Dual-Cropping Loblolly Pine for Biomass Energy and Conventional Wood Products

D. Andrew Scott and Allan Tiarks

ABSTRACT

Southern pine stands have the potential to provide significant feedstocks for the growing biomass energy and biofuel markets. Although initial feedstocks likely will come from low-value small-diameter trees, understory vegetation, and slash, a sustainable and continuous supply of biomass is necessary to support and grow a wood bioenergy market. As long as solidwood products are more valuable, bioenergy production will not be the primary market for southern pine. A study exploring a dual-cropping system for southern pine bioenergy and solidwood products was begun in 1982 in Louisiana to determine the phosphorus (P) nutritional requirements of the system. Fertilization of 60 kg ha^{-1} of P was required to produce 90% of the maximum volume at the age of 22 years. Direct-seeding pine in the interrows of a traditional pine plantation produced about 10.2 Mg ha^{-1} of biomass for energy at the age of 5 years but had no lasting effect on the planted pine height, diameter, or standing volume. The system is a viable method to produce both bioenergy and solidwood products. Herbaceous competition control and nitrogen (N) fertilization likely would make the system even more productive and profitable.

Keywords: fertilization, phosphorus, competition, stand development

Interest in alternative energy sources, especially bioenergy, has increased recently in the United States. Market-based strategies for biomass energy and biofuels have been developed and will increase in part because of the Energy Policy Act of 2005, which established the Renewable Fuels Standard that will reduce crude oil imports by 2 billion barrels by 2012. The most successful biobased energy market to date in the United States is that of corn (*Zea mays* L.)-based ethanol. Ethanol has become the third largest market for corn (Renewable Fuels Association 2006), which has, in turn, altered corn agribusiness dynamics and land-management decisions and likely will continue to do so in the future (World Agricultural Outlook Board 2006). Similar markets are being developed for other agricultural crops, such as switchgrass (*Panicum virgatum* L.).

Wood-based biofuel technology, including wood biomass gasification to ethanol, also is being developed, and this new technology will create additional wood biomass markets. These markets may create a strong demand for previously low-value small-diameter trees, woody understory, and slash. However, wood biomass plants likely will be located near other wood-demanding industries because of logistics, and competition for wood may result. In these cases, landowners may wish to maximize total economic value by producing wood biomass for energy in addition to higher-value solidwood products.

The concept of growing trees with an additional crop usually is considered in the context of the agroforestry practice of alley cropping. Alley cropping consists of an agricultural crop grown between widely spaced tree rows. The trees selected usually provide multiple economic products, such as nut and wood production, and have different root system architectures from the crop plant. This system has been adopted successfully in developing countries and by some landowners in the United States as a way to diversify economic returns. Within the United States, the most successful example is that of cropping corn or other agricultural crops with black walnut (*Juglans nigra* L.) plantations in the Midwest. These systems generally work well only where the soil is conducive to row crop production with or without trees.

In contrast to high-quality agricultural lands of the Midwest, dual-cropping pine is more compatible in the southern states where forest soils are too dry, wet, or infertile for the annual row crop component of an alley-cropping system. Grasses can be productive on some of these lands, and research has shown some success with growing grasses as cattle forage amid widely spaced southern pine trees in silvopastoral systems (Clason 1999). However, in practice, silvopastoral systems require a high degree of skill with both range and forest management and frequent management activities.

In pine plantations, control of both herbaceous and interspecific woody competitors is vital for maximum pine plantation productivity (Miller et al. 2003, Borders et al. 2004). Conversely, maximum biomass growth of pure pine plantations per unit area occurs in dense stands because of maximum photosynthetic light interception (Zeide 2004). In these systems, therefore, intraspecific competition is not as deleterious to total production as interspecific competition. Therefore, dual cropping a conventional pine stand with additional pine seedlings for biomass production may provide a viable alternative to row crops or grasses and require only forestry expertise and occasional stand management activities.

This basic proposal was developed originally in the late 1970s after the oil crisis, when interest in alternative energy increased. Koch (1980) developed the components of a combined biomass and solidwood products forest system that would use direct seeding to establish a very dense stand of pine that would be progressively

Received May 14, 2007; accepted September 4, 2007.

