural range of loblolly pine and may represent the future climate conditions of other portions of the range if precipitation decreases in the southeastern USA. Alternatively, climate change may cause the range further of loblolly pine to shift northward. We found that second generation improved loblolly pine exhibited better survival than first generation improved shortleaf pine and outgrew shortleaf pine and pitch X loblolly pine F1 hybrid while having similar SG and bark thickness. Therefore, planting loblolly is the best option for expanding the commercial pine range. However, the shortleaf pine might be considered to reduce risk when considering potential damage from the ice storms or increased incidence of drought.

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Tables

Table III- 1 Research sites and associated key characteristics

Site Characteristics	Antlers	Cavanal	Idabel	Shinewell
Latitude, Longitude	$34^{o}20'$N, $95^{o}35'$W	$35^{o}06'$N, $94^{o}43'$W	33^{o} $54'$N, $94^{o}45'$W	$33^{o}53'$N, $94^{o}34'$W
Soil Unit	Carnasaw-Stapp association	Bengal-Pirum-Clebit complex	Adaton and Kullit	Belvins and Kullit
Soil texture	Clay and stony fine sandy loam	Clay loam and very stony fine sandy loam	Loam and fine sandy loam	Loam and fine sandy loam
Soil pH	5.1	5.1 - 5.3	5.0 - 5.8	5.2 - 5.8
Slope (%)	8 - 12	5-15	0 - 3	1 - 3
Annual precipitation (cm)	122	113	131	131
Annual temp (avg lowest - avg highest) (^{o}C)	16.2 (-3.9 - 38.3)	15.7 (-5.0 - 37.2)	16 (-2.2 - 36.1)	16 (-2.2 - 36.1)
Depth to water table (cm)	>200	>180	60 - 90	60 – 90 (seasonal excess surface water)

Soils data 0 to 40 cm are only included. Average precipitation and temperature values were calculated from year 2001 to 2010 for the closest stations to the research sites. The farthest station from which data were taken was Wister and was 63 km away from Cavanal research site. Precipitation includes rain and liquid equivalent of frozen and freezing precipitation (e.g. snow, sleet, freezing rain and hail) (Source: NCDC 2002; Oklahoma Climatological Survey 2013; USDA 2013).

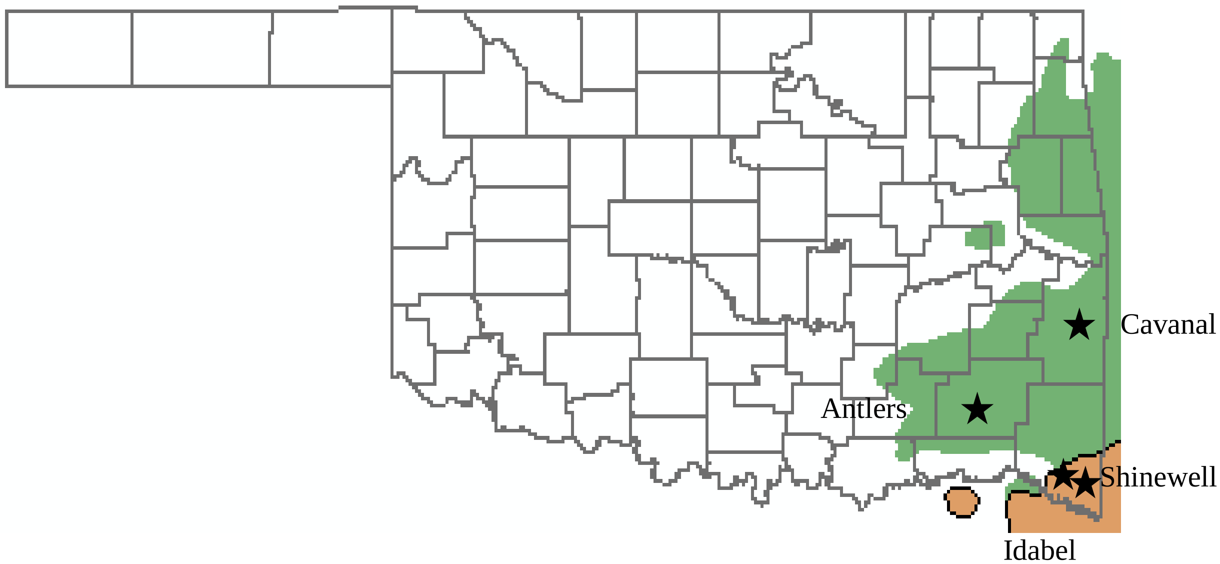
Table III- 2 Tree dimensions and specific gravity after 10 growing seasons

Sites	Genotype	Height (m)	dbh (cm)	Specific gravity
Antlers	Loblolly	8.68 (0.76)	15.55 (1.62)	0.49 (0.01)
	Shortleaf	6.77 (0.30)	13.16 (0.62)	0.51 (0.01)
	Pitch X loblolly	8.34 (0.26)	14.63 (0.07)	0.51 (0.01)
Cavanal	Loblolly	8.42 (0.40)	16.19 (0.43)	0.51 (0.01)
	Shortleaf	5.02 (0.44)	8.88 (0.82)	0.55 (0.01)
	Pitch X loblolly	6.97 (0.04)	16.19 (0.43)	0.52 (0.01)
Idabel	Loblolly	10.63 (0.31)	17.07 (0.92)	0.51 (0.02)
	Shortleaf	7.44 (0.57)	12.17 (0.93)	0.50 (0.02)
	Pitch X loblolly	9.51 (0.42)	14.76 (1.16)	0.50 (0.01)
Shinewell	Loblolly	9.51 (0.10)	16.87 (0.24)	0.48 (0.02)
	Shortleaf	7.63 (0.16)	12.55 (0.28)	0.47 (0.02)
	Pitch X loblolly	7.94 (0.20)	14.17 (0.41)	0.49 (0.02)

Values within the parentheses indicate standard error (s.e.).

