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Research Article

Economics

Financial Returns for Biomass on Short-Rotation Loblolly Pine Plantations in the Southeastern United States

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Abstract

Rising demand for renewable energy has created a potential market for biomass from short-rotation pine plantations in the southeastern United States. Site preparation, competition control, fertilization, and enhanced seedling genotypes offer the landowner several variables for managing productivity, but their combined effects on financial returns are unclear. This study estimated returns from a hypothetical 10-year biomass harvest in loblolly pine plantation using field studies in the Coastal Plain of North Carolina and the Virginia Piedmont testing combinations of tree genotype, planting density, and silviculture. Although enhanced varietal genotypes could yield more biomass, open-pollinated seedlings at 1,236–1,853 trees ha^{-1} under operational silviculture had the greatest returns at both sites, with mean whole-tree internal rates of return of 8.3%–9.9% assuming stumpage equal to current pulpwood prices. At a 5% discount rate, break-even whole-tree stumpage at the two sites in the optimal treatments was \$8.72–\$9.92 Mg^{-1}, and break-even yield was 175–177 Mg ha^{-1} (roughly 18 Mg ha^{-1} yr^{-1} productivity), although stumpage and yield floors were higher if only stem biomass was treated as salable. Dedicated short-rotation loblolly biomass plantations in the region are more likely to be financially attractive when site establishment and maintenance costs are minimized.

Study Implications: Our study suggests that dedicated loblolly pine plantations in the US Southeast may be managed to generate positive financial yields for biomass over relatively short (10 year) rotation windows, even at lower stumpage value than at present for pulpwood in the region (<80% current). Intensive use of costly inputs like fertilizer, vigorous chemical competition control, and elite genetics in planting stock did improve biomass yields. However, the management combinations that favored the highest financial returns emphasized the least expensive open-pollinated stock, lower-input operational silviculture, and moderate-to-high planting density.

Keywords: loblolly pine, bioenergy, genotype, varietals, net present value

The ongoing global policy effort to limit increases in atmospheric greenhouse gas concentrations continues to raise interest in renewable fuel sources that do not release fossil carbon to the atmosphere, particularly for use in the electricity sector (Jones and Warner 2016). European Union countries are fueling demand for biomass from pulpwood and harvest residues increasingly drawn from the pine forestry industry in the southeastern US (Proskurina et al. 2016, Duden et al. 2017, Beagle and Belmont 2019). Residues alone (without supplementation with pulpwood stock) are unlikely to meet growing future bioenergy demand (Abt and Abt 2013). Growing demand has raised the possibility of dedicated biomass production in short-rotation pine plantations, where shorter harvest schedules may be better matched to the time horizons of prospective investors (Clutter et al. 2005). Furthermore, intensive plantations of loblolly pine (*Pinus taeda* L.) in the region may allow these forests to produce more fiber or fuel on a smaller land base than would be possible in unmanaged forests (Fox et al. 2007b).

Loblolly plantations in the region tend to be managed for longer rotations (20–40 years) optimized for sawtimber and pulpwood rather than bulk biomass. There has long been interest in the potential for intensive silvicultural practices like site preparation, precommercial thinning, competition control, fertilization, optimized planting density, and improved tree genetics to enhance growth and economic performance in plantations focused on wood and fiber products (Yin et al. 1998, Lauer and Zutter 2001, Fox et al. 2007a, Ferreira et al. 2020). Prior studies of biomass production potential and financial returns in loblolly plantations have often focused on biomass generated as a co- or byproduct of sawtimber or pulpwood production (Shrestha et al. 2015, Gallagher et al. 2017, Jonker et al. 2018).

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In light of persistent demand, there is emerging interest in exploring the financial returns achievable for tree crops grown specifically for bioenergy (Hinchee et al. 2011), but relatively few formal analyses of short-rotation loblolly biomass plantation systems have been reported to date. Munsell and Fox (2010) showed that, at a relatively low stumpage value of \$5.40 Mg^{-1} for whole-tree biomass, net present value (NPV) at an 8% discount rate was negative in three consecutive eight-year biomass rotations of loblolly, whereas returns were positive in a single 24-year rotation sawtimber-and-pulpwood plantation that also used residual biomass. By comparison, another study showed that at approximately \$10 Mg^{-1} stumpage, 12-year rotations optimized for biomass could reach positive NPV (5% discount rate) over most of the native range of loblolly pine (Perdue et al. 2017). A further modeling-based study parameterized using field observations in Alabama examined short-rotation whole-tree biomass with 22–25 year rotations for timber products using harvest residues (Kantavichai et al. 2014). Break-even prices at a 5% discount rate on the low-lying Coastal Plain region were approximately \$16 Mg^{-1} for a nine-year rotation versus \$12 Mg^{-1} in the upland Piedmont region for a 14-year rotation — higher than the then-current stumpage value of pulpwood. An empirical study of yield and returns for several different styles of short-rotation woody biomass plantations on land under remediation in North Carolina suggested that loblolly pine might garner a lower break-even price and higher economic value than other fast-growing species but was not expected to generate positive returns until >15 years of growth (Ghezehei et al. 2015).

Improved genetics of tree planting stock has in particular been anticipated to raise yield and production efficiencies in loblolly plantations, with ongoing studies examining the effect of tree genetics on yield and its interaction with other site management factors (Albaugh et al. 2020). One modeling study, treating genetics as a simple change in site index, showed potential for financial gains with elite genetics when deployed for sawtimber (McKeand et al. 2006). However, we are unaware of any studies to date that have specifically attempted to examine the interaction of seedling genetics with other site factors in the economics of short-rotation biomass plantations. It also remains unclear the extent to which widely used numerical models of loblolly growth under varying conditions (e.g. Amateis et al. 2000, Landsberg et al. 2001) can accurately capture the additional effect of genotype in interaction with other silvicultural and environmental effects.

Leveraging the results of long-term field studies (Vickers et al. 2012, Albaugh et al. 2016), the current study compares economic returns for different genotypes of loblolly pine under varying site conditions and cultivation practices to assess the viability of a hypothetical 10-year bioenergy rotation. Our objectives were to (1) use recent biomass yield measurements and records of site establishment and management practices to reconstruct costs and estimate revenues for these study plots over a 10-year (2009–2019) rotation window, (2) contrast the effects of genetics, planting density, and silvicultural practice to identify which combinations offer the most financially attractive returns in a short-rotation dedicated biomass harvest, and (3) evaluate the sensitivity of these results to fluctuations in input prices and the value of the resulting biomass. Our work highlights some of the conditions under which short-rotation loblolly pine plantation for biomass production might be profitable in the southeastern US.