D. Andrew Scott (andyscott@fs.fed.us) and Allan Tiarks (aetiarks@worldnet.att.net), US Forest Service, Southern Research Station, 2500 Shreveport Highway, Pineville, LA 71360.
Rick Stagg and Morris Smith Jr. performed the field measurements at age 22 years. Jeff Goelz provided helpful suggestions toward data analysis and provided constructive comments on an earlier draft. Christine Bliss and Michael Blazier provided constructive comments on an earlier draft.

thinned to provide biomass energy wood and, later, sawtimber-suitable trees. Alternatively, he proposed incorporating direct-seeded trees in the interrows of planted pines. Tiarks (1985) adapted this second concept by incorporating the direct-seeded biomass cropping concept within a standard plantation system. Early results from this study focused on initial phosphorus (P) fertilizer responses and on the production and energetic value of the direct-seeded biomass crop, which was about 10.2 Mg ha^{-1} at age the of 5 years (Tiarks 1993).

While this concept was developed as a way to use direct seeding as an economical way to establish dense stands for energy biomass, the concept of creating a dense understory of pine under a more conventional pine plantation also could be used to increase water or nutrient uptake. For example, direct-seeding pine within a young pine plantation could provide greater sediment control near riparian areas while the plantation was developing. Additionally, the concept potentially could be used to reduce hydrologic inputs to streams to help control stream degradation.

As long as the market value of solidwood products greatly exceeds that of biomass energy crops or other small-diameter wood products, this system should not restrict growth of the planted trees, either in terms of volume production or of higher-value product classes for maximum economic efficiency to be realized. Accordingly, our objectives were to determine (1) planted tree growth responses to fertilizer and biomass energy cropping systems after 22 growing seasons and (2) temporal stand dynamics related to biomass energy cropping systems.

Materials and Methods

Study Location and Establishment

The study was performed on the Longleaf Tract of the Palustris Experimental Forest in central Louisiana (31.008°N, 92.616°W). Before harvest, it had been in native grasses with scattered small hardwoods. The site was plowed in 1980 and disked three times in 1981 to reduce grass competition. The soil is a Beauregard silt loam (fine-silty, siliceous, superactive, thermic Plinthaquic Paleudults), which is very common to central Louisiana (USDA Soil Conservation Service 1980).

The study was double-planted in January–February of 1982 with 1–0 bareroot loblolly pine from a single half-sib family on a 2 × 3 m spacing with 15 rows of 11 planting spots per 0.1 ha (22 × 45 m) main plot (Figure 1). The seedlings were reduced to one live seedling per planting spot during the winter of 1982–1983. Nitrogen (N) was applied as urea to all plots (40 kg ha^{-1}) in April 1982. The study was established as a split-plot design with four P fertilizer rates (0, 81, 162, and 324 kg ha^{-1}) applied as triple superphosphate (TSP 0-46-0) in April 1982 to the main plots. The split-plot treatments consisted of three interrow, direct-seeded biomass production treatments: no seeding (NS), seeded and harvested at the age of 5 years (SH), and seeded but not harvested (SNH). The NS treatment served as the operational control treatment, and the SH treatment tested Koch's (1980) concept. The two seeded treatments were designed originally to be harvested at two different ages (ages 4 and 5 years) to determine the optimal age of biomass harvesting. In practice, the SNH plots, which originally were designed to be harvested at the age of 4 years, were never harvested. This treatment provided a comparison of stand dynamics of a system in which the biomass energy crop was not able to be harvested for some reason, or of a system with high levels of early intraspecific competition but little interspecific competition. The biomass production split plots were

Figure 1. Photo depicting half-sib, 1–0 planted seedlings on a 2 × 3 m spacing with unimproved pine seedlings direct seeded in the interrow area for biomass energy after one full growing season..

seeded with unimproved, woods-run loblolly pine seed in February 1982 by placing 3–10 seeds in spots 0.25–0.5 m apart in a 1.5-m swath in the middle of the planted tree rows (Figure 1). In 1984, the direct-seeded trees were hand thinned to the tallest seedling per planting spot. Measurement plots consisted of five rows of three trees each with a border row between each split plot (Figure 1). Each treatment was replicated three times.