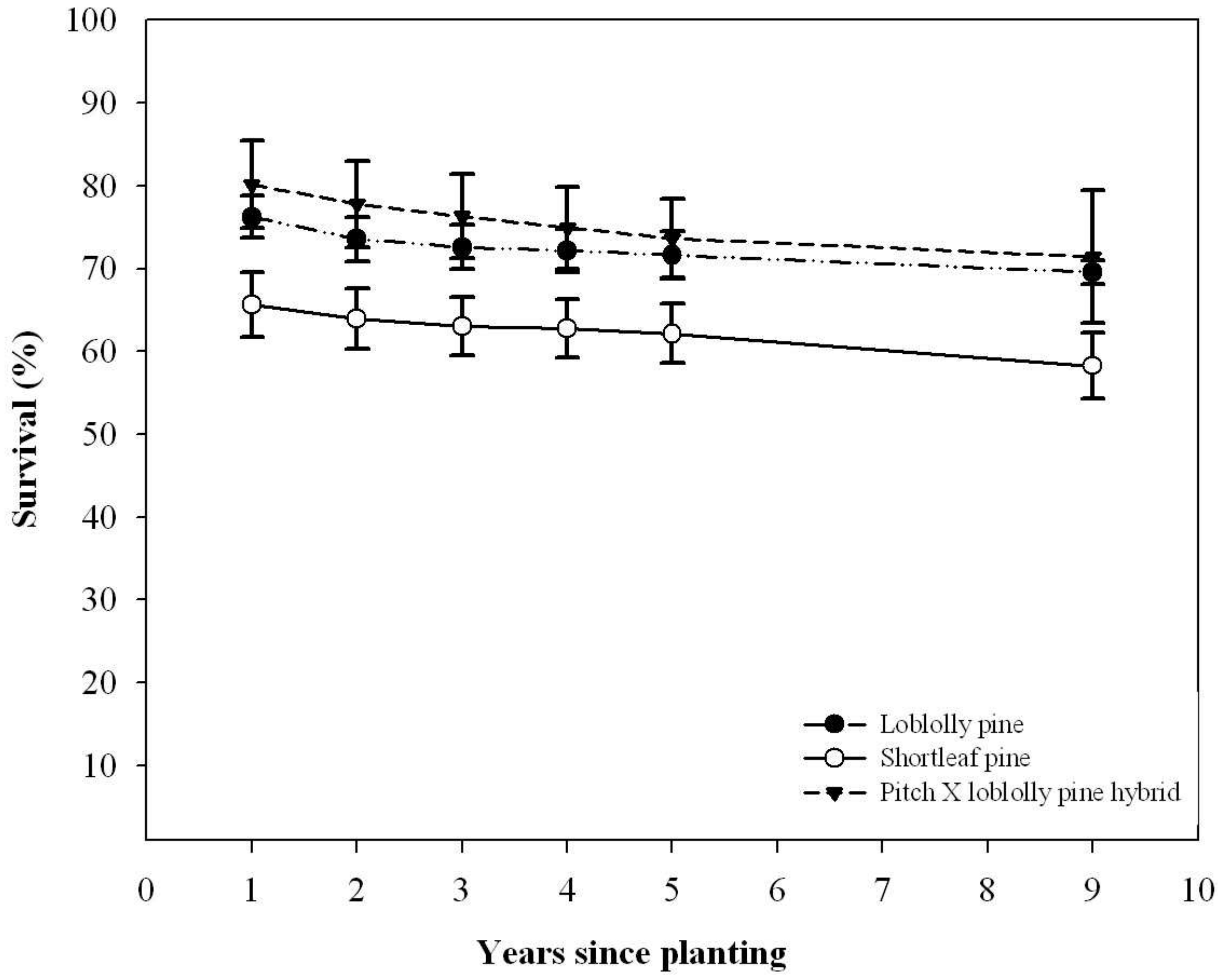
Figures

Figure III- 1 Map of Oklahoma showing study sites



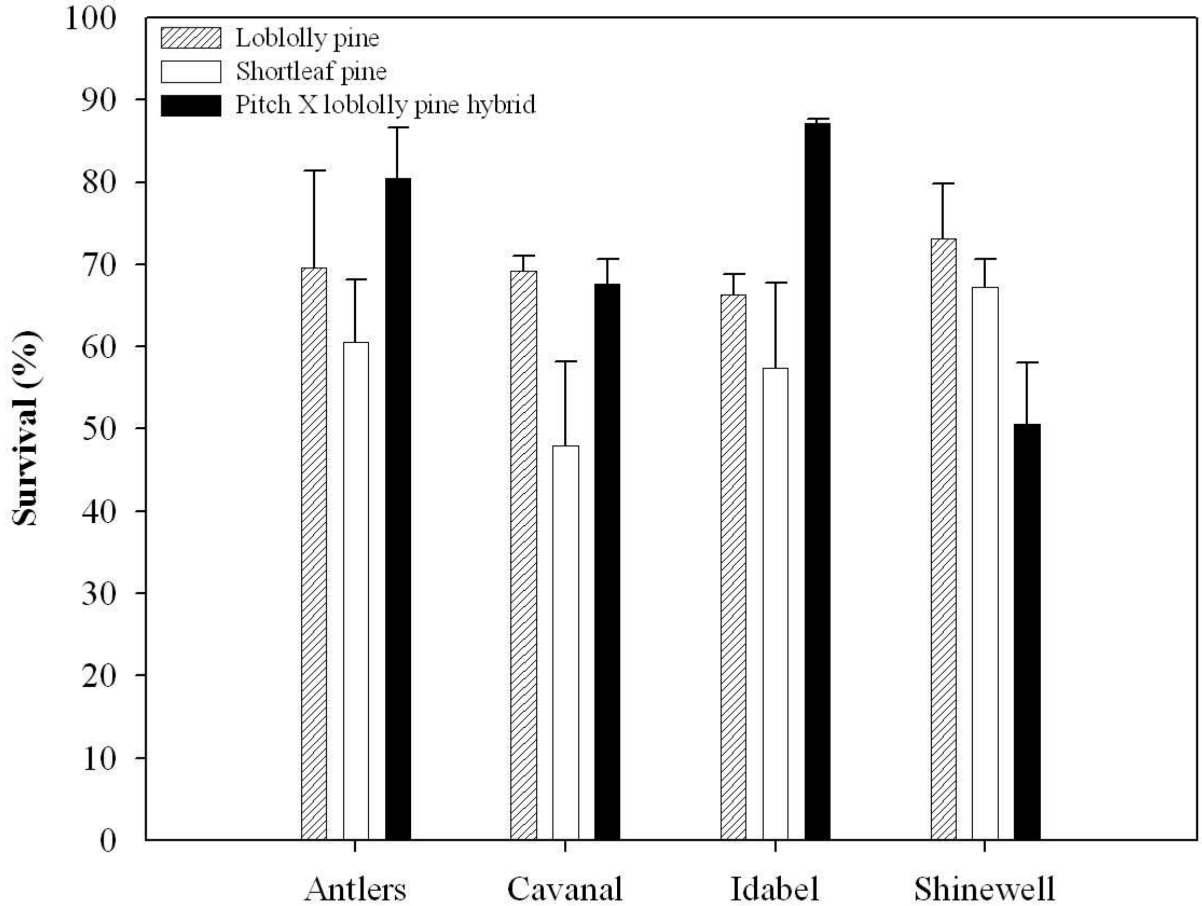
*The lower colored region shows the overlapping natural ranges of loblolly pine and shortleaf pine. The upper colored region shows the natural shortleaf pine range only (Source: Based on shapefiles from www.usgs.gov).