Methods

Biomass Yield Experiment

In March 2009, two loblolly pine growth trials were established, one at the Reynolds Homestead in the Piedmont region of Virginia on a well-drained site and one at the Bladen Lakes State Forest in the lower Coastal Plain region of North Carolina on a poorly drained site. (Details on sites and experimental treatments were reported in Albaugh et al. [2016, 2018, 2020] and Vickers et al. [2012], as well as in the Supplemental Materials.) At each site, randomized replicated split-split-plot trials were established testing combinations of six genotypes, three planting densities, and two levels of silviculture (Figure S1 and Supplemental Materials). Each block was split between an “operational” silviculture (OS) treatment zone with banded vegetation control at establishment and a “high” silviculture (HS) treatment zone with repeated broadcast herbicide, nitrogen, phosphorus, potassium, and boron fertilizer, and fipronil injection treatments for control of pine tip moth intended to allow for maximum growth potential (treatment details in Supplemental Materials and Table S1). The OS and HS plots were further split into subplots planted in one of six genotypes encompassing four clonal varietals (Var 1–4) with differing crown form (Aguiar 2018, see Supplemental Materials), a mass-control-pollinated family (MCP), and an open-pollinated (OP) family. Each genotype was identical between sites, and no genotype was chosen for any special adaptation to or performance differential at either site. Within the subplots, three planting densities were randomly assigned at 618, 1,236, and 1,853 trees per hectare (TPH, equivalent to 250, 500, and 750 trees US $acre^{-1}$). There were three blocks at Bladen Lakes (108 total subplots), and four blocks at Reynolds Homestead (144 total subplots). Subplots were planted in nine rows approximately 32.8 m wide by 38 m, 25.3 m, and 12.7 m long depending on planting density, containing 81 trees each at planting.

In January 2019, after 10 years of growth, stem diameter and tree height were measured on the central 25 trees in each plot. Allometric equations were used to estimate dry weight of branch, foliage, and outside-bark stem biomass for each tree (Gonzalez-Benecke et al. 2014), accounting for tree size and adjusting for age, stand density, and basal area. Dry mass was converted to fresh mass using a factor of 0.425 dry g per g fresh for stem biomass based on harvest sampling at the site, and assuming 0.5 g g^{-1} for branch and foliar biomass. Living whole-tree and stem-only biomass per tree, excluding mortalities, was summed for each plot and scaled by area ($Mg\ ha^{-1}$).

Cost and Biomass Value Estimation

To quantify the net financial returns to the forest landowner (\$ ha^{-1}), we calculated NPV from the basis year of site establishment (2009) by estimating input, management, and land carrying costs and the final (2019) stumpage value according to records of management activities and biomass yield by plot, as well as publicly and privately available estimates of cost components (Table 1; see Table S2 for equivalent US customary units). A default discount rate of 5% was chosen following previous discounted cash flow analyses of pine timber returns (Biblis et al. 1998, Huang et al. 2005, Guo et al. 2010, Mills and Stiff 2013, Kantavichai et al. 2014, Perdue et al. 2017, Callaghan et al. 2019, Tanger et al. 2020). The 10-year rotation length was chosen because periodic field sampling

Table 1. Price estimates used to calculate NPV in the experimental treatments, 2020 dollar equivalents. Costs based on post-2009 estimates were deflated to their equivalent at the time of their occurrence using the PPI of Lumber and Wood Products: Logs, Bolts, Timber, Pulpwood and Woodchips (WPU0851). Sensitivity ranges were ±25% unless noted.

Parameter	Estimate	Range evaluated	Reference
Site establishment			
Pre-planting herbicide, \$ ha^{-1}	232	174–290	FDP 2019/20
Bedding plow (Bladen Lakes), \$ ha^{-1}	293	219–366	FDP 2019/20
Site burning (Reynolds Homestead), \$ ha^{-1}	110	83–137	FDP 2019/20
Seedlings, \$ per 1,000			
Varietals (containerized)	352	264–440	See Methods
Mass control pollinated (MCP) (bareroot)	151	113–189	ArborGen 2008/09
Open pollinated (OP) (bareroot)	67	50–84	ArborGen 2008/09
Hand planting	202	NA	Site records
Post-planting silviculture			
Banded weed control, \$ ha^{-1}(OS only)	183	137–229	FDP 2019/20
Soil injected tip moth control, \$ tree^{-1} (HS only)	0.30	0.23–0.38	See Methods
Broadcast competition control, \$ ha^{-1} (HS only)	232	174–290	FDP 2019/20
Establishment fertilizer, \$ ha^{-1} (HS only, year 1)	256	192–320	FDP 2019/20
Subsequent fertilizer, \$ ha^{-1} (HS only, year 5)	219	165–274	FDP 2019/20
Annual maintenance, \$ ha^{-1} yr^{-1}	4.94	NA	Guo et al. (2010); Parajuli et al. (2019)
Harvest, land carry costs, and time value assumptions			
Stumpage, pulp wood, \$ Mg^{-1}(2019)	12.72	2.18–21.76	TimberMart South 2019
Forest Land rent, \$ ha^{-1} yr^{-1}	81	61–101	Cubbage et al. (2007); Guo et al. (2010); Kantavichai et al. (2014)
Land taxes (NC and VA), \$ ha^{-1} yr^{-1}	4.94	3.71–6.18	Guo et al. (2010); Parajuli et al. (2019)
Discount rate	0.05	0.01–0.25	Guo et al. (2010); Parajuli et al. (2019)

on the sites only provides data for biomass accumulation up to that point in the development of the stands. The reported costs of inputs and activities were adjusted to the equivalent dollar values for the year of their occurrence using the annually averaged producer price index (PPI) for the commodity Lumber and Wood Products: Logs, Bolts, Timber, Pulpwood and Woodchips (WPU0851) (Tanger et al. 2020).

In the summer of 2008, the Bladen Lakes site was cleared of slash with a V-blade and bedded with a Savannah plow, while the Reynolds Homestead site was cleared of slash via burning. These costs were represented by the midrange reported for 2019–2020 prevailing rates reported for District 8 by the North Carolina Forest Service's Forest Development Program (FDP) (FDP 2019). Costs for seedlings planted in 2009 were estimated using the 2008/2009 ArborGen seed catalog for the cost-per-thousand of MCP and "Select" OP bareroot seedlings. Costs for containerized varietals were estimated based on 2008/2009 MCP cost and the ratio of MCP:Varietal costs quoted in the 2018/2019 ArborGen seed catalogue. We assumed a \$0.16 tree^{-1} hand planting cost in 2009 based on payment records at the sites, reflecting the generally large fraction of cost for labor in planting seedlings (Callaghan et al. 2019). Costs for banded chemical competition control in the OS treatments and broadcast chemical control and fertilization in the HS treatments were modeled according to costs reported for the FDP District 8 prevailing rates (FDP 2019, see Supplemental Material). Costs for the tip moth control agent and labor for application were estimated based on prevailing prices (Supplemental Material).