Total heights and diameters (rootcollar diameter at the age of 1 and 2 years, dbh [1.3 m] thereafter) were measured at ages 1, 2, 3, 4, 5, 6, 7, 9, and 22 years after planting and fertilizer application. Stem volume outside bark from a 0.15-m stump to the stem tip was calculated using equations developed for unthinned loblolly pine in Louisiana (Baldwin and Feducca 1987) and scaled to the areal level.

Analysis

We analyzed the 22-year growth responses (height, diameter, stand density, and volume) to treatments with analysis of variance (SAS Institute, Inc., 1994). We determined the fertilizer requirement by fitting individual subplot biomass at the age of 22 years to the P fertilizer applied to a modified Mitscherlich function (Mitscherlich 1909; Equation 1) and calculating the fertilizer required to produce 90% of the maximum biomass. We chose 90% as a yield goal because 90% of maximum yield is commonly used to determine nutrient critical levels (Epstein 1972). In practice, the appropriate fertilizer rate should be determined by the marginal revenue gained by the increase in yield and the marginal cost associated with the additional fertilizer,

$$Y = b_0 + b_1 * (1 - e^{-b_2 * P}) \quad (1)$$

where b_i are parameters to be estimated, P is kilograms of phosphorus, and Y is volume (m^3 ha^{-1}).

We compared temporal growth patterns by determining the difference among treatments with highlight short-term responses in height and diameter to the biomass treatments. Finally, we determined the frequency of trees from each treatment in 2-cm diameter classes and performed a chi square test of distribution equality.

Results

Planted Tree Responses to P Fertilizer and Cropping System

Fertilization had significant effects on mean height, diameter, and stand volume at the age of 22 years and did not interact with

Table 1. Probabilities of a greater *F*-value for mean tree and stand characteristics of 22-yr-old loblolly pine stands subjected to four P fertilization rates and three direct-seeded interrow biomass energy cropping systems.

Effect	df	Height	Diameter	Density	Volume
F	3	0.0015	0.0030	0.6456	0.0012
CS	2	0.0503	0.3515	0.7277	0.0219
F × CS	6	0.9638	0.7059	0.1957	0.1087

CS, cropping system; F, fertilization.

Table 2. Mean height, diameter, stand density, and stand volume of 22-yr-old loblolly pine stands subjected to four P fertilization rates and three direct-seeded interrow biomass energy cropping systems.

Treatment	Height (m)	dbh (m)	Density (trees ha^{-1})	Volume (m^3 ha^{-1})
Fertilization				
0 kg ha^{-1} P	19.5b	0.191b	1531a	448b
81 kg ha^{-1} P	21.8a	0.212a	1469a	587a
162 kg ha^{-1} P	22.4a	0.216a	1420a	607a
324 kg ha^{-1} P	22.6a	0.216a	1469a	633a
Biomass				
NS	21.7a	0.211a	1491a	587a
SH	21.8a	0.210a	1472a	579a
SNH	21.2b	0.206a	1454a	541b

Main-effect means within a column and treatment type followed by the same letter are not significantly different at $P < 0.05$.

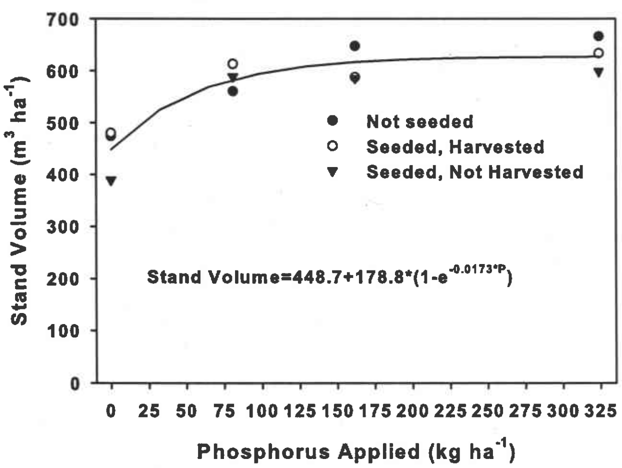

Figure 2. Unthinned loblolly pine stand biomass at the age of 22 years in relation to P fertilizer rate applied at stand establishment.

cropping system (Table 1). P fertilization increased the mean height, diameter, and stand volume by 14, 12, and 36%, respectively, over the plots receiving no P fertilizer (Table 2). Regression analysis indicated the expected yields for this site were 449 and 627 m^3 ha^{-1}, for 0 and 324 kg ha^{-1} added P, respectively (Figure 2). Based on Equation 1, 60 kg ha^{-1} of P was needed to produce 90% of the maximum expected yield (564 m^3 ha^{-1}).

