Loblolly Pine Range and Yield – A Review

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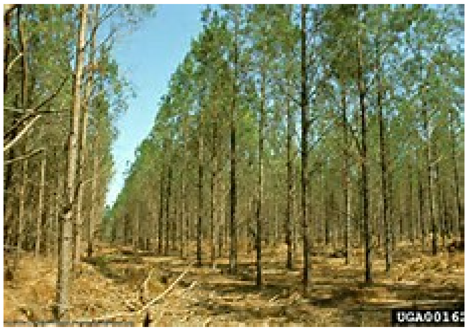
Introduction

The need to reduce the Nation's dependence on foreign oil as a source of energy has been elevated in recent years as a national priority. To achieve this vision, efforts have focused on developing a broader portfolio of energy sources for domestic use. Renewable energy will play an important role in diversification, and considerable investment has been directed to advancing the commercial feasibility of these technologies. Current legislation, The 2007 Energy Independence and Security Act (EISA), provides direct guidance for alternative liquid transportation fuels by mandating production of 36 billion gallons per year of biofuels by 2022. This goal includes 21 billion gallons of advance fuels derived from cellulosic biomass such as perennial grasses and woody resources, as well as residue from current industrial operations. The 2010 United States Department of Agriculture Biofuels Strategic Production Report estimates that the southern region will produce almost fifty percent of the supply of advanced biofuels, reflecting the suitability of this region for cellulosic biomass production.


(Courtesy of William M. Ciesla, Forest Health Management International)



The deployment of a cellulosic biofuels industry in the South requires the reliable supply of large volumes of lignocellulosic biomass at competitive prices that are produced using sustainable management practices. As noted, the region offers many potential options for feedstock including annual and perennial herbaceous crops and short rotation woody crops. One unique solution, however, is loblolly pine (*Pinus taeda* L.). Today there are approximately 45 million acres, or 22 percent of the timberland (Smith et al. 2009), of planted pine stands in the South. Of these stands, 30 million acres are loblolly-shortleaf pine. The photos[5] on the right show representative loblolly pine plantations with different stand densities (top and middle), and a stand after thinning

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[5] Picture credits: Top photo is by David Stephens (http://forestryimages.org/browse/subthumb.cfm?sub=2181); middle photo is courtesy of William M. Ciesla, Forest Health Management International; bottom photo is from the University of Georgia

(bottom). Grown primarily for pulpwood and other conventional forest products, the current resource is the result of decades of research and leading-edge innovations in pine planting stock development and plantation management. Because of its general cultural acceptance and extensive management knowledge, high yields, and favorable production economics, loblolly pine is also a key candidate feedstock for renewable fuels and energy.

The Sun Grant Initiative and the Department of Energy's Bioenergy Technologies Office formed the Regional Biomass Feedstock Partnership[6] in 2009 to define the current state of the science of biomass feedstock production, and establish the baseline for yield potential of major biomass sources. Short rotation hardwood crops are an important component of that work, involving a national network of trials to accurately assess productivity of improved varieties of hybrid poplar and willow. The data generated by the partnership are the foundation of interactive yield maps that provide insight into future yield potential for these two woody crop species (see report on poplar by Berguson et al. 2013; on willow by Volk et al. 2013). Although loblolly pine is not a trial species within the scope of the Partnership, a yield map was developed as part of this project because of its anticipated contribution as a biomass feedstock in the southern region.

Extensive studies on the impact of planting density and management practices on growth and yield of loblolly pine have been conducted; however, information is still needed to more completely understand the factors impacting biomass yield across the entire management range. As part of the Regional Feedstock Partnership's program, interactive maps based on current best management practices and regional climatic, soil and land use conditions have been created. This report provides a background for loblolly pine yield summarizes the assumptions made in producing the map, and discusses the data used for calibration and validation of pine yield.

Background

Planted southern pines are an important commercial forest crop in the South, accounting for about 80% of all trees planted and contributing nearly half of the industrial wood supply (Smith et al. 2009). Loblolly pine is the most important and widely cultivated southern pine species because it grows rapidly over a wide range of sites. Loblolly responds well to management inputs and is the best choice on good sites with better-drained soils where hardwood competition is a problem (US DOE 2011).