Forest land rent was included as an annual cost, estimated via a review of the literature on land expectation value (LEV) for loblolly pine plantations in the southeastern US managed under traditional longer rotation length. Using the discount rate reported in each study, values for LEV were annualized to equivalent annual income, which was used as a proxy for land rent (Bullard and Straka 2011). Rent costs determined for the region ranged from −\$45 (net loss under forestry) to \$236 ha^{-1} yr^{-1} in 2020 equivalents (Biblis et al. 1998, Gan et al. 1998, Huang et al. 2005, Cubbage et al. 2007, 2020, Guo et al. 2010, Mills and Stiff 2013), although short-rotation plantations under ordinary price conditions tended to fall in the lower end of the range (Kantavichai et al. 2014, Perdue et al. 2017). In this study, we set the default land rent cost to \$81 ha^{-1} yr^{-1}, within the recently reported range for intensively managed loblolly pine plantations in the region (Cubbage et al. 2007, Guo et al. 2010, Kantavichai et al. 2014). By contrast, 2020 cash rent values for nonirrigated cropland reported to USDA National Agricultural Statistics Service (NASS) in the region of the two studies were somewhat higher, at \$198 ha^{-1} yr^{-1} near Bladen Lakes and \$106 ha^{-1} yr^{-1} near Reynolds Homestead (USDA NASS 2021). The rates used in this study are lower than prevailing agricultural land rental rates in the area, as used in other studies (Stanton et al. 2021), and below the possible market land lease rate (Munn et al. 2018), but are arguably more appropriate representatives of the value of likely alternate productive land use in the study regions. Annual property taxes were estimated at \$4.94 ha^{-1} yr^{-1}, similar to previous studies in the region and representative of taxes on productive forest land following a review of current tax rules in the counties comprising the study site regions in North Carolina and Virginia (Guo et al. 2010, Commonwealth of Virginia 2018, NC Dept of Revenue 2019, Parajuli et al. 2019, NC Use-Value Advisory Board

2020, Virginia Dept of Forestry 2020). Annual miscellaneous management fees were set to \$4.94 ha^{-1} yr^{-1} following previous timber economics studies in the region (Guo et al. 2010, Parajuli et al. 2019).

Stumpage value for a 2019 hypothetical harvest was estimated as the mean of the quarterly 2019 pulpwood stumpage prices (converted to \$ Mg^{-1}) reported by TimberMart South for both North Carolina and Virginia, following other studies (Ghezehei et al. 2015, Perdue et al. 2017). Stumpage value at harvest on each plot was calculated both with 2019 fresh whole-tree biomass (stem, branches, and foliage), treating all biomass as salable for the energy market, as well as fresh stem-only biomass similar to the pulpwood market. The analysis focuses on whole-tree returns, as many investigations have identified either the current practice of or favorable potential for the use of timber residues (including bark, limbs, and treetops), mill wastes and offcuts, precommercial thinnings, and otherwise unmarketable roundwood as viable biomass for pellet feedstock (Westbrook et al. 2007, Picchio et al. 2012, Lloyd et al. 2014, Arranz et al. 2015, Lu et al. 2015, Mandalika et al. 2019, Masum et al. 2020). A major pelletization plant exporting to the European bioenergy market and sourcing feedstock from near the Bladen Lakes site also reports the majority of its feedstock is drawn from similar otherwise unmarketable roundwood and harvest residue (Sustainable Biomass Program Limited 2020). The value of wood and paper products over the past 20 years has been relatively stable (Callaghan et al. 2019), and pulpwood stumpage price was taken as a best estimate of the value of biomass to the prospective landowner given that biomass and pulpwood processors often compete for the same kinds of materials (Kanieski da Silva et al. 2019), while recognizing the value of biomass can vary significantly between the price paid to the landowner and the costs for raw materials paid by the biomass processor (Gonzalez et al. 2011, Visser et al. 2020). Stumpage value for 2019 was not deflated prior to discounting to more closely approximate the relative present-day value of the current standing biomass on the site.

Analysis and Sensitivity Assessment

The NPV of producing both whole-tree and stem-only biomass was determined for each plot for the basis year of 2009 by summing costs and projected cashflow discounted from the time of their occurrence using a discount rate of 5% (Formula 1, Supplemental Materials).

The total cost of annual expenses (land rent, property taxes, and miscellaneous maintenance) were each determined using the formula for the present value of a terminating annual series (Bullard and Straka 2011, see Formula 2, Supplemental Materials). We also calculated a nominal internal rate of return (IRR) for each plot by iteratively solving for the discount rate that would approximately balance discounted costs and revenues (Fox et al. 2007a). This IRR metric presents the landowner's value analogously to the interest rate received on an investment maturing at the time of harvest.

The response variable of NPV was modeled separately for each site within a linear mixed model framework (Tanger et al. 2020), with fixed factors for genotype, planting density, and silviculture as well as their two-way interactive effects and a random effect for block. The significance of the fixed effects was evaluated using Wald's test (Christensen 1996). The significance of interactions was tested via the likelihood ratio test (Lewis et al. 2011). We used Welch's independent samples *t*-test to compare the mean NPV in HS and OS for identical genotype and planting density treatments to evaluate the cost and yield tradeoffs of the additional HS inputs (Fox et al. 2007a).

Sensitivity of NPV estimates to model assumptions was assessed by independently varying the discount rate, stumpage value, and input costs across a range of values varying by ±25% from the default estimates (Table 1). Prices were varied together for related packages of inputs, including seedlings (varietals, MCP, and OP per 1000), fertilizer (establishment and midrotation applications), chemical control (banded herbicide, broadcast herbicide, and fipronil treatment), site preparation (bedding plow, preplanting herbicide, burning), and land carrying costs (land rent and property taxes). Stumpage value was varied by approximately ±80% of the input value in sensitivity assessment to locate break-even limits for all treatments. Labor cost for hand planting and fipronil injection and miscellaneous annual management costs were not varied in sensitivity assessment.

Calculations and statistical analysis were performed in R version 3.6.3 (R Core Team 2020), with the *data.table* (Dowle and Srinivasan 2019) and *glmmTMB* (Brooks et al. 2017) packages. Pairwise means comparison using the Tukey's correction was done at a 0.05 significance threshold with PROC GLIMMIX (SAS Institute, Cary, NC). Because coefficient estimates in mixed models may not be normally distributed, we estimated confidence intervals for the coefficients via 1,200 bootstrapped model fits using the bias-corrected and accelerated central 95% limits, determined using the *boot* package (DiCiccio and Efron 1996, Davison and Hinkley 1997, Canty and Ripley 2020). Final cost and revenue figures after discounting were reported in 2020 US dollar equivalents adjusted via the PPI for the Lumber and Wood Products: Logs, Bolts, Timber, Pulpwood and Woodchips (WPU0851) (Tanger et al. 2020).

