The Value of Forest Biotechnology: A Cost Modeling Study with Loblolly Pine and Kraft Linerboard in the Southeastern USA

Gary F. Peter[1,2,*], David E. White[2,3], Rafael de La Torre[4], Rajan Singh[3], David Newman[2,4]

1. School of Forest Resources and Conservation, University of Florida, Gainesville, Florida, 32611-0410, USA
2. Center for Paper Business and Industry Studies, Georgia Institute of Technology, Atlanta, Georgia, 30318, USA
3. Institute of Paper Science and Technology, Georgia Institute of Technology, Atlanta, Georgia, 30318, USA
4. Daniel B. Warnell School of Forest Resources, University of Georgia, Athens, Georgia, 30602-2151, USA

* Corresponding Author

*Gary F. Peter
School of Forest Resources and Conservation
PO Box 110410
University of Florida
Gainesville, FL 32611-0410 USA
gfpeter@ufl.edu
T: 1-352-846-0896
F: 1-325-846-1277

David E. White
Institute of Paper Science and Technology
Georgia Institute of Technology
Atlanta, GA, 30332-0620, USA
David.white@ipst.gatech.edu

Rafael de La Torre
Daniel B. Warnell School of Forest Resources
University of Georgia
Athens, Georgia, 30602-2151, USA
Red1675@owl.forestry.uga.edu

Rajan Singh
Institute of Paper Science and Technology
Georgia Institute of Technology
Atlanta, GA, 30332-0620, USA
Rajan.singh@ipst.gatech.edu

David Newman
Daniel B. Warnell School of Forest Resources
University of Georgia
Athens, Georgia, 30602-2151, USA
newman@forestry.uga.edu

ABSTRACT

Commercialization of biological technologies for forest tree species promise to dramatically lower raw material costs, maximize processing efficiencies, minimize environmental impacts, and improve product performances. The economic value of such biotechnological changes to wood and fiber quality traits in forest trees has not been well quantified due the complexity of producing wood and paper products. As a case study we used multidimensional cash flow modeling of a loblolly pine plantation and an integrated kraft pulp and paper mill to quantify the potential value of trees with improved growth, wood and fiber properties for linerboard production in the southeastern U. S. A. The results show that genetically improved trees with faster growth and better wood properties can dramatically increase mill profitability. All of the traits modeled increased linerboard mill profitability, with the greatest increase estimated for higher fiber tensile strength followed by increased specific gravity, growth and increased cellulose to lignin ratio. If trees with a 20% increase in specific gravity captured 20% of the loblolly pine seedling market in the U. S. A., then the overall value of this wood quality improvement just for linerboard production alone was estimated at $300 million per year. These results strongly support the forest industry goal of using biotechnology to improve tree growth and wood quality.

Keywords: biotechnology, genetic engineering, forest tree, wood quality, economics, cost modeling, breeding

Biographical notes: Gary Peter is an Associate Professor of Forest Genomics in the School of Forest Resources and Conservation and the Genetics Institute at the University of Florida, USA. David White is a Principal Research Engineer and Rajan Singh is an MS student at the Institute of Paper Science and Technology at Georgia Tech. Rafael de la Torre is a PhD student in Forest Business and David Newman is a Professor of Forest Economics in the Warnell School of Forest Resources at the University of Georgia. G. Peter, D. White and D. Newman are also on the research faculty of Center for Paper Business and Industry Studies at Georgia Tech a Sloan Foundation Industry Center.

INTRODUCTION

Forests provide a complex set of ecological, economic and social benefits. The social benefits lie in the communities that live off the forest and in their intrinsic aesthetic value. The economic value lies in the usefulness of the wood for fuel, construction, and communication. It is this economic value that in part has contributed to the worldwide loss and degradation of natural forests. The ecological benefits of forests for biodiversity, erosion control and soil improvement have long been recognized, but benefits like carbon sequestration and improved air and water quality have only recently been recognized. These later ecological benefits increase or decrease in proportion to the amount of forest land. Deforestation continues today mostly in developing countries that have increased needs for fuel and food. In contrast, developed countries are recognizing the ecological benefits of forests and are responding by conserving forests (1-3). Growth in the world's population and its rising wealth are putting greater demands on forests for increased economic, social and ecological benefits than ever before, challenging forest policy to both conserve natural forests and to produce more wood for fuel and industrial forest products.