In the 2010 Resource Planning Act (RPA) assessment, investments in plantations are expected to partially offset timberland declines. Under RPA scenarios with the highest timber demand, planted pine areas in the Southern Region are projected to expand by more than 70 percent in the next 50 years (USDA Forest Service 2012). By 2060 projected planted pine area ranges from 47 to 67 million acres, depending on future land use and market projections (USDA Forest Service 2012) (Figure 1.). Loblolly pine is also considered to be one of the most productive species for supplying biomass as a feedstock for alternative fuels (Gonzalez et al. 2009).

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[6] http://www.sungrant.org/Feedstock+Partnerships/

Production and Silviculture[7]

Southern pine productivity has increased 6 fold in the past 7 decades as the transition from natural stands to intensively managed pine plantations for fiber production has evolved. Southern pine management is one of the major success stories in plantation forestry (Fox et al. 2007). Loblolly pine seedlings are usually grown in tree nurseries from genetically improved seed stock for higher yield and disease resistance. They are then planted as 1-year-old seedlings using improved planting techniques on prepared and fertilized sites.

In the past half-century, many improvements have led to highly productive loblolly pine in the South (Stanturf et al. 2003; Fox et al. 2007). Improved nursery and field planting practices were just the beginning. Careful breeding and selection contributed to improved genetic varieties and clones. Competition control, first by mechanical means and now by herbicides, increases yield. Site preparation and fertilization, including adding micronutrients, further improve yield. Studies continue to show the potential for increased yield through intensive management practices, like those used in loblolly pine plantations (Cobb et al. 2008; Martin and Jokela 2004; Roth et al. 2007; Samuelson et al. 2008; Will et al. 2006).

Yields

Stanturf and others (2003b) report an average yield of aboveground biomass to be about 4 dry tons per acre annually for loblolly pine across the South. A review of yields in the Billion Ton Update (DOE 2011) reports non-fertilized research plots average about 3.3-3.8 dry tons per acre per year while fertilized plots produce about 3.6-5.2 dry tons per year per year. Research plots with site preparation, weed control, and fertilization also yield in the range of 3.6 to 5.2 dry tons per acre per year of biomass. Adding higher levels of fertilizers plus irrigation in some cases has shown yields to be 5.1 to 7.3 dry tons per acre per year of biomass (DOE 2011). On the best sites at the highest management intensity with the best genotypes, yields are in the 5.4 to 8.5 dry tons per acre per year; however, these extremely high yields from the research plots may not be economic operational at this time.

Energy Plantations

Loblolly pine stands in the South are managed currently for pulp and timber at a stand density of about 600 seedlings per acre. These stands are usually thinned after 15 years and then grown to a 25-year rotation (Gonzalez et al. 2009). This management approach can provide resources for bioenergy, primarily in the form of residues from harvesting or the thinning of small, unmerchantable trees. For energy plantations, a different management regime would provide more feedstock.

One management concept that has been advocated to produce both timber and bioenergy products, involves widely spaced rows of trees for timber and tightly spaced rows for bioenergy (Gonzalez et al. 2009; Scott and Tiarks 2008). The bioenergy rows would be harvested in 5 to 8 years and the widely spaced row for lumber production to be harvested at 18 to 22 years. A more efficient feedstock production approach is to use dedicated energy plantations. Such plantations are likely to be planted at significantly higher densities and managed on much shorter rotations.

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[7] The authors want to acknowledge the use of and refer readers to the Southern Pines section of the U.S. Billion-Ton Update (http://www1.eere.energy.gov/bioenergy/pdfs/billion_ton_update.pdf). This section was written by Lynn Wright.

Although much work has been completed in maximizing loblolly pine yields through stand density management, more information is needed for optimal stand density and harvest age for bioenergy. At establishment with stand densities of 454 to 670 trees per acre, acceptable growth rates continue until about 10 to 15 years (Samuelson et al. 2008). At a density of about 1,200 trees per acre, annual increment in growth slows by age 5, but still continues to increase (Roth et al. 2007). Studies have shown that biomass yield increases with higher planting density in the short term such as in 5 years (Burkes et al. 2003; Will et al. 2005; Will et al. 2006). For longer rotations (e.g., 25 years) initial density had little or no effect on biomass yield (Cardoso et al. 2013). Shelton (1984) investigated a range of initial planting densities up to 25 years and concluded that density had no effect on biomass production in the long term. Zhao et al. (2012) reported on aboveground biomass allocation in pine plantations at age 12, concluding that a more intensive management increased stand-level stem, bark, and branch biomass, but did not affect foliage biomass. Planting density did significantly affect stand-level aboveground biomass accumulation and partitioning up to about 900 trees per acre – more biomass went to the stems as planting density increased. Reports have also suggested that current annual increment is not just dependent on tree density as the maximum occurs at different densities across different sites (Hennessey 2013).