Results

Costs of Inputs, Activities, and Land Carry

The discounted costs for initial site preparation through planting were \$690–\$1,551 ha^{-1} at the Coastal Plains site and \$507–\$1,368 ha^{-1} at the Piedmont site (\$2,020 equivalent), differing between sites due to bedding at the poorly drained Coastal Plain site (Figure 1). Seedling costs were the dominant site establishment costs with greater planting density, and the additional cost of varietals was as much as \$529 ha^{-1} higher than OP at the 1,853 trees per hectare (TPH) density. Total discounted costs, including postplanting costs and land carrying costs, were \$1,574–\$3,542 ha^{-1} at Bladen Lakes and \$1,391–\$3,359 ha^{-1} at Reynolds Homestead.

The present values of land carrying costs for the 10-year rotation were approximately \$624 ha^{-1} and \$38 ha^{-1} for rent and taxes, respectively, making land carry consistently among the largest costs at both Bladen Lakes (21%–42% of present value of total costs) and Reynolds Homestead (20%–46%). Seedling costs (including planting labor) ranged from 7% (OP) to 46% (varietals) of total costs. Site preparation ranged from 10%–33% of total costs and was lower at Reynolds Homestead where land was cleared via burning. Chemical pest and competition control ranged from 8% to 28% of total costs, claiming a larger share in the HS treat-

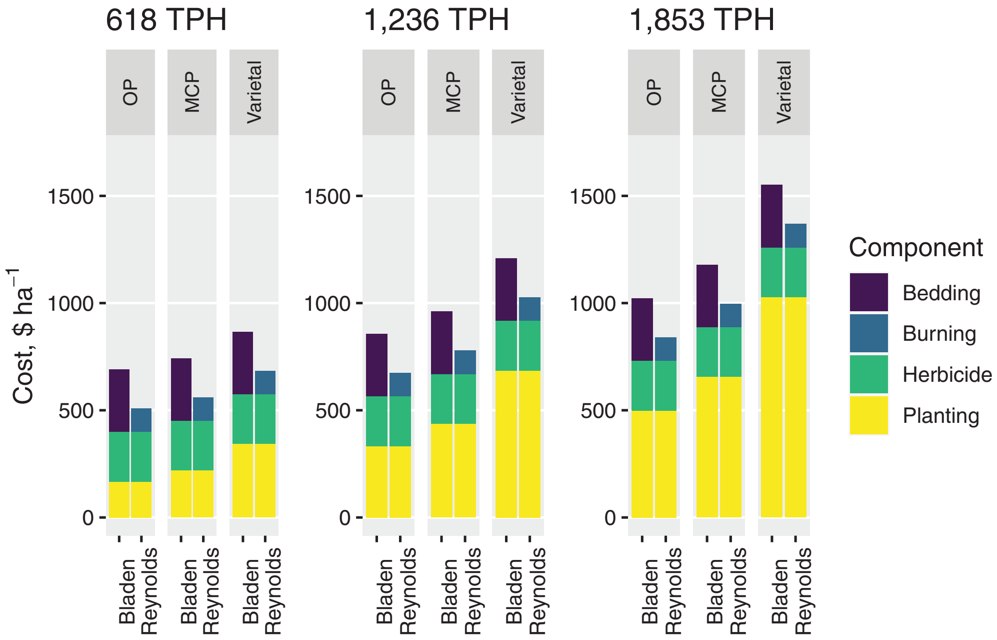

Figure 1. Cost of site establishment by component at Bladen Lakes, NC, and Reynolds Homestead, VA, experimental sites, by planting density (TPH), 2020 dollar equivalents. Values do not include any costs for postplanting herbicide, fertilizer, or insecticide treatments, which differed between OS and HS treatments.

ments. Fertilizer inputs amounted to 22%–23% of total input costs in the HS treatments only.

The additional cost of inputs between equivalent OS and HS treatments was \$734–\$1,107 ha^{-1}, with fertilizer being the largest single additional input cost under HS practices. The cost of incrementally raising planting density within the same genotype was generally comparable to or less than opting for costlier genotypes at the same density (Table S3).

Effects of Genotype, Density and Silviculture on NPV of Planting Loblolly Pine for Biomass

Biomass yield under OS was generally higher at Reynolds Homestead than Bladen Lakes, whereas site preparation costs were somewhat lower, resulting in generally higher NPV in all treatments (Figure 2). The differences in NPV between the sites could be in part a product of lower mean survival at 10 years across the OS treatments at Bladen Lakes (80%–99%) compared with OS treatments at Reynolds Homestead (90%–100%) (Table S4). Within the OS treatments, higher biomass yield was associated with greater NPV. However, treatment combinations with marginally lower yield often showed higher NPV than combinations with higher yield due to lower inputs costs.

At Reynolds Homestead, maximum mean NPV assuming current pulpwood stumpage occurred under OS with OP/1853 TPH (\$791 ha^{-1}), followed by Var 1/1,853 TPH (\$626 ha^{-1}), OP/1236 TPH (\$622 ha^{-1}), and Var 2/1853 TPH (\$602 ha^{-1}). Within the OS treatments, mean NPV in OP/1,853 TPH was significantly higher than the lowest 10 of the 18 treatments ($P < 0.05$) but was similar to the top eight treatments (Table S5). Mean NPV showed complex variation along the axes of density, genotype, silviculture, and site, with different genotypes performing relatively well or poorly dependent on density and silviculture class (Figure S2). In a model of the effect of all treatment factors and their two-way interactions, mean NPV at Reynolds Homestead tended to be lower in the HS treatment and higher at 1,853 TPH density compared to the OP/1236 TPH/OS treatment, an operationally common combination in commercial plantation forestry (Table 2). A significant silviculture × genotype interaction indicated that Var 4 had a lower NPV penalty under HS treatment, possibly because of a larger differential in mean biomass yield between OS and HS treatments with Var 4. However, the potential interaction with density × genotype implied that the expected relative NPV gain at 1,853 TPH was not as strong with Var 4, probably due to its unusually poor biomass yield at 1,853 TPH relative to other densities (not shown). The three-way interaction term was not significant ($P = 0.23$).