One potential solution to meet these competing demands on forests is to segment forest lands such that specific forest types maximize social, ecological and economic benefits. For example, the pressure to supply industrial wood from natural forests of high conversation value could be reduced by increases in the productivity of select forest tree species grown on intensively managed plantations (1-3). With this approach the productivity of select forest tree species is increased through simultaneous genetic improvement and optimization of farming or silvicultural practices. Over the last few decades this approach has begun to be implemented for a few select forest tree species such as radiata pine, southern pines and select Eucalyptus species. Tree plantations are seen as an economically viable alternative to harvesting wood from natural forests. Wood coming from trees grown on plantations now accounts for approximately 15% of the industrial supply and is increasing rapidly (2-4).

Commercial interest in forest tree biotechnology comes from the potential to dramatically improve the productivity of plantation grown trees by increasing growth rates and disease resistance as well as by enhancing the efficiency of converting trees into solidwood, pulp and paper products and biomass derived energy and new biobased products (4). The commercial success of genetically engineered crop plants that increase yield and require less chemical and energy inputs provides a roadmap to forest products and forest tree biotechnology firm's application of biotechnological methods to improve select tree species. Like crop biotechnology, forest biotechnology is composed of a suite of technologies. For forest trees these technologies include methods used for clonal or mass vegetative propagation of superior individual tree genotypes, molecular breeding and genetic engineering. These advanced technologies complement traditional breeding programs and share the same primary goal: to create faster growing trees that better resist insects and other pathogens and have wood properties that improve conversion into valuable products (5).

Vegetative propagation of commercially important hardwood, softwood species as well as hybrids has been successfully used to select for and deploy genetically improved trees on plantations in Australia, Brazil, Chile, New Zealand, and Portugal. Commercially important hardwood and softwood tree species have also been genetically engineered (GE) by public and private sector scientists. For example, because reduced lignin content in wood can be expected to have economic and environmental benefits for chemical pulp production, researchers have genetically engineered hardwood species to contain as much as 40% less lignin (6). Hardwood trees have also been engineered to contain increased amounts of syringyl relative to guaiacyl lignin (7,8). Because syringyl lignin is removed twice as fast as the guaiacyl lignin during kraft pulping (9) and pulps obtained from young trees enriched in syringyl over guaiacyl lignin show dramatically higher brightness after bleaching (10). Field trials for some of these trees are now in place to assess the growth, wood properties, processing improvements and environmental benefits in trees of commercial size.

A number of technical, social and economic barriers still limit the commercial use of biological technologies with forest tree species. Vegetative propagation systems in some commercially important species still need further development to reduce the cost and increase the quality of clonally propagated seedlings. Unlike most crop plants, tree species are undomesticated, long lived out crossing perennials. These differences together with the fact that many native species are used for plantation forestry support the need to better understand the environmental risks associated with planting of GE trees, in particular whether these GE trees will show increased invasiveness, and the extent to which inserted transgenes will spread to wild populations and if they do whether they will have substantial negative impacts on existing forest ecosystems or on non-target organisms (11-13). The public acceptance of plantations of GE trees and the wood and fiber products made from them is unknown (13). Land owners, wood merchandisers and processing facilities need to be convinced of the increased value of genetically improved trees that grow faster and have improved wood properties. A significant driver for public and private sector investments to develop and commercialize these biotechnologies comes from the predicted raw material cost savings when trees grow faster and have wood properties that increase processing efficiencies and decrease environmental impacts. However, little information is available that quantifies the environmental and cost savings that could come from planting genetically improved trees with increased growth rates and altered wood properties to a pulp and paper mill.

Only a few economic analyses have been published that quantify the potential cost savings for chemical pulp production which could come from increased volume growth and specific gravity, a key wood quality trait. Greaves and Borralho describe a theoretical cost model of a Greenfield wood yard and pulp mill developed to estimate the cost of producing unbleached kraft hardwood pulp (14). The model includes capital and operating costs as a function of specific gravity and pulp yield for each stage of the pulp mill including chemical recovery and bioenergy generation (14). Results from this model show that when wood specific gravity is increased by 50% (0.4 to 0.6) the cost of unbleached kraft Eucalyptus pulp decreases by 18-22% depending on the cost structure of the pulp mill. Greaves extended this initial analysis by inclusion of a forest cost component to determine the economic importance of standing volume at harvest, basic density, pulp yield, and stem form on the total cost of pulp production (15). They concluded that standing volume and specific gravity account for 95% of the possible gain from these four traits and hence are the key traits for the reducing the cost of Eucalyptus bleached pulp (15). For pines an analysis from the 1970s investigated changes in rotation age and specific gravity of loblolly pine using a linear programming model developed to optimize net profit of a mill that met specific paper quality standards (16). The analysis compared 14 different cases for linerboard production and showed that selecting trees with increased volume growth and specific gravity improved mill profitability; however the amount of profit increase was not determined (16). More recently Lowe et al. following the method of Borralho (17) estimated changes in profitability associated with increases in loblolly pine growth rates and specific gravity for unbleached kraft pulp production (18). They concluded that deploying seedlings from parents selected for higher specific gravity increased pulp mill profits by about ten fold over parents selected solely for fast growth (18). This analysis assumed that ubleached kraft pulp was the final product and estimates for the impact of genetic improvements on the profitability of linerboard were not determined.