The inter-row direct-seeding system in which the trees were harvested as planned at the age of 5 years (SH) had no impact on height, diameter, or stand volume at the age of 22 years compared with the NS treatment, but when the direct-seeded trees were allowed to remain on the site (SNH), height and stand volume were reduced by 3 and 7%, respectively, compared with the SH treatment plots (Table 2). Stand density was not affected by any of the seeding treatments (Table 2).

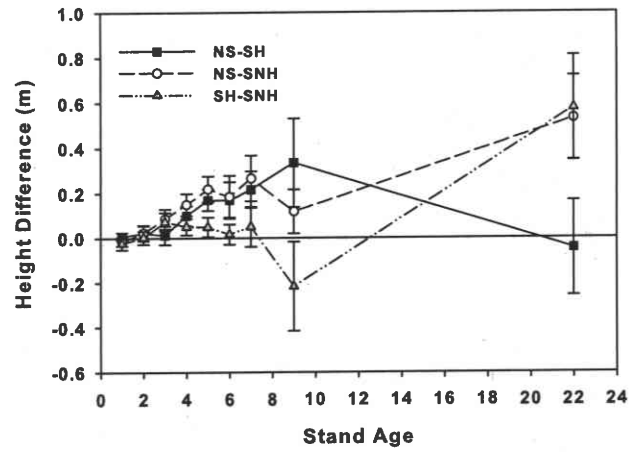

Figure 3. Mean height difference between interrow biomass production systems (NS = nonseeded; SH = seeded, harvested at the age of 5 years; SNH = seeded, not harvested) through 22 growing seasons. Example: NS-SH indicates the mean relative height difference between the NS plots and the SH plots. A positive value indicates trees on the NS plots were taller than the trees on the SH plots. Error bars represent one standard error.

Temporal Stand Dynamics of the Planted Trees in Three Cropping Systems

The difference in mean height between the NS and SH plots increased through the age of 9 years, when the trees on the NS treatment plots were about 0.3 m taller (Figure 3). The height difference of the NS treatment trees compared with the SNH trees also steadily increased through the age of 7 years to a maximum of 0.27 m. Given that until the age of 5 years the SH and SNH treatments were the same treatment (both were direct seeded but neither was harvested), the lack of height growth difference between these plots through the age of 7 years is not surprising. At the age of 9 years, however, the SH treatment trees were 0.33 and 0.22 m shorter than the NS and SNH treatment trees, respectively. At the age of 22 years, the impact of the direct seeding was clear; the NS and SH treatment trees were almost 0.75 m taller than the SNH treatment trees but were not different between each other.

Difference in diameter of the planted trees among the three direct-seeded treatments followed similar patterns (Figure 4). Through the age of 5 years, trees planted in the NS treatment had 0.5-cm larger diameters than the planted trees in the SH or SNH treatments, respectively. Diameter growth of the planted trees responded quickly to harvesting the direct-seeded trees on the SH plots. Within a year after the direct-seeded trees were harvested, the planted trees on the SH plots had 0.27-cm larger diameters than the planted trees on the SNH treatment. By the age of 9 years, the trees on the NS and SH treatment plots had similar diameters and were about 0.5 cm larger than the planted trees on the SNH plots. The diameter growth was unchanged after the age of 9 years, although the diameter differences among the NS, SH, and SNH treatments were not significant at $\alpha = 0.05$ at the age of 22 years because of an increase in variation (Table 1; Figure 4).

At the age of 22 years, not only were the diameters similar among the biomass harvest treatments, but the diameter distributions were similar as well (Figure 5). The SNH treatment resulted in fewer trees in the 19-23-cm diameter range than the other treatments and more trees in the 17-cm diameter class, but the distributions were not statistically different based on the chi-square test of distribution equality ($P > 0.3389$).