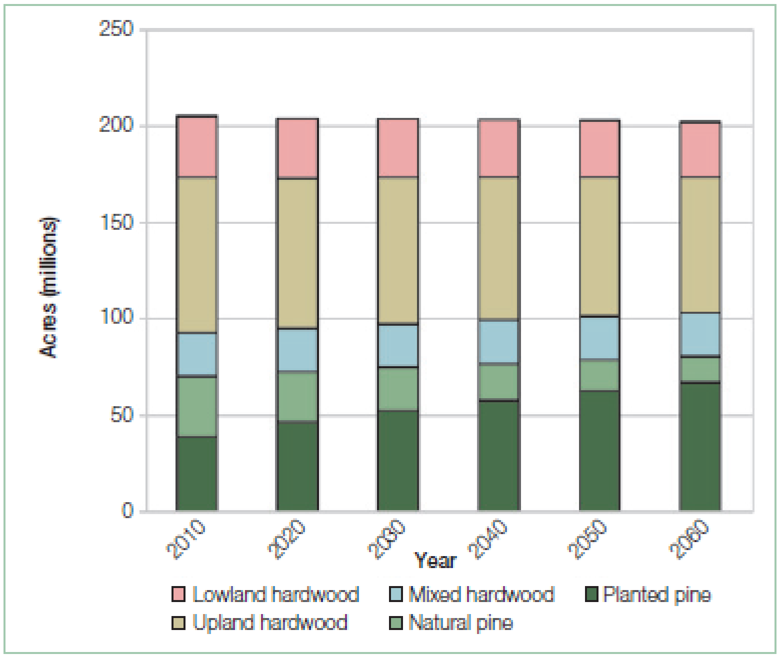

Figure 1. Projected future management types (figure 35, U.S. Forest Service 2012).

Recognizing that silvicultural practices may afford further controls, the production goal for pine as a source of biomass is then to capture the fastest growth, most wood volume, and largest tree size in the shortest time. Tree size is important as it dictates the cost of harvest and processing, and influences characteristics that impact process behavior (e.g., bark to wood ratio, density, etc.).

To realize tangible benefits for landowners and maximize yield for biomass production, loblolly pine must be managed accordingly. Amateis et al. (2012) stated that woody crop managers must practice optimal planting densities in order to get the quantity and quality of wood that is desired. Amateis et al. (2012) evaluated establishment densities over a 25 year period and found that the amount of merchantable wood is associated with and directly linked to management practices, specifically initial planting densities. Additional intensive management practices include fertilization, irrigation, weed control, planting method, among others. All are proven methods to increase yield; however, this report focuses on the biophysical potential yields of pine with operational intensive management.

Previous studies have focused on loblolly pine due to the strong biomass to bioenergy potential. Zhao et al. (2012) and Munsell and Fox (2010) suggested that loblolly pine is the most important species in the south because of this traditional and non-traditional (i.e., biofuels and bioproducts) use, and its potential for high returns on investment to landowners. In shorter-term studies, intensive management practices have shown a positive increase in total biomass productivity (Munsell and Fox 2010; Zhao et al. 2012; Cardoso et al. 2013; Subedi et al. 2012). This included an increase in merchantable stem as well as branches, bark and foliage (Zhao et al. 2012). Specifically, previous studies have shown that fertilization and weed control significantly affect biomass production (Zhao et al. 2012). There is considerable inconsistency in the literature regarding the effect of initial spacing on biomass production, or the yield benefit of intense management practices. Additional research is needed to get a better understanding of the effects on loblolly pine biomass production.

Methods and Procedures

The pine study was a late addition to the Partnership's research priorities with no field trial research implemented. However, in order to include another high-yielding feedstock and to include a species that dominates the southern landscape, historical pine data and new biomass yield maps were included in the woody crop program.