Figure III- 2 Survival of the genotypes during the study period



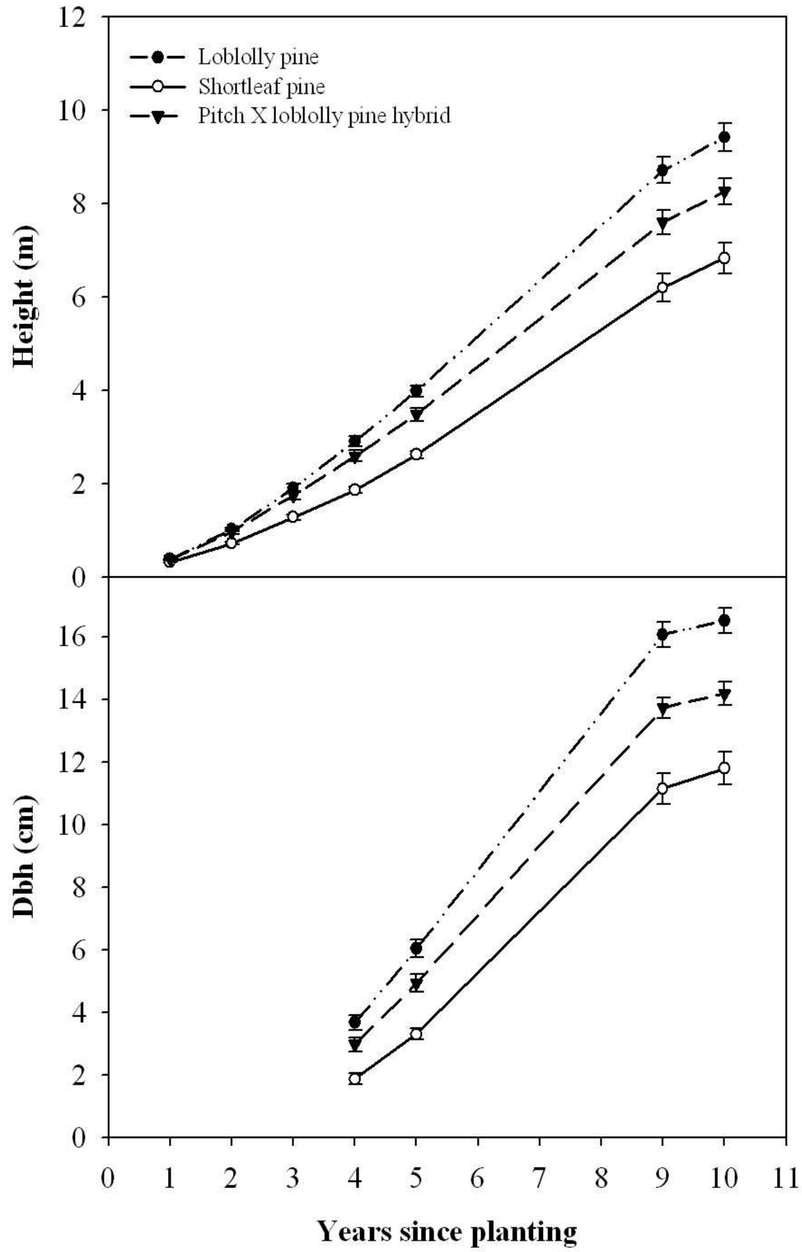
*No measurements were taken after 6th, 7th, and 8th growing seasons except for Idabel site where trees were thinned after 8th growing season following the measurements. For ease in comparison, survival data after 8th growing season at Idabel was used as survival after 9th growing season.

Figure III- 3 Survial of the genotypes at individual study sites



a

Figure III- 4 Annual growth of the genotypes, (a) height, and (b) dbh



*Notice the dbh growth lines starting from age 4 (on the x-asis in Figure b), this is because most of the trees did not reach the breast height until after 4^{th} growing season.

Figure III- 5 Genotypes standing outside bark stemwood volume across the sites

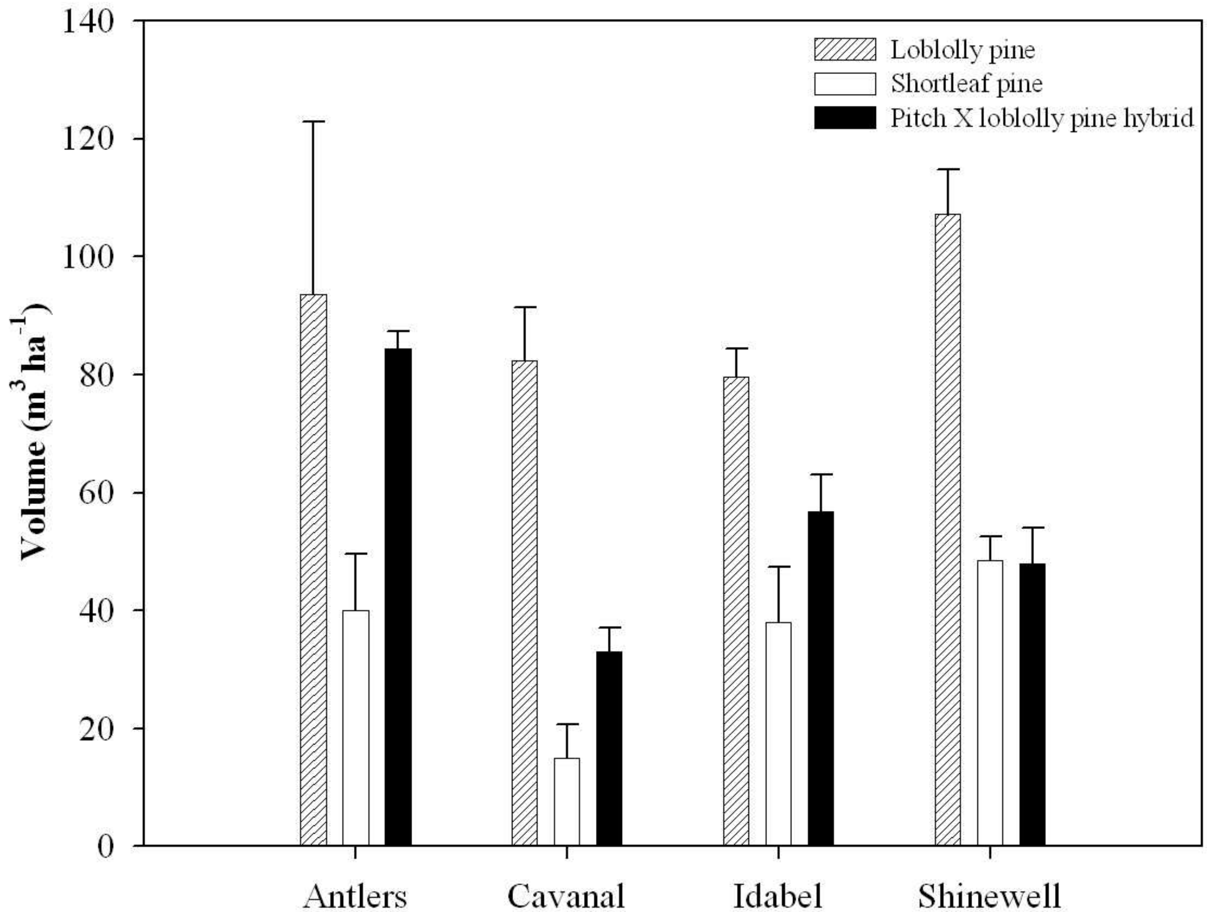
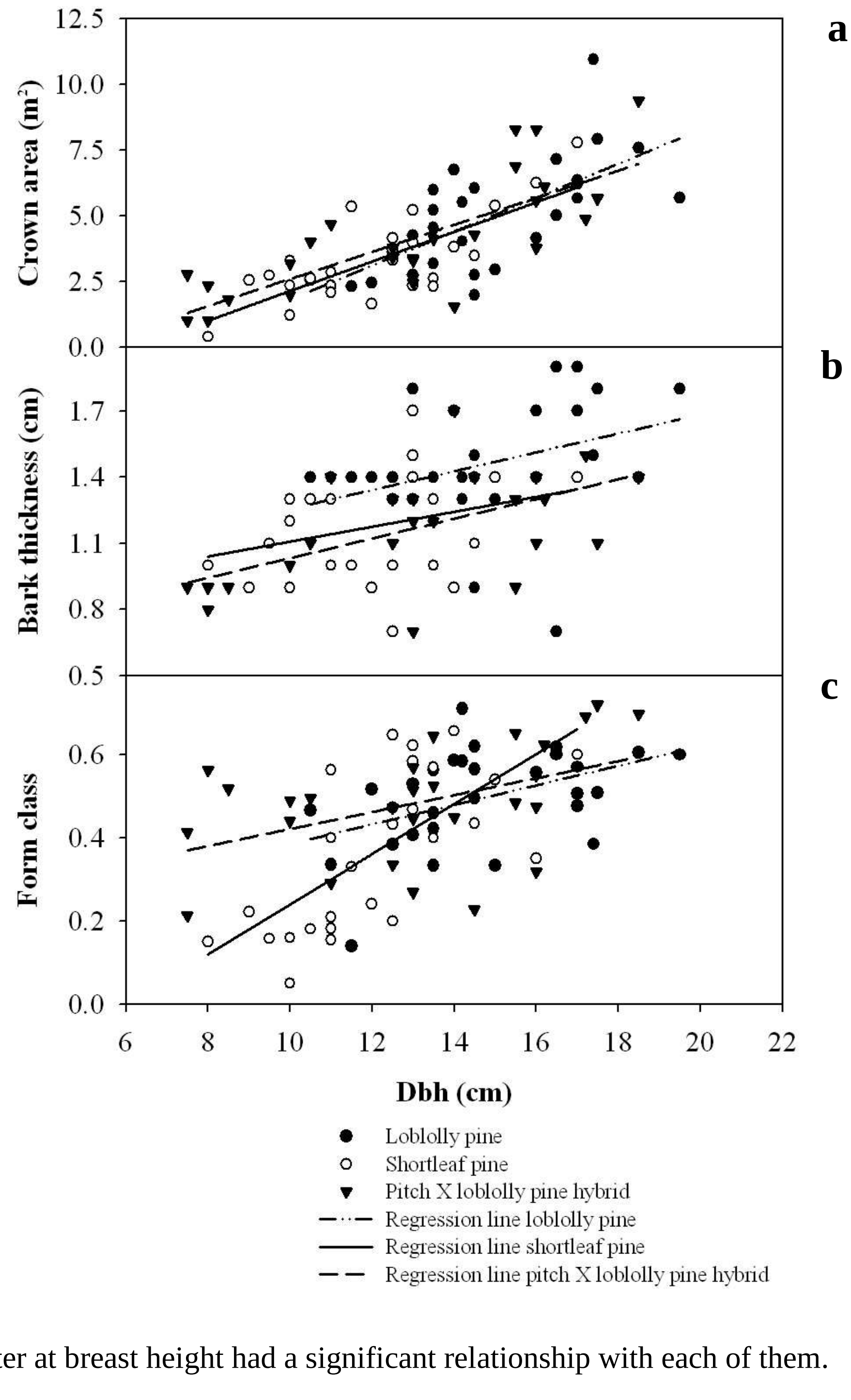