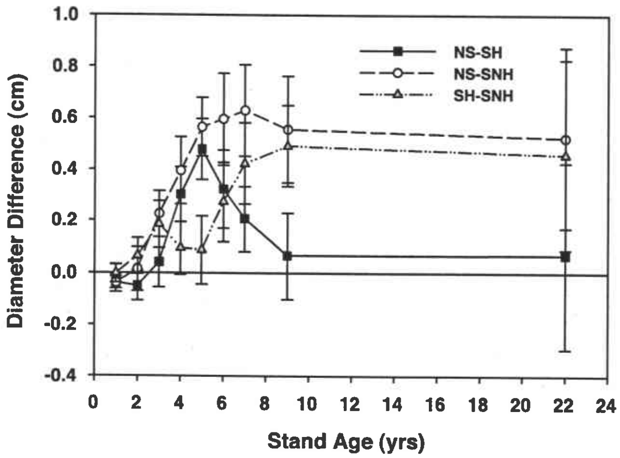

Figure 4. Mean diameter difference at breast height (dbh) difference between interrow biomass production systems (NS = nonseeded; SH = seeded, harvested at the age of 5 years; SNH = seeded, not harvested) through 22 growing seasons. Example: NS-SH indicates the mean relative dbh difference between the NS plots and the SH plots. A positive value indicates that trees on the NS plots had greater diameters than trees on the SH plots. Error bars represent one standard error.

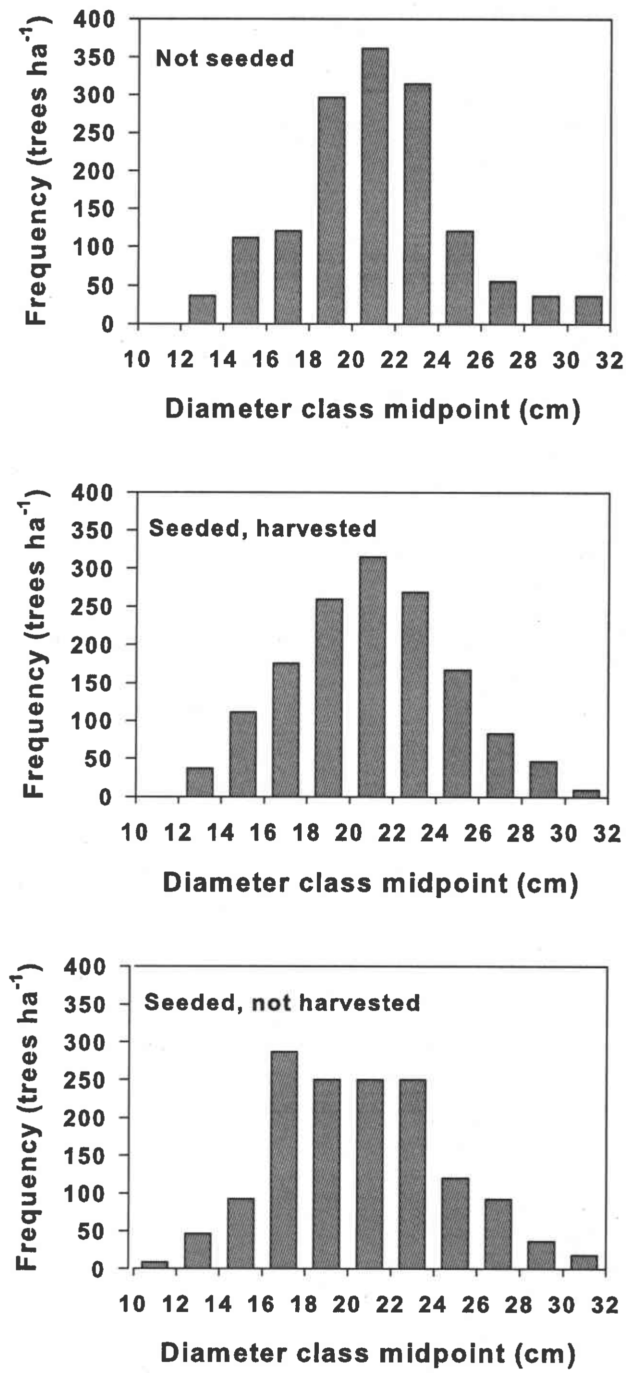

Figure 5. Planted pine diameter frequencies in 2-cm classes by inter-row biomass production system (NS = nonseeded; SH = seeded, harvested at age 5; SNH = seeded, not harvested) at the age of 22 years.