At Bladen Lakes, comparable to Reynolds Homestead, the maximum mean NPV was found under OS with the OP genotype at 1,236 TPH (\$487 ha^{-1}), followed by OP/1,853 TPH (\$290 ha^{-1}) and MCP/1,236 TPH (–\$12 ha^{-1}). Within the OS treatments, mean NPV in OP/1,236 TPH was statistically similar to these other top treatments, but was significantly higher than the lowest 14 of 18 treatment combinations ($P < 0.05$) (Table S5). At Bladen Lakes, NPV tended to be lower in the HS treatment, at 618 TPH, and among all genotypes other than OP. A significant silviculture × genotype interaction indicated that OP had higher NPV under OS but was more similar to other genotypes under HS, possibly due to its similar underlying cost but lower biomass yield under HS. A significant density × genotype interaction showed that whereas the OP genotype tended to have higher NPV at the 1,236 and 1,853 TPH densities, this relative enhancement was absent at 618 TPH due to relatively poor biomass yield in OP/618 TPH, although the effect might have remained at work with Var 4/618 TPH. As at Reynolds Homestead, the silviculture × density effect was not significant, and the three-

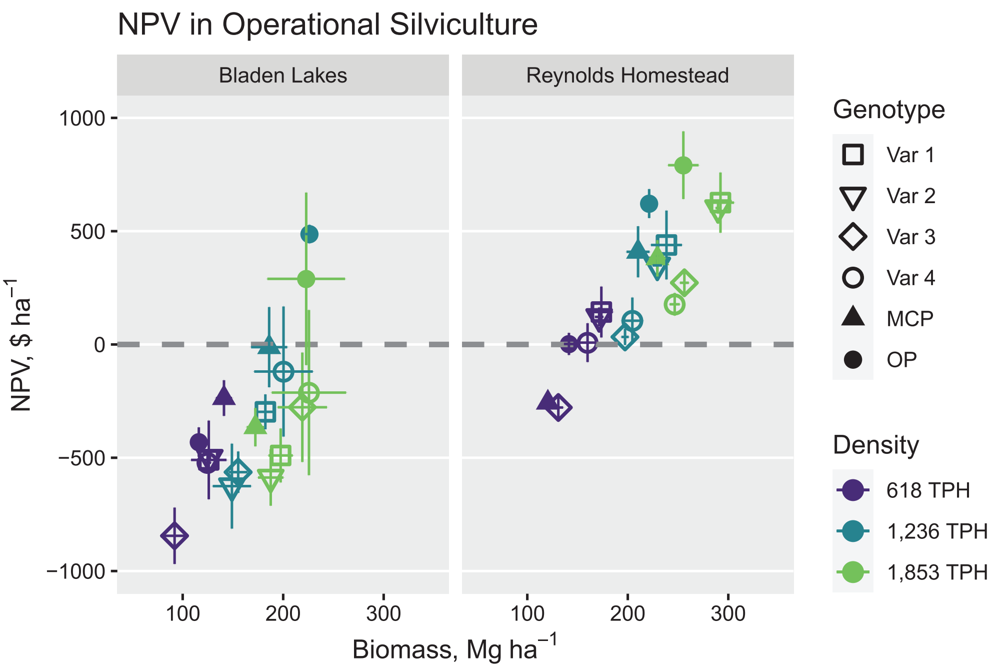

Figure 2. Mean biomass yield (Mg ha^{-1}) versus mean NPV of biomass ($ ha^{-1}, 2020 dollar equivalents) under OS at Bladen Lakes, NC (left), and Reynolds Homestead, VA (right), at 2019 stumpage price of $12.72 Mg^{-1}. Point centers correspond to mean plot biomass and mean estimated NPV with standard errors shown by bars.

way interaction term was also not significant (P = 0.56). Yield under OS at Bladen Lakes appeared to be more variable, and survival seemed particularly negatively affected in the more intensive HS treatments at this site (Table S4), an unexpected outcome further discussed below. These differences likely contributed to the generally lower NPV and yield at Bladen Lakes, as well as the greater NPV penalty in HS.

Analysis of stem-only returns showed similar influences of genetic, density, and silvicultural factors, but with reduced overall NPV in all treatments (Table S6). Maximum stem-only NPV was found in the same groups of treatments as whole-tree NPV. No HS treatments at either site showed positive mean NPV for stem-only harvest. The only positive mean stem-only NPV with OS at Bladen Lakes was in OP/1,236 TPH ($19 ha^{-1}), whereas at Reynolds Homestead, the top mean NPVs were in OP/1,853 TPH ($299 ha^{-1}), OP/1,236 TPH ($174 ha^{-1}), and Var 1/1,853 TPH ($87 ha^{-1}).

Economics of High Silviculture Inputs and Internal Rates of Return

Additional site inputs in HS treatments generally resulted in increased whole-tree biomass yield and subsequent revenue, but also raised costs by a comparable or greater degree (Figure S3), resulting in similar or reduced financial returns. The difference in mean NPV for whole-tree biomass between otherwise identical HS and OS treatments at Bladen Lakes was –$1,253 ha^{-1} to –$2 ha^{-1} (loss with HS), and at Reynolds Homestead was –$1,058 ha^{-1} to –$121 ha^{-1}. Significant mean NPV reduction with HS (t-test P < 0.05) was found at Reynolds Homestead in several of the varietal genotypes and, at Bladen Lakes, in some of the MCP and OP treatments (Table S7). NPV was significantly reduced with HS at both sites in the OP/1,236 TPH density treatments, which had among the highest financial returns overall in OS at either site. Significant gains in whole-tree biomass yield with HS were only found with varietal genotypes, but none of these genotypes saw an increase in mean NPV, and Var 4/1,853 TPH and Var 2/1,236 TPH at Reynolds Homestead showed a significant increase in biomass yield paired with a significant decrease in mean NPV. The mean discounted value of revenue associated with additional biomass yield in HS treatment was worth –$286 ha^{-1} (loss) to $1,103 ha^{-1} at Bladen Lakes, and –$154 ha^{-1} (loss) to $800 ha^{-1} at Reynolds Homestead. Compared to the $921–$1,107 ha^{-1} additional costs associated with greater inputs with HS silviculture, investment in these inputs seldom resulted in a gain in NPV. The break-even yield for HS treatments at $12.72 Mg^{-1} pulpwood stumpage was 74.6–112.4 Mg ha^{-1} higher than the break-even yield in OS treatments. In comparison, mean yield changes between otherwise equivalent HS and OS treatments were typically somewhat less, from –29.1 Mg ha^{-1} (loss) to 112.0 Mg ha^{-1} at Bladen Lakes and –15.7 Mg ha^{-1} (loss) to 81.2 Mg ha^{-1} at Reynolds Homestead.