Figure III- 6 Relationships between dbh and (a) crown area, (b) bark thickness at breast height, and (c) Girard form class



*Diameter at breast height had a significant relationship with each of them.

CHAPTER IV

LOBLOLLY PINE STAND GROWTH AFTER 4 YEARS OF SIMULATED ICE DAMAGE

Abstract

We simulated ice damage by manually shooting a portion of live crown from mid-rotation loblolly pine (*Pinus taeda* L.) stands in southeastern Oklahoma to study the post-ice damage effects. Non-thinned stands were compared to stands that had recently undergone either thinning or thinning and pruning. In addition, we compared the growth response associated with an increasing percent of trees that were damaged during the simulation. Four years after damage, diameter growth was faster in the thinned plots than the non-thinned plots. Relative basal area growth (rBA_{growth}) decreased as the percent of live crown ratio loss (LCR_{loss}) increased (rBA_{growth} = -0.25 LCR_{loss} + 0.58; P = 0.02) in all stands, however, the effect was pronounced more in the non-thinned stands. Sub-plots with 100 and 75% of the trees damaged had higher rBA_{growth} than the plots with 50% damaged trees but not than sub-plots with 25% damaged trees. Thinned stands already had open canopies, therefore canopy opening due to the simulated damage had no positive growth effect on the undamaged trees, and trees still had to compete for other resources. The stem form of the damaged trees did not show any change. Based on these findings, moderate (less than 50%) loss of live crown resulted in fairly small decreases in growth and did not change stem form. Therefore, stands can be allowed to recover from

moderate ice storm damage without large loss in production, whereas thinning of the damaged stand would be a plus.

Introduction

Natural disturbances, such as ice storms, may cause significant changes in the forest dynamics (Warrillow and Mou 1999, Bragg et al. 2003). The southern United States is periodically hit by ice storms, the latest major events being in 1995, 2000 (twice), and 2007. Pines represent a major forest cover type in the southern United States (Schultz 1997). Because pines retain foliage throughout the year, they have ample surface for ice accumulation which can lead to considerable damage (Schultz 1997, Aubrey 2007, Guldin 2011). Major damages by ice storms include reduced timber production and altered wildlife habitat, which are also accompanied by secondary damages such as risks to soil erosion, wildfires, plant invasions in the open areas, disease and pest outbreaks, damage to recreational areas, and other unpredictable damages (Meyers and McSweeney 1995, Warrillow and Mou 1999).

Improved planting stock and intensive management practices have been important keys to the success of pine plantation management in the South (Atwood et al. 2002, Fox et al. 2004). The area of pine plantation has substantially increased from the 1950's and is likely to increase in the coming several decades in the southern United States (Alig and Butler 2004, Fox et al. 2007, Wear and Greis 2012). Loblolly pine (*Pinus taeda* L.) is one of the fastest growing and important species among the southern pines (Samuelson et al. 1992, Zeide and Sharer 2002, Jokela et al. 2004, Diéguez-Aranda et al. 2006, Dipesh et al. unpublished). Of the seedlings planted in the South, more than 80% are loblolly pine (Martin and Shiver 2002, McKeand et al. 2003).

Loblolly pine stands are susceptible to ice storms (Samuelson et al. 1992, Aubrey et al. 2007) that occur on average every 6 years in the South (Schultz 1997). Loblolly pine is relatively more tolerant to ice than some pine species such as longleaf pine (*P. palustris* Mill.), slash pine (*P. elliottii* Englem.), sand pine [*P. clausa* (Chapm. Ex Englem.)]. However, hail or ice storm may severely affect the growth of loblolly pine causing stem breakage, severe tree bending or uprooting (Belanger et al. 1996). Loss of 70% crown or severe stem bending or uprooting is usually fatal to the loblolly pine (Bragg et al. 2003). Therefore, loblolly pine plantations near or beyond the northern limit often have not been that successful due to winter damage (Groninger et al. 2000), and successful establishment of loblolly pine plantations at these locations is questionable because of exposure to severe ice storms (Schultz 1997).

Silvicultural practices such as thinning and pruning manipulate the availability of the resources such as light, water and nutrients and improve individual tree diameter growth rate (Jokela et al. 2004, Sword Sayer et al. 2004, Allen et al. 2005). Mid-rotation stands with a diameter range of 18-25 cm are more susceptible to ice damage. Thinning-pruning may improve the stem diameter growth rate and thus reduce the risk of ice damage by providing less exposure time of these stems to the potential ice storm events (Belanger et al. 1996, Bragg et al. 2002, Zeide and Sharer 2002). Following ice damage, managers must decide whether to clear cut for replanting, salvage the damaged trees, or do nothing (Bragg et al. 2003). There are several studies on immediate effects of ice damage in loblolly pine. For example, wood of bent stems of loblolly pine is weakened, although specific gravity is not affected (Dunham and Bourgeois 1996). Similarly, diameter growth of the damaged loblolly pine trees is reduced in the first few years after damage (Belanger 1996, Wiley and Zeide 1991). However, detailed quantitative assessments of loblolly pine stand response to varying levels of ice damage in conjunction with pre-storm data on individual trees is usually not available. Following stand and tree growth after damage for a sufficiently long time post-damage and comparison to pre-damage tree conditions will allow us to understand the effect that varying levels of damage has on growth and what sizes and types of trees are best able to recover from damage. We also are limited by the information on the ice storm damage effects to the stands that have undergone different silvicultural practices, e.g. thinning and pruning. Information on tree taper post ice damage is lacking while it is of importance as it describes stem profile and helps determine the bole volume (Newnham 1991, Muhairwe 1994).