Discussion

Plantation growth was excellent across all treatments through age 22. The mean annual increment averaged 20.4 and 27.7 $m^3\ ha^{-1}\ yr^{-1}$ for the unfertilized and fertilized treatments, respectively. These growth rates are comparable to the average of 26.6 $m^3\ ha^{-1}\ yr^{-1}$ reported for six 10 to 12-yr-old, intensively managed plantations in Georgia (Borders and Balley 2001) and the 24.6 $m^3\ ha^{-1}\ yr^{-1}$ reported for 25-yr-old stands in Hawaii (DeBell et al. 1989). These stands were about 40% more productive than the best plots of four 10-yr-old sites in the Louisiana Long-Term Soil Productivity study (Sanchez et al. 2006).

The response to P fertilization was highly positive and sustained. This indicates that P fertilization increases productivity on soils similar to the Beauregard soil. This finding is supported by previous studies in this region and across the South that have found substantial growth responses to P fertilizer (Pritchett and Comerford 1982, Haywood et al. 1997). Similarly, evidence from studies of intensive harvesting in coastal plain pine stands has indicated the potential for growth reductions because of a reduction in nutrient availability (Tiarks and Haywood 1996, Johnson et al. 2002, Scott and Dean 2006). Although much of the recent research on intensive forest management and forest nutrition is focused on N fertilization, this research assumes that P limitations have been avoided through site selection or fertilization, as has been accomplished on many industrial forestlands. This assumption is not valid across all lands, where fertilization may not have been a common component of management. In addition, the optimal P rate found in this study (60 $kg\ ha^{-1}$ P) is essentially the same as the common establishment rate of 56 $kg\ ha^{-1}$ of P. However, the estimated 60 $kg\ ha^{-1}$ P rate is substantially less than the 162 $kg\ ha^{-1}$ of P estimated by the P sorption isotherm procedure used to determine the fertilizer rates before study establishment and the 117 $kg\ ha^{-1}$ of P rate estimated rate after 1 year of growth on this site (Tiarks 1983). These P fertilization rates were determined early in the rotation, when N availability was likely higher because of the recent soil disturbance at harvesting (assart effect). Had N demand been met throughout the rotation with midrotation N applications, as many intensively managed loblolly pine plantations are, the relative P demand likely would have been greater throughout the rotation.

Second, growing pines in the interrows of a relatively commonly spaced pine plantation had no significant impact on the standing volume of the planted pines at the age of 22 years when the biomass crop was harvested. Conceivably, a landowner might initiate a similar dual-crop system but be unable to harvest the biomass crop for various reasons. This might happen if the market value for biomass changed or if the system was installed for another reason, such as soil stabilization in a riparian area. In this case, which was tested with the other split plot, the planted tree volume was reduced by about 18.5 m^3 ha^{-1} compared with the single-crop system.

The competitive effect of the direct-seeded trees occurred early in the stand development, but the stand recovered when the direct-seeded trees were removed. The mean planted tree diameter and height were increasingly reduced by the presence of direct-seeded trees through the age of 9 and 22 years, respectively (Figures 4 and 3, respectively). After the direct-seeded trees were harvested at the age of 5 years on the SH plots, the planted tree heights and diameters recovered relative to the trees on the NS plots. The tree diameters were similar after only 4 years after the biomass crop harvest (Figure 4), and trees planted on the SH plots remained shorter until 15 years after the biomass crop harvest (Figure 3) at the age of 20 years. Because the direct-seeded trees were substantially shorter than the planted trees (Tiarks 1993), they competed with the planted trees primarily more for nutrients and water than for light. By the age of 22 years, no direct-seeded trees survived. Additional N fertilization likely would have precluded the early reduction in height and diameter growth and improved both direct-seeded and planted tree growth.

Conclusions

This study has shown that Koch's (1980) concept for southern pine bioenergy plantations is biologically viable, and over 22 years produced over 10 Mg ha^{-1} of pine biomass for energy and up to an additional 633 m^3 ha^{-1} of wood that could be used for either biomass energy or for various solidwood products. Thinning likely would have increased solidwood product value in the stands through increasing diameter growth. The inclusion of the direct-seeded trees for biomass had no long-term impact on stand biomass production, although early height and diameter growth was impeded by the biomass planting. Forest managers interested in managing southern pine stands for productivity, especially if they plan on intensive harvesting of either a biomass crop or of entire planted trees, should ensure their stands have adequate P. Although this study did not incorporate repeated N fertilization and herbaceous competition control, these treatments would improve the overall system production.