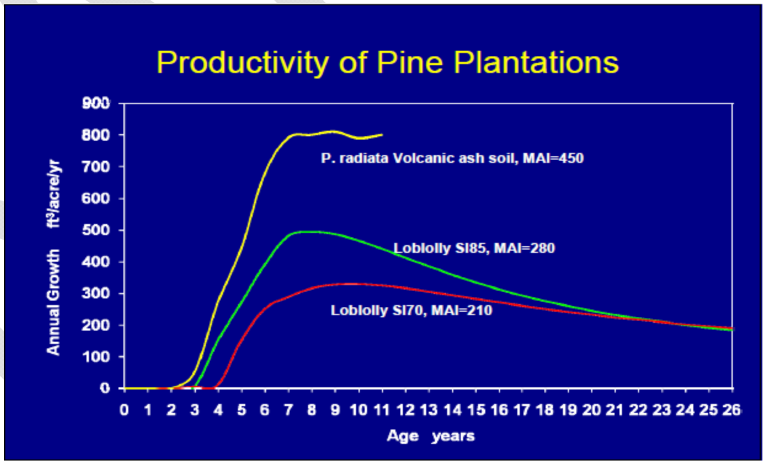

Figure 2. Annual growth as function of age (Allen 2009).

In late 2013, several Partnership researchers, members of Oregon State University's PRISM Climate Group, and representative of the Oak Ridge National Laboratory, prepared a map of the potential yield distribution of woody crops across the U.S. under long-term, average climate conditions. The team incorporated estimates of long-term yields in the PRISM-EM environmental suitability model to produce biophysical potential yield maps that reflect the knowledge of the participating experts and a review of the literature. The methods used and results from the model in regards to pine potential, are described in this report.

The data used in this report were collected from published reports on loblolly pine productivity on sites distributed across the Southeast. The data is an extrapolation and interpretation of that published data. This effort would benefit greatly from additional data since few studies representing the target conditions (10-year rotation and 1,500 trees per acre) were found. As discussed above, stand age and planted trees per acre are important to maximizing total above ground biomass at the lowest cost. Mean annual increment, i.e. annual growth, is usually very aggressive during the early years of stand establishment and then tapers off over time. The age that this occurs is dependent on many factors such as genetics, management treatments, site conditions, and weather (see Figure 2). For this study, a single age of 10 years was chosen, primarily to simplify the mapping procedure while capturing the early, high growth for improved economics. The mapping process was further simplified by considering only a single stand density, initial trees planted at establishment. Although the literature is not consistent, 1,500 trees per acre was selected as the representative bioenergy scenario providing significant biomass accumulation within the 10-year rotation. This process is an oversimplification of the growing of loblolly pine in intensively managed plantations. More research is needed to better understand the interactions of age, stand, management, site and weather for maximizing biomass production across the site. This study does, however, provide a relative yield comparison across the range in which loblolly grows in the South.

Geographic and Environmental

This report included a total of 13 research sites. Latitude and longitude information were not reported in several of the selected manuscripts (Shiver and Harrison 2004a; Shiver and Harrison 2004b). Shiver and Harrison (2004a; 2004b) and Land et al. (2004) were assigned "best guess" locations based on the information provided (i.e., east Mississippi, the coastal plain of Georgia and Florida). The additional trial locations had latitude and longitude provided in the published reports (Amateis et al. 2012; Will et al. 2004; Subedi et al. 2012).

Limiting Factor Approach

The Prism Model calculates yield by determining the lowest relative yield resulting from the following functions:

- Water Balance/Model
- Winter Low Temperature Constraint
- Summer High Temperature Constraint
- Soil pH
- Soil Salinity
- Soil Drainage

The calibration, modeling, and mapping processes are explained in detail by additional papers on this website.

Interpretation and Extrapolation

Of the selected manuscripts, the range of planting densities varied greatly. The density listed by Amateis et al. (2012) ranged from 303 to 2,272 trees/acre. Similarly, the range reported by Subedi et al. (2012) was 300 to 1800 trees per acre. To reach the desired density of 1,500 trees per acre, data was averaged to calculate the selected density rate. For example, data from Land et al. (2004) with tree densities of 981 to 2,207 was averaged to reach the target of approximately 1,500 trees per acre.