To address these uncertainties, we compared varying levels of crown damage (only breaking) and different percentages damaged trees within unthinned mid-rotation stands, recently thinned stands, and recently thinned and pruned stands in southeastern Oklahoma near the northern and western margin of the loblolly pine commercial range. We hypothesized that 1) basal area growth is reduced in proportion to the percentage of live crown removal, 2) growth of both undamaged and damaged trees increases as the percentage of damaged trees increases, 3) the effects of crown damage are less in thinned stands compared to nonthinned stands, and 4) tree taper in damaged trees increases. This research helps serve as a guide for forest managers to understand the stand dynamics after ice storms and therefore help them decide the best actions to take after ice damage.

Methods

Study area

In March 2008, six mid-rotation loblolly pine stands were located in McCurtain County in southeastern Oklahoma. Because one stand was later disturbed by a logging crew, a replacement stand was located in early 2009. These stands are owned by Weyerhaeuser Co. (Federal Way, WA) and administered by their Kiamichi Tree Farm (Broken Bow, OK). Average 24-hour minimum temperature at the study area is -2.2^{o}C (January) and average 24-hour maximum temperature (August) is 36.1^{o}C with approximately 131 cm of annual precipitation [Oklahoma Climatological Survey 2013 (2001-2010 data)]. Number of frost free days at the sites ranges from 190-230 days. Soil characteristics and water table depth at the locations were similar (Table IV-1). Stands ranged in planting year from 1992-1994.

Study design and measurements

The study was established as a split-plot design. Two replications of three stand-level treatments each (only thinning-OT, thinning and pruning-TP, no thinning and no pruning-NTNP) served as whole plots and were established in late winter and early spring of 2008. Thinning was conducted less than a year before study establishment and reduced tree density from approximately 1110 trees ha^{-1} to 285 trees ha^{-1}. Pruning was conducted by hand shortly after thinning and removed the lower branches to a height of 6.5 m.

Each site was then divided into five sub-plots for ice damage simulation. Each sub-plot was randomly assigned to have 0, 25, 50, 75, or 100% of trees damaged. Prior to ice damage simulation, trees were measured for their height, diameter at breast height (dbh; 1.37 m above ground level), and crown height (base of live crown). Tree and crown heights were measured using Haglöf Vertex IV Hypsometer with Transponder T3 (Haglöf, Längsele, Sweden) to the nearest tenth of a meter. Diameter tapes were used to measure tree dbh to the nearest tenth of a cm. Trees within the sub-stands were selected randomly for ice damage simulation. Selected individual trees had up to 50% of their crown length removed by shooting the stem multiple times with a rifle. Immediately after shooting, diameter at the broken point and length of the broken region were recorded. Height, dbh and crown height measurements were again taken after the fourth growing season following the ice damage simulation. Additional measurements of crown diameter (in two perpendicular directions) using diameter tapes and stem diameter at approximately 5.3 m height using Gator Eyes Laser Pointers (Haglöf, Inc. of Sweden) were carried out after fourth growing season. Ice damage simulation and every measurement in the replacement plot were done a year later than the other five sites for comparison at a common time since treatment.

Calculations and Analyses

To account for the initial tree sizes on the growth response, we calculated relative basal area growth (rBA_{growth}) of individual trees [(BA after four growing seasons – BA before ice damage simulation)/BA before ice damage simulation]. We also calculated live crown ratio loss ($LCR_{loss,}$) i.e. percentage of live crown reduction for the damaged trees. Tree taper was calculated as the ratio of diameter at 5.3 m height to dbh. Assuming the tree crowns were elliptical in shape, we calculated tree crown area using two perpendicular crown widths and the formula for an ellipse.

To test the effects of crown damage on stem growth, we conducted an ANCOVA that included the split-plot structure for the main effects of silvicultural treatment (whole-plot; n = 2) and percent of trees damaged (split-plot; n=6). Our response variable was rBA_{growth} and the covariate was LCR_{loss} (PROC GLM of SAS 9.2; SAS Institute Inc. 2011). We used 0.10 probability level of significance. We also determined the response of undamaged trees in relation to silvicultural treatment and percent of damaged trees using a split-plot analysis.

Results

At time of treatment, tree size averaged 12.39 m [standard error (s.e.) = 0.15] height and 19.45 cm (s.e. = 0.22) dbh, whereas live crown ratio (LCR) before treatment was 0.53 (s.e. = 0.01) (Table IV-2). Height, dbh, and lcr were not statistically different among silvicultural treatments (P > 0.13) or percent damage subplots (P > 0.34).

On average, 2.41 m (s.e. = 0.06) of the crown was removed to simulate ice damage with the amount ranging from 2.05 to 3.24 m. This resulted in an average live crown ratio reduction from 0.53 to 0.42 such that approximately 22% of the live crown was removed (Table IV-2). Immediately after simulation, the damaged trees were approximately 18% shorter than the undamaged trees.

After four years of growth, undamaged trees averaged 14.94 m (s.e. = 0.18) height and 24.55 cm (s.e. = 0.32) dbh (Table IV-2). The damaged trees were only 0.78 m shorter than the undamaged trees but the difference between damaged and undamaged trees was still statistically significant (P = 0.0001). The damaged trees had a diameter of 23.85 cm (s.e. = 0.19) and were significantly smaller than the undamaged ones (P = 0.01). Damaged trees recovered their crown size and after four years of treatment, both damaged (0.50, s.e. = 0.01) and undamaged trees (0.53, s.e. = 0.01) had similar live crown ratios (P = 0.92) (Table IV-2).

Relative basal area growth of individual trees decreased with increased LCR_{loss} ($rBA_{growth} = -0.25\ LCR_{loss} + 0.58$; P = 0.02; R^2 = 0.01; Table IV-3). The relationship between rBA_{growth} and LCR_{loss} was shifted downwards (P = 0.09) for trees in the NTNP stands compared to the OT and TP stands (Figure IV-1), but the slopes did not differ among treatments (*P* = 0.63). Relative BA growth over 4 years for the damaged trees in OT stands, TP stands, and NTNP stands were 0.68 (s.e. = 0.01), 0.64 (s.e. = 0.01), and 0.23 (s.e. = 0.01), respectively. Relative BA growth differed among the sup-plots (*P* = 0.01) with values of 0.55 (s.e. = 0.02), 0.53 (s.e. = 0.02), 0.52 (s.e. = 0.03), and 0.50 (s.e. = 0.02) for the 100, 75, 25, and 50% treatment plots respectively. Sub-plots that had 100% and 75% of trees damaged had rBA_{growth} higher than the sub-plots with 50% damage, whereas growth in sub-plots with 25% damage were similar to others. However, the slopes of the relationship between rBA_{growth} and LCR_{loss} differed among the various sub-plots with different percent of trees damaged (*P* = 0.05, Figure IV-2). Sub-plots with100, 75, 50, and 25% damaged trees had slopes of -0.42, -0.11, -0.44, and -0.24, respectively.