Mean nominal IRR for whole-tree biomass in OS treatments ranged lower at Bladen Lakes, from –4.12% to 8.25%, relative to 2.23%–9.92% at Reynolds Homestead, assuming current pulpwood stumpage (Table S7). Mean IRR averaged across planting density at Bladen Lakes in OS treatments was 5.07%, 3.37%, and 1.31% for OP, MCP, and varietal genotypes, respectively, and at Reynolds Homestead, 8.15%, 5.82%, and 6.11%, respectively. Mean IRR averaged across genotype did not differ as much between planting densities, with mean IRR in OS treatments at Bladen Lakes in 618, 1,236 and 1,853 TPH densities of 0.04%, 3.55%, and 3.25%, respectively, and in OS treatments at Reynolds Homestead, 4.44%, 7.17%, and 7.60%, respectively. Consistent with the results for mean NPV, mean IRR in the OS treatments at Bladen Lakes was highest in the OP/1,236 TPH, OP/1,853 TPH, and MCP/1,236 TPH treatments at 8.25%, 6.40%, and 4.80%, respectively. At Reynolds Homestead, the mean IRR

Table 2. Estimates of fixed effects for of silviculture, genotype, and density on NPV. Coefficients marked * were significantly different from zero based on 95% bootstrapped confidence interval. *P* values correspond to results of Wald's test for each term (three-way interactions were not significant). Model base estimate (intercept) is operational silviculture, OP genotype, 1,236 TPH density, and model coefficients estimate NPV under other combinations of treatment factors.

Model terms	Coefficients	
	Bladen Lakes	Reynolds Homestead
(Intercept)	476*	454*
Genotype	$P < 0.001$	$P = 0.007$
Var 1	−837*	80
Var 2	−1051*	3
Var 3	−981*	−402
Var 4	−636*	−311
MCP	−483*	−134
Silviculture	$P < 0.001$	$P < 0.001$
High silviculture (HS)	−1185*	−721*
Density	$P < 0.001$	$P < 0.001$
618 TPH	**−810***	-362
1853 TPH	-272	417*
Silviculture × Genotype	$P < 0.001$	$P < 0.001$
HS × Var 1	827*	209
HS × Var 2	988*	−99
HS × Var 3	839*	212
HS × Var 4	596*	524*
HS × MCP	584*	94
Density × Genotype	$P = 0.030$	$P = 0.060$
618 TPH × Var 1	600*	−64
618 TPH × Var 2	812*	−42
618 TPH × Var 3	522*	15
618 TPH × Var 4	519	214
618 TPH × MCP	494*	−166
1853 TPH × Var 1	268	−383
1853 TPH × Var 2	281	−308
1853 TPH × Var 3	390	−196
1853 TPH × Var 4	187	−407*
1853 TPH × MCP	−4	−314
Silviculture × Density	$P = 0.135$	$P = 0.305$
618 TPH × HS	240*	72
1853 TPH × HS	103	−80

for the top NPV treatments under OS was found in OP/1,853 TPH, Var 1/1,853 TPH, OP/1,236 TPH, and Var 2/1,853 TPH at 9.92%, 8.03%, 9.54%, and 7.96%, respectively. Equivalent IRRs for stem-only harvest in the top-performing treatments were 5.13%, 3.32%, and 1.78% for OP/1,236 TPH, OP/1,853 TPH, and MCP/1,236 TPH, respectively, under OS at Bladen Lakes, and 7.03%, 5.43%, and 6.43% for OP/1,853 TPH, Var 1/1,853 TPH, and OP/1,236 TPH under OS at Reynolds Homestead.

Sensitivity Assessment

Fourteen treatment combinations were sensitive enough to any input cost within ±25% of the default estimate to potentially change the sign on mean whole-tree NPV (Table S8). Most were at Reynolds Homestead ,where many treatments were nearer to mean NPV of zero and included treatments with both marginally positive and negative mean NPV under the default assumptions. None of the sensitive treatments were in the top ranks of mean NPV for whole-tree biomass in either site. All the identified treatments were sensitive to land-carrying costs, but some were also sensitive to seedling, site preparation, fertilizer, and herbicide costs. In terms of stem-only NPV, eight treatments were sensitive enough to the test parameters to change the mean NPV sign, including the only positive mean NPV treatment at Bladen Lakes and two of the four treatments at Reynolds Homestead with positive mean stem-only NPV (Table S8). Like the results for whole-tree biomass NPV, all the identified treatments were sensitive to land-carrying costs, but some were also sensitive to other input costs. Only OP/1,236 TPH/OS and OP/1,853 TPH/OS at Reynolds Homestead maintained a positive predicted mean NPV for stem-only harvest within the tested range of uncertainty in the costs of inputs and land carry, though other treatments could also show small positive stem-only NPV under marginally more favorable cost and stumpage conditions.

At Bladen Lakes, relative reductions in the cost of MCP or varietal seedlings would not have allowed these treatments to match the mean NPV of the maximum OP/1,236 TPH/OS treatment, likely in part because the OP treatment had the highest OS biomass yield. At Reynolds Homestead, relatively large seedling cost reductions in the Var 1 and Var 2 genotypes at 1,853 TPH could have made these treatments competitive with the maximum NPV OP/1853 TPH in OS, likely because these varietal treatments had considerably higher mean whole-tree biomass. These higher-performing varietal treatments would have been competitive with reductions of seedling cost from $352 per 1,000 to, respectively, $132 and $100 per 1,000, (approximately 37% and 28% of their estimated costs) compared to $67 per 1,000 for OP. Similarly, for stem-only NPV, no reduction in seedling costs at Bladen Lakes would allow the other treatments to equal the mean stem-only NPV of OP/1,236 TPH/OS, and at Reynolds Homestead, even greater reductions in varietals cost would be needed to reach parity (to approximately 20% and 10% of their estimated costs for Var 1/1,853 TPH and Var 2/1,853 TPH, respectively).

Examining NPV across a range of stumpage values (holding other cost assumptions constant), the rankings of IRR among the different treatment combinations did not vary substantially at any given stumpage value (Table S9). Compared to one of the better-performing varietals (Var 1) and the MCP genotype at 1,236 TPH density, OP maintained the highest returns across the tested range of whole-tree stumpage values at both sites (Figure 3). The best-performing treatment combination at Bladen Lakes (OP/1,236 TPH/OS) maintained positive mean NPV at a 5% discount with whole-tree stumpage price above $9.93 Mg^{-1} and had potential for positive cashflow (above a discount rate of 0%) down to $6.20 Mg^{-1}. At Reynolds Homestead, break-even price floors were somewhat lower, where the best-performing treatment combination (OP/1,853 TPH/OS) had positive NPV above a stumpage price of $8.72 Mg^{-1}, and potential positive cashflow down to $5.48 Mg^{-1}. Price floors for stem-only returns were higher than for whole-tree returns. At Bladen Lakes, positive NPV at 5% discount in the best-performing treatment required stem-only stumpage above $12.59 Mg^{-1}, with a positive cashflow limit of \$7.84 Mg⁻¹. For Reynolds Homestead, the limits were again lower than at Bladen Lakes, at \$10.84 Mg^{-1} for positive NPV and \$6.81 Mg^{-1} for positive cashflow.