The range of ages was less variable with establishment years ranging from 1983 to 1998. Most of the studies were measured around age 8 to 12. Will et al. (2004) was only at age 4. Mean annual increment (MAI) was utilized to interpolate from reported ages to age 10. Age 10 was selected as a harvest age since the mean annual increment "generally flattens" about that age (Figure 2). Shiver & Harrison (2004b) was interpolated from age 8 to age 10. Will et al. (2004) was interpolated from age 4 to age 10. Subedi et al. (2012) was interpolated back from age 12 to age 10. Finally, Shiver & Harrison (2004a) was interpolate from age 6 to age 10.

The wide variation in establishment years created uncertainty because over that 15-year period new varieties were developed. Yield differences could be due to cultural differences instead of the environmental differences that were important to the model yield extrapolation. All field data were put on 2013-year yields by using an annual biomass increase factor of 2%, e.g. each year's biomass measurement was increase by 2% each year until 2013. The correction assumed genetic improvements. This factor was determined from the DOE High-Yield Scenario Workshop Series Report and selected 2% (U.S. DOE 2010). The 2% was a conservative estimate as several other density studies have used a larger adjustment rate. For example, Munsell and Fox (2010) reported a 400% increase within five decades, or roughly 8% yearly, due to new management practices and experienced landowners observing site indices, which include soil type, site preparation, fertilization and irrigation. With additional data this rate may fluctuate depending on new research findings.

Also, the field plot data were reported in various forms such as total above biomass, stem volume inside and outside bark, and merchantable volume. For consistency, the volumes were converted to merchantable stem volume, and then increased to total above ground biomass. A 20% rate was applied to the merchantable stem volume. Heath et al. (2008) suggested a 20% addition for total biomass volume (above ground) over stem volume. Total biomass includes stem, bark, top, and limbs. Again, this was also a conservative approximation and would depend on individual tree size and form.

Biomass Yield Study

The PRISM-EM environmental suitability model was used to produce the potential yield map for pine (Figure 2.). The potential yields range from 0 to 100 percent of the maximum. The long-term yields reported in the selected manuscripts, revised to include the improved stock yield correction and the total biomass volume, was entered into the model. These yields plus the knowledge of the woody crop team formed the potential pine yield map.

Range

The southeast, with its diverse landscape can host millions of acres of pine and other cellulosic feedstocks. The Department of Energy High-Yield Scenario Workshop Series Report (U.S. DOE 2010) found that loblolly grew well across the southern U.S. on most soil types and different levels of moisture. The potential yield map (on this website) provides a better understanding of the geographical and environmental range of loblolly pine.

At the top of the southeastern region, (i.e., central Kentucky and Virginia) temperatures drop, weather patterns change and there is less biological potential for pine to thrive. In this area of the region, potential pine yields drop below 31 percent of maximum yield. At this low production potential, landowners will probably not invest in pine. The lack of high yield in this area is equivalent to a lack of returns for landowners. This same factor has limited the amount of research plots in this area, creating a lack in available yield data to include in the model. To the west of the region (i.e., eastern Texas) the lack of water becomes a factor, and the ability of pine to survive drops. Pine is less drought tolerant and therefore, not able to prosper past east Texas.

The lack of data causes gaps in productivity, and is only indicative of yields across the south and into the fringe areas. The areas where pine yields increase and produce upwards of 60 to 100 percent are Louisiana, Mississippi, southern Alabama, southern Georgia, South Carolina and Florida. This range is consistent with the data reported.

Yields

The map is a biologically accurate representation of potential pine yields based on the available data used in the analysis. Areas less than 20% yields were excluded because of the uncertainty and amount of the data in those areas. With little or no plot data, it was not feasible to map the yield potential in much of the fringes to the southeastern U.S. This omission should not reflect on the capability of the model, simply a lack in trial locations and data. These assumptions do not imply that loblolly pine will not growth outside the Southeast, but only that there were not sufficient data outside this area to accurately map the yields. Pine will probably not be planted in the fringe locations because the potential yield is so low. The map extent highlights areas in which there are suitable yield observations from cited field trials.