When comparing rBA_{growth} among the undamaged trees, rBA_{growth} was similar for the OT stands (0.85, s.e. = 0.02) and TP stands (0.66, s.e. = 0.01) and lower in the NTNP (0.30, s.e. = 0.01) stands (*P* = 0.006). Relative basal area growth of the undamaged trees inside the sub-plots with 75, 50, 25, and 0% damage were 0.61 (s.e. = 0.03), 0.58 (s.e. = 0.02), 0.63 (s.e. = 0.02), and 0.56 (s.e. 0.02) respectively with rBA_{growth} differing between the 0 and 25% treatments (*P* = 0.06). There was a slight interaction between percent of trees damage and stand type (*P* = 0.07) because the order of ranking differed. When each stand type was analyzed separately, the effect of percent trees damaged on rBA_{growth} was not significant (*P* > 0.13), and the regression models were not significant either (*P* > 0.15) probably because of low power due to fewer observations.

Tree taper of damaged trees was not affected by LCR_{loss} (*P* = 0.86; Tapering = -0.003 LCR_{loss} + 0.83; Figure IV-3). Tree taper of the stand types was similar (*P* = 0.97) among the TP (0.85, s.e. = 0.01), OT (0.84, s.e. = 0.01) and NTNP (0.80, s.e. = 0.01) treatments. Similarly, percent of trees damaged did not significantly affect tree taper; taper in the 25% (0.85, s.e. = 0.01), 50% (0.83, s.e. = 0.01), 75% (0.83, s.e. = 0.01), and 100% (0.82, s.e. = 0.01) damage levels were similar (*P* = 0.96).

Discussion

Although an average of 2.4 m of the tops were removed at time of treatment, we found that the damaged trees had mostly caught back up in height compared to the undamaged trees when measured four years later (0.8 m difference). Loblolly pine is a fast growing species and top damage usually stimulates height growth. Typically at least one lateral branch bends upwards to become the terminal leader (Belanger et al. 1996, Bragg et al. 2003, Aubrey et al. 2007). Compared to height growth which can accelerate to compensate for damage, dbh growth rate is reduced in damaged trees (Belanger et al. 1996). In our study, the damaged trees had smaller dbh than the undamaged ones. As expected, thinning had a positive effect on dbh growth, but not height in the four to five years post thinning.

Trees may start showing stem growth reduction at 20% loss of leaf area (Pinkard 2003), because less live crown, in general, means less leaf area and thus less photosynthesis and less tree growth. In our study, we had removed up to 50% of the crown length from the top. The upper part of the crown is the most productive, the removal of which significantly reduces the tree growth (Pinkard and Beadle 2000). Similar to results reported by Belanger et al. (1996), rBA_{growth} decreased with increased loss of live crown from the top in our study. However, the R^2 value for the relationship between live crown ratio loss and rBA_{growth} in our study was low (0.01). When thinning and pruning were added to the model, the R^2 increased to 0.64 indicating the importance of accounting for silviculture practices when trying to predict stem growth. However, variables that we couldn't account for such as available open space and altered structure due to damage to the neighboring trees, and the architecture of the remaining crown may also influence the growth of the damaged trees (Smith 2000). Additionally, damaged stems and branches are likely to have insect or disease attack which may affect the growth after damage.

Although the slopes between rBA_{growth} and LCR_{loss} were similar for the thinned and non-thinned stands, the trees in the non-thinned stands suffered a proportionately greater decease in rBA_{growth} because the regression relationships for these stands had lower intercepts. For instance, using the slope of -0.25, a 25% reduction in LCR reduced rBA_{growth} by 19% and a 50% reduction in LCR reduced by rBA_{growth} 38% in non-thinned stands. For thinned stands, the reductions were only 9% and 17%, respectively. Thus, depending upon the extent of damage to the crown, thinning of the stand might be worth considering if the stand has not been thinned prior to the damage.

Thinned stands have larger diameter trees with larger crown area and can accumulate large volumes of ice during ice storm, thus exposing individual trees to more damage due to the storm (Belanger et al. 1996, Aubrey et al. 2007). Trees in mid-rotation stand with 18-25 cm average dbh are more susceptible to damage, and stands exposed to the ice storm immediately after thinning experience more damage due to a storm (Belanger et al. 1996, Zeide and Sharer 2002, Bragg et al. 2003). Thus, timing of thinning is important to consider so that the trees grow quickly through the 18-25 cm dbh range and they have a smaller time window for severe damage due to ice storms. As our study simulated ice storm damage, we could not account for differences in damage within thinned vs. nonthinned stands.

The relationship between live crown removal and basal area growth varied among the stands with different percent of trees damaged, but these differences in the relationship were small and difficult to interpret. Overall, damaged trees in sub-plots with 50% of trees damaged had less relative BA growth than the 75% and 100% damage plots, whereas the sub-plots with 25% of trees damaged were similar to others. Less growth for trees in the stands with 50% of trees damaged compared to the stands with a greater number of trees damaged could be due to a greater proportion of undamaged trees that compete with the shorter, damaged trees. If this were the case, however, the least basal area growth of damaged trees should have been in the sub-plots with 25% damaged trees, but this was not the case.

Growth of undamaged trees might accelerate as the proportion of damaged trees increases if competition for light decreases for the undamaged trees. However, the percent of trees damaged in a stand did not affect the growth of the undamaged trees. This suggested that although the canopy was more open in the top portion of the canopy, the trees still had to compete for the nutrients and water, and the competition for water and nutrients remained the same despite the amount of crown damage to the neighboring trees. Also, the thinning treatment in the TP and OT reduced competition for light such that the simulated ice damage probably did not have a large effect on light capture of undamaged trees. As with the damaged trees, however, relative basal area growth of undamaged trees increased due to thinning. Thinning favors the remaining trees by reducing competition between the trees for nutrients, moisture and sunlight, which increases diameter growth. Pruning of already thinned stands did not have a significant effect on the growth of undamaged trees.

Tree taper is affected by thinning as open space allows more stem growth at the bottom than the above (Karlsson 2000). Similarly, pruning reduces the crown size of a tree, because it is equivalent to increasing stand density resulting in more cylindrical stems (Muhairwe et al. 1994). Crown length is one of the factors affecting tree taper as trees with longer crowns have more swollen bases resulting in increased taper (Muhairwe 1994). Removal of crown from the top is likely to have some effect on the stem form but probably only in the long run. We did not find any effects of thinning, pruning or crown loss, because the proportional change of diameters at the two fixed points used for calculating taper is less likely to be significant in a relatively short four-year period.

Conclusion

Understanding how loblolly pine responds to ice damage is important for the management of damaged stands. We simulated the ice damage to the mid-rotation loblolly pine stands which had recently undergone thinning, thinning and pruning, and no-thinning-no-pruning silvicultural practices. We conclude that after ice damage, the mid-rotation stands should be assessed for crown loss because basal area growth after the damage is dependent upon it. However, loss of a large proportion of live crown results in a small decrease in basal area growth, especially in thinned stands, and tree height mostly recovers within a few years. Therefore, unless a majority of the crown (≥70%) is lost, it is probably best to allow the stand to continue to grow. If the stands have not yet been thinned, thinning that removes the damaged trees will improve the stand and increase the growth of residual trees. Even if it is necessary to leave some residual trees that are damaged, accelerated diameter growth due to thinning will minimize the effects of crown damage. Moderate crown loss (up to 50%) does not appear to affect stem form.