In terms of minimum salable biomass yield, the break-even limits in the best-performing treatments at the 2019 mean stumpage price of \$12.72 Mg^{-1} for positive NPV at 5% discount were 176.6 Mg ha^{-1} and 175.1 Mg ha^{-1} for Bladen Lakes and Reynolds Homestead, approximately 78% and 69%, respectively, of the whole-tree biomass yields actually measured (Table S4). Minimum limits for positive cashflow were 121.5 Mg ha^{-1} and 121.2 Mg ha^{-1} at Bladen Lakes and Reynolds Homestead, approximately 53% and 47%, respectively, of the mean whole-tree yields actually measured. These yield floors were higher as a fraction of total stem biomass yield observed, at 99% and 85% of the measured stem-only yields for positive NPV, and positive cashflow limits were 68% and 59% of the measured stem-only yields at Bladen Lakes and Reynolds Homestead, respectively.

Discussion

Our results suggest that, with inexpensive genetics and moderate-to-high planting density, management for short-rotation biomass could be economically feasible at current pulpwood stumpage of \$12.72 Mg^{-1}, even across sites that contrasted in biophysical characteristics and establishment requirements. Positive NPV at a 5% discount rate was expected even down to 10-year whole-tree yields 20%–30% lower than the yields measured over the initial 10 years of this field study, or at stumpage values 22%–31% below the recent rate for pulpwood. These results also held when including estimated land-carrying costs, which have been argued to present ambiguity in interpreting the true financial incentives faced by forest landowners (Cubbage et al. 2020). However, although the estimated costs used in this study are taken from recent practical cases in the southeastern US, these findings also assumed access to a market for small diameter biomass and that whole-tree biomass could be sold near recent pulpwood stumpage prices. This material may prove costlier to harvest and deliver and is occasionally assumed to receive a lower premium for fuel feedstock versus pulpwood (Guo et al. 2010, Munsell and Fox, 2010, Ghezehei et al, 2015, Jonker et al. 2018). Our findings also suggest that overall financial risk might be greater at sites requiring more costly establishment practices; for example, sites that have competing vegetation that is difficult to control or that require bedding, in addition to other site factors that would tend to limit survival or productivity.

Comparable with previous studies, our analysis predicts break-even stumpages for dedicated biomass production of roughly \$9–\$10 Mg^{-1}, and aligns with previous work predicting lower break-even biomass stumpages for well-drained upland sites versus poorly drained lowland sites, in part due to the anticipated lower costs of site preparation (Kantavichai et al. 2014, Gallagher et al. 2017). Mean nominal IRR in the highest-returning treatments were comparable to or greater than IRR estimated for studies examining biomass as a single end-product on a 12-year rotation, as a coproduct of a longer rotation sawtimber system, or generated over a 15-year rotation in marginal sites (Ghezehei et al. 2015, Gallagher et al. 2017, Perdue et al. 2017). Previous analyses have predicted higher whole-tree break-even stumpage for dedicated biomass plantations in the Alabama Piedmont (\$14–\$16 Mg^{-1}) and Coastal Plain (\$11–\$12 Mg^{-1}) but also

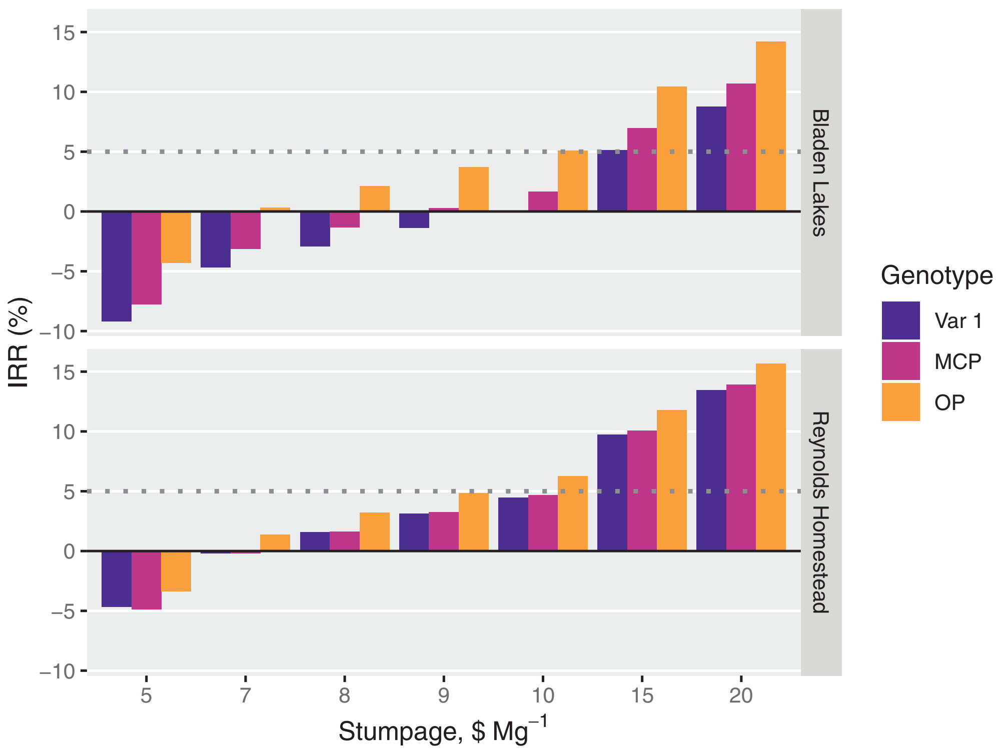

Figure 3. Mean nominal IRR for selected genotypes under operational silviculture at 1,236 TPH density versus whole-biomass stumpage price at Bladen Lakes, NC, (top) and Reynolds Homestead, VA (bottom). Line at 5% IRR indicates treatments would have positive NPV assuming 5% discount rate.

assumed lower productivities than those observed in this study (Kantavichai et al. 2014). Another study suggested $10 Mg^{-1} stumpage for short-rotation biomass should be sufficient for competitive financial returns across most of the native range of *Pinus taeda*, although it also predicted minimal returns in the region of Virginia and North Carolina (Perdue et al. 2017). Other studies have suggested stand management geared toward producing and harvesting more thinnings and harvest residuals could be attractive even at stumpage of $5–$9 Mg^{-1} when included as part of longer-rotation timber plantations of *P. taeda*, but would not support managing for biomass as a standalone product (Guo et al. 2010, Munsell and Fox 2010, Gallagher et al. 2017).