Yields in central Alabama and Georgia have a lower yield range of 41 to 60 percent and lower reported yields primarily due to soil issues (i.e., drainage and slope). Yields increase in the “deep” South with an 81 to 100 percent range. The dark green represents areas where pine has sufficient moisture, productive soils, and warmer temperatures. Pine will biophysically thrive in these areas. The Ohio Valley shows the extent of the loblolly pine range, but the low potential yields may exclude commercialization in the area. Biological potential is only listed on the map and does not consider land use, economics, or other factors.

The yields from the literature, after adjusting for age, genetic improvements, and total biomass ranged from 3.2 to 10.2 dry tons as the mean annual increment. The map derived the yields across the South from less than 2 dry tons to over 5 dry tons per year. As expected, the higher yields were in the areas that have shown historically to be areas with many acres of planted pine, specifically loblolly. Again, as noted before, the areas with less than 2 dry tons per acre per year are excluded from the loblolly pine range primarily for the lack of data as the biological potential decreases according to the model. Furthermore, as the literature indicates, the highest yields can be much higher than the 5 dry tons per acre per year used in bracketing the higher yields on the map.

Restrictions and Limitations

A limitation of this study is the small sample size of the available yield data. Also, there were few data at higher density and shorter rotations than the current yield information based on pulpwood and sawtimber management. Also, much extrapolation, interpolation, and interpretations were required to extract and utilize the data from the various studies. Therefore, this data summary and the yield maps should be used with caution and only as a general indicator of both loblolly pine yields and range. Hopefully, additional data will be forthcoming in the near future as researchers continue to improve biomass yields and range for loblolly pine.

Conclusions

Results from this study conclude that loblolly pine is a promising and important biomass feedstock and could have an important bioenergy role in the Southeastern United States. The study used yields from past research and new mapping techniques from the PRISM Climate Group to explore the yield gradients across the South and the extent of the loblolly pine range. The map indicates that loblolly grows across the Southeast, as known, but does have an extended range into the northern and western areas of the South. Yield is affected by the biophysical conditions of the soil and climate with higher yields in those areas and a reduction in yields in the colder and dryer areas.

The map is based on very little data with much extrapolation and interpolation. The map should not be used for assessing absolute yields, but rather to better understand yield and location interactions and to provide on general yields and range of loblolly pine.

This study does show the need to the need to develop additional datasets and to conduct imperial field research to look at the effects of stand density, harvest age, soils, and climate on yield. Studies are also needed to better understand the range of loblolly pine growth outside the "deep" South. This continued research would give producers and landowners more information on loblolly pine plantation investment and management.

Literature Cited

Allen, H. Lee. 2009. Managing productivity and resource limitations in pine plantations in Chile and SE USA. Downloaded from website on December 18, 2013. http://www.ces.ncsu.edu/forestry/feop/Chile/LAllen_08042009.pdf

Allen H.L., T.R. Fox, and R.G. Campbell. 2005. What is ahead for intensive pine plantation silviculture in the South? *Southern Journal of Applied Forestry*, 29(2):62–69.

Amateis, R.L. and H.E. Burkhart. 2012. Rotation-age results from a loblolly pine spacing trial. *Southern Journal of Applied Forestry*, 36(1):11-18.

Aspinwall, M.J., J.S. King, S.E. McKeand, and B.P. Bullock. 2011. Genetic effects on stand-level uniformity and above- and belowground dry mass production in juvenile loblolly pine. *Forest Ecology and Management*, 262(4):609–619.

Borders B.E., R.E. Will, D. Markewitz, A. Clark, R. Hendrick, R.O. Teskey, and Y. Zhang. 2004. Effect of complete competition control and annual fertilization on stem growth and canopy relations for a chronosequence of loblolly pine plantations in the lower coastal plain of Georgia. *Forest Ecology and Management*. 192(1):21–37.

Bryars, C., C. Maier, D. Zhao, M. Kane, B. Borders, R. Will, and R. Teskey. 2013. Fixed physiological parameters in the 3-PG model produced accurate estimates of loblolly pine growth on sites in different geographic regions. *Forest Ecology and Management*, 289(2013):501–514.

Burkes, E.C., R.E. Will, G.A. Barron-Gafford, R.O. Teskey, and B. Shiver. 2003. Biomass partitioning and growth efficiency of intensively managed *Pinus taeda* and *Pinus elliottii* stands of different planting densities. *Forest Science*, 49(2):224–234.