Literature Cited

Baldwin, V.C., Jr., and D.P. Feduccia. 1987. *Loblolly pine growth and yield prediction for managed west gulf plantations.* US For. Serv. Res. Pap. SO-236. US For. Serv., Southern For. Exp. Stn., New Orleans, LA. 27 p.

Borders, B.E., and R.L. Bailey. 2001. Loblolly-pine pushing the limits of growth. *South. J. Appl. For.* 25:69–74.

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. *For. Ecol. Manag.* 192:21–37.

Clason, T.R. 1999. Silvopastoral practices sustain timber and forage production in commercial loblolly pine plantations of northwest Louisiana, USA. *Agroforest. Syst.* 44:293–303.

DeBell, D.S., W.R. Harms, and C.D. Whitesell. 1989. Stockability: A major factor in productivity differences between *Pinus taeda* plantations in Hawaii and the southeastern United States. *For. Sci.* 35:708–719.

Epstein, E. 1972. *Mineral nutrition of plants: Principles and perspectives.* John Wiley & Sons, New York. 412 p.

Haywood, J.D., A.E. Tiarks, and M.A. Sword. 1997. Fertilization, weed control, and pine litter influence loblolly pine stem productivity and root development. *New For.* 14:233–249.

Johnson, D.W., J.D. Knoepp, W.T. Swank, J. Shan, L.A. Morris, D.H. Van Lear, and P.R. Kapeluck. 2002. Effects of forest management on soil carbon: Results of some long-term resampling studies. *Environ. Pollut.* 116:S201–S208.

Koch, P. 1980. Concept for southern pine plantation operation in the year 2020. *J. For.* 78:78–82.

Miller, J.H., B.R. Zutter, S.M. Zedaker, M.B. Edwards, and R.A. Newbold. 2003. Growth and yield relative to competition for loblolly pine plantations to midrotation—A southeastern United States regional study. *South. J. Appl. For.* 27:1–16.

Mitscherlich, E.A. 1909. The law of the minimum and the law of diminishing soil productivity [in German]. *Landwirtschaft Jahrbuecher.* 38:537–552.

Pritchett, W.L., and N.B. Comerford. 1982. Long-term response to phosphorus fertilization on selected southeastern coastal plain soils. *Soil Sci. Soc. Am. J.* 46:640–644.

Renewable Fuels Association. 2006. *From niche to nation: Ethanol industry outlook 2006.* Renewable Fuels Association, Washington, DC. 22 p.

Sanchez, F.G., D.A. Scott, and K.H. Ludovici. 2006. Negligible effects of severe organic matter removal and soil compaction on loblolly pine growth over 10 years. *For. Ecol. Manag.* 227:145–154.

SAS Institute, Inc. 1994. *SAS/STAT user's guide.* SAS Institute, Inc., Cary, NC. 5,136 p.

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

Tiarks, A.E. 1985. Phosphorus requirements for establishment of dual-cropped loblolly pine. P. 390–394 in *Proc. of 3rd Biennial Southern Silvicultural Research. Conf.*, Shoulders, E., (ed.). US For. Serv. Gen. Tech. Rep. SO-54. US For. Serv., Southern For. Exp. Stn., New Orleans, LA.

Tiarks, A.E. 1993. Biomass production of loblolly pine seeded between rows of planted loblolly pine. *Biomass Bioenerg.* 4:61–67.

Tiarks, A.E., and J.D. Haywood. 1996. Site preparation and fertilization effects on growth of slash pine for two rotations. *Soil Sci. Soc. Am. J.* 60:1654–1663.

USDA Soil Conservation Service. 1980. *Soil survey of Rapides Parish, Louisiana.* USDA Soil Conservation Service, Washington, DC. 86 p.

World Agricultural Outlook Board. 2006. *USDA agricultural baseline projections to 2015.* USDA World Agricultural Outlook Board, Baseline Rep. OCE-2006-1, Washington, DC. 108 p.

Zeide, B. 2004. Optimal stand density: A solution. *Can. J. For. Res.* 34:846–854.