Besides land-carrying costs, which may be a large fraction of the cost of biomass production, as suggested in other studies (Stanton et al. 2021), the cost of seedlings and planting was a major component of site establishment, especially at moderate-to-high planting densities (1,236–1,853 trees ha^{-1}) and with more expensive genotypes. Although previous studies have shown variously higher growth along several biomass metrics in varietal genotypes (McKeand et al. 2006, Albaugh et al. 2018), this study also accounted for cost differentials between genotypes, demonstrating that investment in less expensive genotypes at higher planting densities generally resulted in greater returns. This outcome was primarily due to the finding that whole-tree biomass in the highest-yielding treatments was overall comparable between genotypes at this stage of stand development, although a large cost increase was incurred for varietal genotypes. In only a few instances at Reynolds Homestead did varietal genotypes under OS produce a sufficient biomass increase versus OP genotypes to potentially reach comparable NPV, had the cost differential with varietal seedlings been lower. The variable yield differences seen in the varietal genotypes between the two sites, noted previously and possibly related to lower survival at Bladen Lakes, are likely in part responsible for their differences in the sensitivity of NPV to seedling costs. More expensive varietal genotypes are generally selected for longer-rotation sawtimber regimes, despite greater upfront costs, not only to raise the rate of stem volume growth but also enhance features of stem form that raise their value for dimensional lumber or veneer (Cumbie et al. 2012). The ability of elite genotypes to reach merchantable size classes more quickly could provide a clear incentive for deploying these lineages, particularly under higher discounting or with a higher premium for sawtimber. The varietal genotypes used in this study were not developed specifically for short-rotation biomass production, although tree improvement programs have pursued this goal in other timber species (Gonçalves et al. 2013, Acquah et al. 2018). These varietals were also not specifically selected for their performance in the conditions of either site, although lineages of loblolly pine can also be selected for specific site conditions or management practices (Stovall et al. 2011, Rubilar et al. 2018). The empirical focus in this study avoided the need for applying loblolly growth and yield models (Amateis et al. 2000, Landsberg et al. 2001) that might not adequately capture early growth dynamics in the relatively recently emerged varietals. However, the nature of sampling in these experimental sites did not allow for an exploration of optimal rotation lengths for production of biomass (or other classes of merchantable timber) in any genotype tested, or an investigation into whether the less costly OP genotypes might maintain the top NPV ranking under other relatively short rotation lengths. If varietals had been chosen that were optimized for these sites or for a different rotation length, it remains an open possibility whether those genotypes could provide competitive financial returns. However, the current cost differential of these varietals implies that robust early growth increases would be necessary to compensate for the higher upfront planting cost.

More intensive silviculture raised the biomass production potential for many of the treatments at these sites, but at a hypothetical 10-year rotation length, did not raise financial returns, despite promising evidence of large yield enhancements in the context of plantation forestry (Mead 2005, Fox et al. 2007b). In only one case (Var 1/1,236 TPH, Table S7) did the HS treatments show positive whole-tree NPV at 5% discount. The divergence of financial returns between OS and HS treatments was in part because OS was less costly while evidently already meeting most of the resource needs of the stand. A notable complication is that, at Bladen Lakes, HS practices may also have been associated with additional tree mortality (Table S5). However, reduction in NPV with HS treatment was also seen at Reynolds Homestead, where mortality did not obviously differ under OS. Some ambiguity also remains over whether the poorer returns with more intensive silviculture would be seen elsewhere, as the optimal rates of inputs such as fertilizer and herbicide are likely to depend on site-specific requirements (Quicke et al. 1999, Everett and Palm-Leis 2009, Rubilar et al. 2018), which was not within the scope for the cost model in this study. With harvest of slash and foliage, some additional soil fertility support may also be necessary over multiple rotations to maintain yield in some sites and soil types (Scott and Dean 2006, Janowiak and Webster 2010). The finding of reduced financial returns with HS is in line with other studies showing that investments in fertilization only enhance returns for higher-value timber products, and where there is sufficient time for a larger growth response to appear (Fox et al. 2007a). On the other hand, if intensive silviculture accelerates biomass increment sufficiently to shorten the rotation length, this approach might improve financial returns, especially when harvesting multiple rotations in the span of a single sawtimber crop (Munsell and Fox 2010). More detailed projections over longer time windows and differing product classes should be attempted once additional long-term growth and yield observations are available for these experimental treatments.

This study estimated the net present value to the forest landowner based on pulpwood stumpage because small-diameter timber is the resource most likely to be tapped with rising biomass demand, as timber harvest and sawmill residues alone will not likely keep pace with the demand from bioenergy markets (Alavalapati et al. 2013). However, as previously noted, whole-tree biomass and pulpwood are not equivalent commodities and could also face differing hauling or processing costs, such that assuming a pulpwood stumpage price may tend to overstate the value of a short-rotation woody crop grown to produce bulk biomass (Guo et al. 2010, Gonzalez et al. 2011, Ghezehei et al. 2015). In addition, allocation of early stand growth to stemwood versus branch, foliage, and other biomass fractions is variable, and their relative value in the bioenergy market is ambiguous (e.g., Guo et al. 2010, Kantavichai et al. 2014, Ghezehei et al. 2015, Jonker et al. 2018). Similarly, distance to processing mills is a key consideration for landowners when managing plantations for biomass production (Smith et al. 2019). Given the many variables that could influence the standing value of whole-tree biomass, at present, the likely stumpage value in short-rotation pine for bioenergy remains unclear.

Conclusions

The results of this study show positive financial returns might be possible for dedicated loblolly pine bioenergy plantations in the region of the study sites. These results account for land-carrying costs, empirical differences in growth rate dependent on planting density, silviculture, and genotype, and the costs of seedling stock and other inputs related to these factors. At both sites, the least expensive genotype (OP) combined with a planting density of 1,233 trees ha^{-1} or 1,853 trees ha^{-1} and with OS treatment resulted in maximum financial returns for a 10-year rotation woody biomass crop. If whole-tree biomass could fetch current average pulpwood prices of $12.72 Mg^{-1}, the estimated nominal IRR for these treatments could compare favorably with other broad investment classes at up to approximately 8.3% at Bladen Lakes and 9.9% at Reynolds Homestead. With the benefit of comparatively short rotations, these plantations might also offer the additional advantage of reducing the loss risk due to, for instance, bark beetle, wildfire, or hurricane damage (Stanturf et al. 2007). The estimated NPVs in the OS treatments were reasonably stable within the range of values tested for the input assumptions, implying that the results should be robust to variability in costs between regions and to minor variations in site management. Future measurements of growth and yield in these ongoing trials will support a more thorough examination of the interactions among silviculture, planting density, and tree genetics as key factors in forest plantation management and investment analysis, including the financial tradeoffs between short- and long-rotation harvests. Similar field experimental studies promise to provide better management-ready insights for prospective timber growers interested in enlisting their forests in producing climate-safer energy.

Supplementary Material

Supplementary material is available at *Forest Science* online.

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Conflict of Interest

The authors declare they do not have any conflicts of interest in the conduct or reporting of this research.

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