Cardoso, D.J., A.E.B Lacerda, M.A.D. Rosot, M.C. Garrastazú, and R.T. Lima. 2013. Influence of spacing regimes on the development of loblolly pine (*Pinus taeda L.*) in southern Brazil. Forest *Ecology and Management*. Available online 12 October 2013, ISSN 0378-1127.

Cobb W.R., R.E. Will, R.F. Daniels, and M.A. Jacobson. 2008. Aboveground biomass and nitrogen in four short-rotation woody crop species growing with different water and nutrient availabilities. *Forest Ecology and Management*, 255(12):4032– 4039.

Fox, T.R., H.L. Allen, T.J. Albaugh, R. Rubilar, and C.A. Carlson. 2007a. Tree nutrition and forest fertilization of pine plantations in the Southern United States. *Southern Journal of Applied Forestry*, 31(1):5–11.

Fox, T.R., E.J. Jokela, and H.L. Allen. 2007b. The development of pine plantation silviculture in the southern United States. *Journal of Forestry*, 105(7):337–347.

Gonzalez, R., J. Wright, and D. Saloni. 2009. Filling a need: forest plantations for bioenergy in the Southern US. *Biomass Magazine*, 2009(8):44–7.

Heath, L.S., M. Hansen, J.E. Smith, P.D. Miles, and B.W. Smith. 2009. Investigation into calculating tree biomass and carbon in the FIADB using a biomass expansion factor approach. In: McWilliams, Will; Moisen, Gretchen; Czaplewski, Ray, comps. Forest Inventory and Analysis (FIA) Symposium 2008; October 21-23, 2008; Park City, UT. Proc. RMRS-P-56CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 26 p.

Hennessey, T.C., R.E. Will, T.B. Lynch, R. Heinemann, R. Holeman, D. Wilson, K. Anderson, and G. Campbell. 2013. Effects of planting density and genotype on canopy size, canopy structure, and growth of 25-year-old loblolly pine stands in southeastern Oklahoma. In: Guldin, James M., ed. 2013. Proceedings of the 15th biennial southern silvicultural research conference. e-Gen. Tech. Rep. SRS-GTR-175. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 497-498. Available online at http://www.treesearch.fs.fed.us/pubs/43968

Kantavichai, R., T.V. Gallagher, and L.D. Teeter. 2013. Assessing the economic feasibility of short rotation loblolly biomass plantations. *Forest Policy and Economics*, 38(2014):126–131. Available online 6 June 2013.

Martin, T.A. and E.J. Jokela. 2004. Stand development and production dynamics of loblolly pine under a range of cultural treatments in north-central Florida USA. *Forest Ecology and Management*, 192(2):39–58.

Munsell, J.F. and T.R. Fox. 2010. An analysis of the feasibility for increasing woody biomass production from pine plantations in the southern United States. *Biomass and Bioenergy*, 34(12), 1631-1642.

Roth, B.E., E.J. Jokela, T.A. Martin, D.A. Huber, and T.L. White. 2007. Genotype × environment interactions in selected loblolly and slash pine plantations in the Southeastern United States. *Forest Ecology and Management*, 238(1–3):175–88.

Samuelson, L.J., J. Butnor, C. Maier, T.A. Stokes, K. Johnsen, and M. Kane. 2008. Growth and physiology of loblolly pine in response to long-term resource management: defining growth potential in the southern United States. *Canadian Journal of Forest Research*, 38(4):721–732.

Scott, A.D. and T.J. Dean. 2006. Energy trade-offs between intensive biomass utilization, site productivity loss, and ameliorative treatments in loblolly pine plantations. *Biomass and Bioenergy*, 30(12):1001–1010.

Scott, A.D. and A. Tiarks. 2008. Dual-cropping loblolly pine for biomass energy and conventional wood products. *Southern Journal of Applied Forestry*, 32(1):33–37.

Shelton, M.G. 1984. Effects of the initial spacing of loblolly pine plantations on production and nutrition during the first 25 years. Ph.D. Dissertation, Mississippi State University, Starkville, Ms.

Shiver, B.D. and W.M. Harrison. 2004a. PMRC SAGS culture/density study: Age 6 analysis. University of Georgia. 2004:2.