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Tables

Table IV- 1 Study sites and the key characteristics

Closest Community	Latitude, Longitude	Soil type	Soil texture (≤40 cm)	Soil pH	Water table depth (cm)	Treatment	Plantation year
Hochatown	34°09'N, 94°46'W	Pickens and Carnasaw-Clebit	Gravelly silty loam-silty clay loam	5.2-5.6	>200	Thinned-pruned (TP)	1992
Hochatown	34°05'N, 94°46'W	Carnasaw-Clebit	Loam-silty clay loam	5.2	>200	Not thinned-not pruned (NTNP)	1994
Eagletown	34°07'N, 94°34'W	Carnasaw-Clebit	Loam-silty clay loam	5.2	>200	Only thinned (OT)	1994
Eagletown	34°08'N, 94°34'W	Pickens and Carnasaw-Clebit	Loam-silty clay loam	5.2-5.6	>200	Thinned-Pruned (TP)	1994
Union Valley	34°08'N, 94°30'W	Carnasaw-Clebit	Loam-silty clay loam	5.5	>200	Not thinned-not pruned (NTNP)	1994
Union Valley	34°04'N, 94 °30'W	Saffell	Gravelly fine sandy loam	5.0	>200	Only thinned (OT)	1994

Table IV- 2 Tree dimensions of undamaged (UND) and damaged (DAM) loblolly pine trees both initially and 4-years after ice damage simulation

		Dbh		Height			LCR		
	Tree condition	**2008**	**2012**	**2008 (pre-treatment)**	**2008 (post-treatment)**	**2012**	**2008 (pre-treatment)**	**2008 (post-treatment)**	**2012**
TP	**UND**	20.18 (0.38)	25.86 (0.44)	12.30 (0.14)	NA	14.56 (0.26)	0.52 (0.02)	NA	0.53 (0.01)
	DAM	20.30 (0.23)	25.89 (0.31)	12.49 (0.10)	10.25 (0.10)	14.18 (0.28)	0.53 (0.02)	0.42 (0.01)	0.50 (0.01)
OT	**UND**	19.42 (0.56)	25.97 (0.56)	11.71 (0.25)	NA	16.45 (0.30)	0.52 (0.01)	NA	0.43 (0.01)
	DAM	18.92 (0.34)	24.40 (0.31)	11.63 (0.17)	9.04 (0.18)	13.06 (0.21)	0.55 (0.01)	0.43 (0.004)	0.50 (0.01)
NTNP	**UND**	19.07 (0.49)	21.77 (0.50)	13.10 (0.26)	NA	16.45 (0.30)	0.52 (0.01)	NA	0.43 (0.01)
	DAM	18.74 (0.30)	20.63 (0.29)	13.08 (0.26)	10.67 (0.30)	15.40 (0.41)	0.53 (0.01)	0.42 (0.01)	0.46 (0.01)

Numbers in parentheses represent standard errors.

Table IV- 3 ANOVA summary table

Source of variation	DF	MS	p-value
Silvicultural treatments	2	1.6220	0.0920
Error I	3	0.2768	
Damage level	3	0.0918	0.0085
Silvicultural treatments*Damage level	6	0.0325	0.0942
Error II	9	0.0124	
LCR_{loss}	1	0.3804	0.02
LCR_{loss}*Silvicultural treatments	2	0.0101	0.6611
LCR_{loss}*Damage level	3	0.0627	0.0534
LCR_{loss} *Silvicultural treatments*Damage level	6	0.0351	0.1964

*Live crown ratio (LCR_{loss}) was used as a covariate to see the effects of silvicultural treatments (whole plots), and damage levels (sub-plots) on the relative basal area growth (rBA_{growth}) of the damaged trees. The analysis was done at $\alpha = 0.10$ level.

Figures

Figure IV- 1 Relationship between relative basal area growth and live crown ratio loss in stands with different treatments

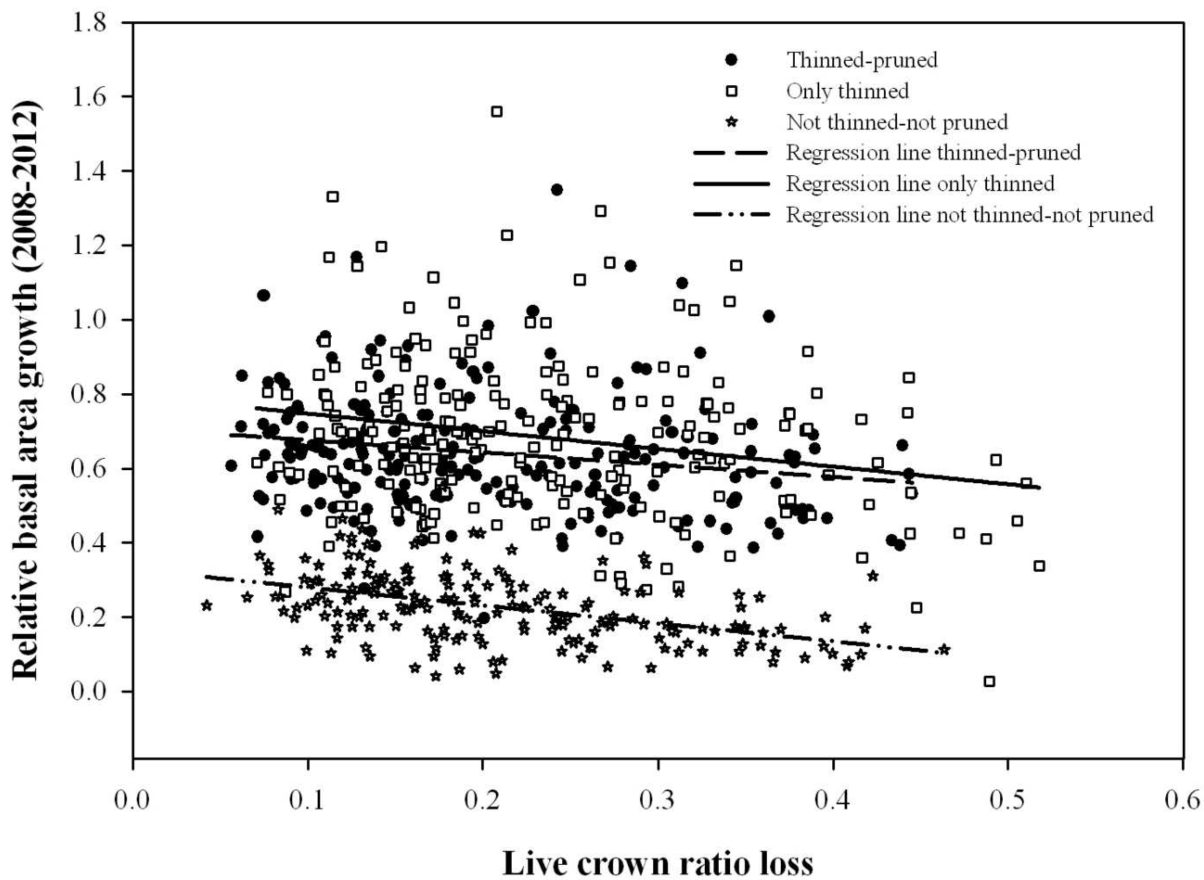


Figure IV- 2 Relationship between relative basal area growth and live crown ratio loss in stands with different levels of damages