Shiver, B.D. and W.M. Harrison. 2004b. PMRC coastal plain culture/density study: Age 8 analysis. University of Georgia. 2004:1.

Smith, W.B., P.D. Miles, C.H. Perry, and S.A. Pugh. 2009. Forest Resources of the United States, 2007. Gen. Tech. Rep. WO–78. Washington, DC: U.S. Department of Agriculture, Forest Service. 336 p.

Stanturf, J.A., R.C. Kellison, F.S. Broerman, and S.B. Jones. 2003a. Productivity of southern pine plantations: Where are we and how did we get here? *Journal of Forestry*, 101(3):26–31.

Stanturf, J.A., R.C. Kellison, F.S. Broerman, and S.B. Jones. 2003b. Innovation and forest industry: Domesticating the pine forest of the southern United States, 1920 - 1999. *Forest Policy and Economics*, 5(4):407–419.

Subedi, S., M. Kane, D. Zhao, B. Borders, and D. Greene. 2012. Cultural intensity and planting density effects on aboveground biomass of 12-year-old loblolly pine trees in the upper coastal plain and piedmont of the southeastern United States. *Forest Ecology and Management*, 267, 157-162.

Taylor, E.L., A.G. Holley, and M. Blazier. 2006. New pine planting strategies for the western gulf states. *Southern Regional Extension Forestry Technology Bulletin SREF-FM-003*. Southern Regional Extension Forestry, Athens, GA. 8 pp.

U.S. Congress, House Committee on Agriculture (HCA). 2008. H.R. 2419, the Food Conservation, and Energy Act of 2008. Washington, DC: 110th Congress, 1st Session. Internet site: http://agriculture.house.gov/inside/FarmBill.html.

U.S. Department of Agriculture, Forest Service. 2012. Future of America's Forest and Rangelands: Forest Service 2010 Resources Planning Act Assessment. Gen. Tech. Rep. WO-87. Washington, DC. 198 p. Available online at http://www.fs.fed.us/research/publications/gtr/gtr_wo87.pdf

U.S. Department of Agriculture. 2010. A USDA Regional Roadmap to Meeting the Biofuels Goals of the Renewable Fuels Standard by 2022; USDA Biofuels Strategic Production Report. United States Department of Agriculture, Washington, D.C. June 23, 2010. Available online at http://www.usda.gov/documents/USDA_Biofuels_Report_6232010.pdf.

U.S. Department of Energy. 2011. U.S. Department of Energy Biomass Multi-Year Program Plan; DOE/EE-0617; U.S. Department of Energy: Washington, D.C., 2011.

U.S. Department of Energy. 2010. DOE-EERE Office of Biomass (2010) Billion-ton Study Update "High-yield Scenario" Workshop Series Summary Report. L.P. Ovard, T.H. Ulrich, D.J.

Muth, Jr, J.R. Hess, S. Thomas, B.J. Stokes (eds.). INL/EXT-10-18930. Idaho National Laboratory, Idaho Falls, ID.

Will, R.E., D. Markewitz, R.L. Hendrick, D.F. Meason, T.R. Crocker, and B.E. Borders. 2006. Nitrogen and phosphorus dynamics for 13-year-old loblolly pine stands receiving complete competition control and annual N fertilizer. *Forest Ecology and Management*, 227(1–2):155–68.

Will, R.E., N.V. Narahari, B.D. Shiver, and R.O. Teskey. 2005. Effects of planting density on canopy dynamics and stem growth for intensively managed loblolly pine stands. *Forest Ecology and Management*, 205(1-3), 29-41.

Will, R.E., N.V. Narahari, B.D. Shiver, R.O. Teskey, and M. Wosotowski. 2006. Effects of planting density on the biomass partitioning of intensively managed loblolly pine stands on the piedmont and upper coastal plain of Georgia. In: Proceedings of the 13th Biennial Southern Silvicultural Research Conference.

Zhao, D., M. Kane, B. Borders, S. Subedi, and M. Akers. 2012. Effects of cultural intensity and planting density on stand-level aboveground biomass production and allocation for 12-year-old loblolly pine plantations in the upper coastal plain and piedmont of the southeastern United States. *Canadian Journal of Forest Research*, 42, 111-122.