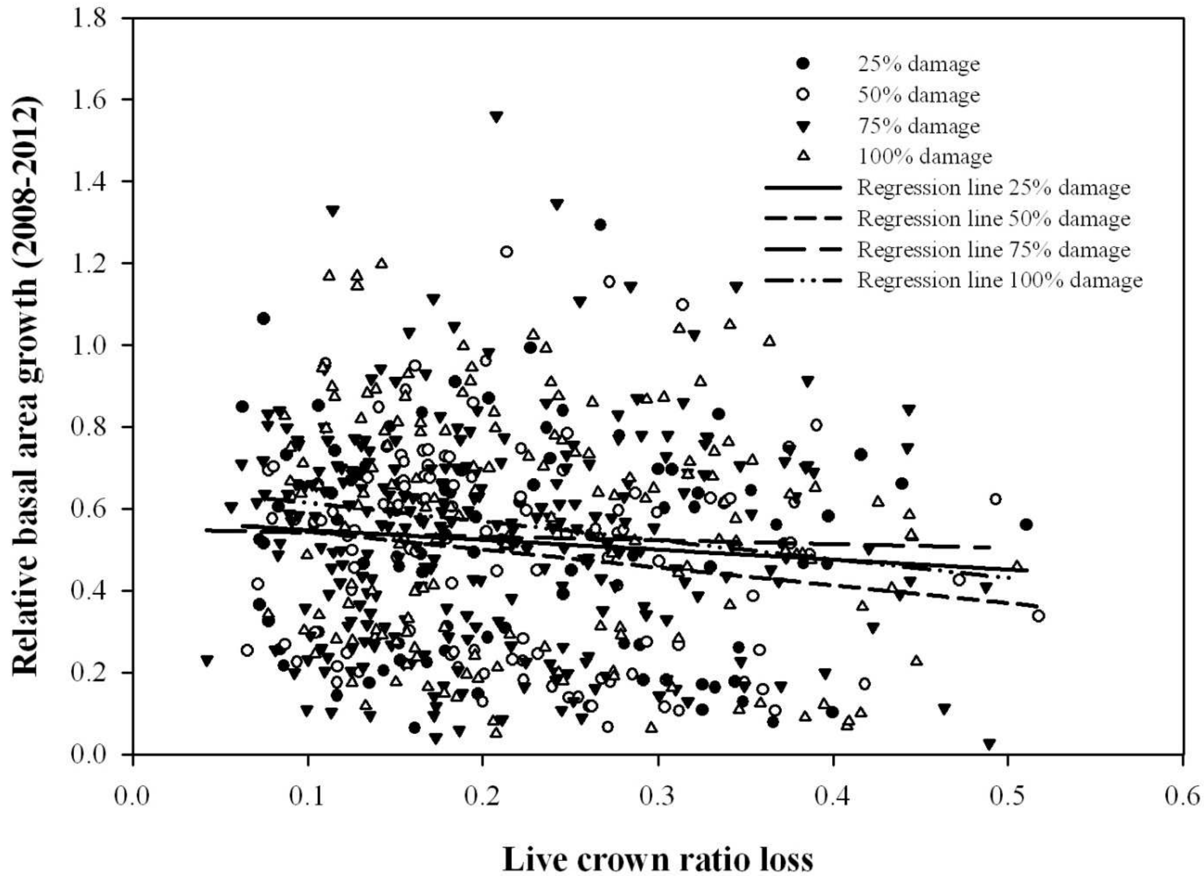
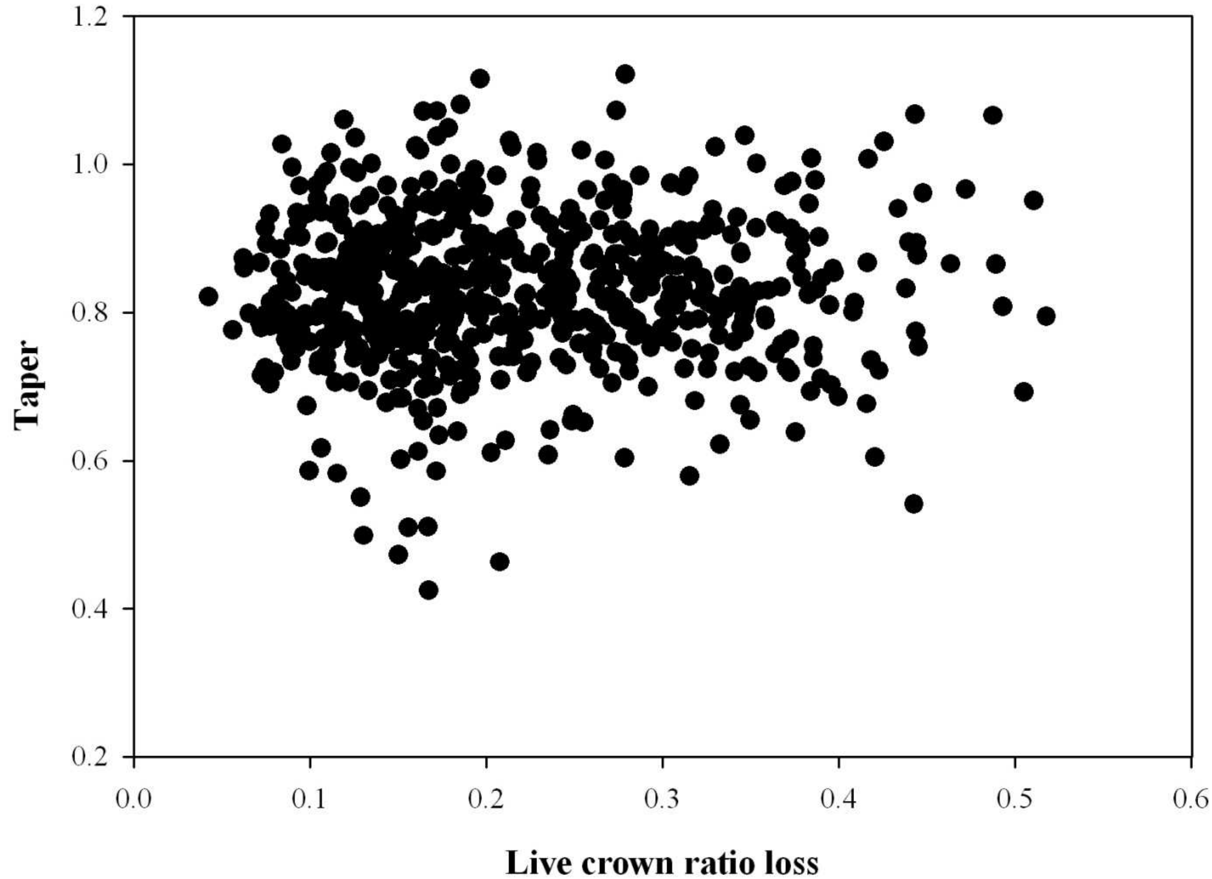


Figure IV- 3 Relationship between taper and live crown ratio loss



*None of the stands exhibited significant relationship between the taper and live crown ratio loss.

CHAPTER V

CONCLUSION

We found out that short-rotation woody crops can be efficient in biomass production and nutrients removal if planted in the nutrient rich conditions. Growth performance of eastern cottonwood and American sycamore were comparatively lower than those planted further east in their natural range. Annual biomass production and nutrient uptake were far higher in eastern cottonwood than the American sycamore. As expected, local cottonwood clone growth performance and nutrient capture was greater than those from other locations.

My second study found that among the pines planted in the western margin of loblolly pine natural range, loblolly pine was the best performer, followed by pitch X loblolly pine hybrid, despite being in the native range of shortleaf pine. Loblolly pine is the best in terms of biomass productivity in the regions, but considering the location receives periodic ice storms and drought, shortleaf pine might also be considered.

Finally, the ice damage simulation study showed that growth and recovery of the damaged stands depend upon the amount of crown damage. Unless the stand has received the major crown damage, it is better to keep the stand as the trees are capable of recovering their height and diameter growth, although diameter growth is resumed later than height. Thinning of the stand immediately after the damage allows more growth. While growth of undamaged trees was not affected due to damage to the other trees, stands with greater percentage of damaged trees showed more growth than the stands with half of the trees damaged.

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