As a case study for the value of forest biotechnology, we quantified the potential cost savings and increases in profitability to an integrated mill producing linerboard for corrugated boxes that might come from using genetically improved loblolly pine trees. Our objectives were to: 1) compare the impact of altering specific softwood/fiber traits on mill profitability, 2) evaluate the biological feasibility of increasing wood growth, improving wood and fiber properties, and 3) identify the potentially most beneficial targets for forest biotechnology research.

Description of Cost Models and Modeling Assumptions

The impact of changes in tree growth, wood and fiber properties on linerboard production costs and mill profit were estimated with multidimensional cash flow models, consisting of a loblolly pine forest plantation model and a theoretical Greenfield, vintage 1995, integrated Kraft pulp and linerboard mill model (Figure 1). Both models contain capital and operating costs for all unit operations in the forest and the mill. Estimates of cost changes from altered tree traits are in real prices and errors due to fluctuations in spot prices for all forest and mill inputs and for the sale price of linerboard were minimized with the use of trend prices obtained from regressions with prices from the last 10-20 years. Wood, slush pulp, and linerboard costs as well as mill profits were projected for year 2018, where the real price of linerboard is expected to drop from the 2002 price of US$424 to US$402.

The forest cost model was built using MS-Excel and contains capital and operating costs for land, seedlings, intensive management regimens, harvesting, and transportation. From data, models, and discussions with researchers in the Plantation Management Research Cooperative (PMRC) at the University of Georgia and with project cooperators, a base case model was formulated. Through this process, silvicultural management regimes were defined for the main physiographic region of the lower coastal plain of the Southeastern U.S., using loblolly pine, with the primary objective of producing fiber for kraft linerboard (i.e. a mill perspective).

Forest regeneration costs were based on formulated prescriptions for an intensive management regime. These costs included activities such as site preparation, herbicide application, seedlings, fertilization, annual management costs, and price or cost/acre. The financial assumptions used to calculate the optimal rotation age were devised using TimberMart South data and personal communication with experts and financial analysts. These assumptions served as input for the Auburn Harvesting Analyzer (AHA) (19), which we used to determine the potential hourly productivity, influenced by tree size, for each machine. The details of the harvesting system also served as input into the AHA. Hauling productivity was calculated as a function of both distance to the mill and payload. Distance is a function of the amount of land needed to supply 1.5 million tons of green wood per year to a hypothetical mill located in the middle of the forest. A hypothetical operational distance was adjusted by a meander factor of 1.5. Once the productive base land was calculated, the gross land base was derived using a factor of 1.3, which represents a non-productive land component (protective areas, power line corridors, secondary road systems, and other non-forest land uses).

Once the data were compiled, an integrated spreadsheet model that could work in harmony with the mill cost model was developed to estimate the cost of growing trees. This cost model was used to determine changes in costs and responses to a variety of silvicultural practices, harvesting techniques, and transportation. The model's objective was to predict baseline production costs using the data and assumptions described below to analyze trends and impacts on production costs by varying a single element or a few inputs. For consistency, the regime developed for the unthinned model (mill perspective) was applied to develop a thinning model (landowner perspective) (Tables 1 and 2). When land cost was included in the forest models a purchase price of $300/acre was used.

The kraft pulp and linerboard mill model was also built in MS-Excel. It contains capital and operating cost estimates for the woodyard; pulp mill; recycling plant; washing and screening; stock preparation; paper machine wet end, driers, dry end; evaporators; steam and power; recovery boiler; lime kiln and recausticizer, water and effluent treatment, and labor. These individual worksheets are integrated into a financial summary with individual costs for fiber, chemicals, energy, labor, maintenance materials, operating supplies, solid waste landfill, general mill overhead, shipping and depreciation estimated. The approximate one billion dollars in capital needed to build this Greenfield mill was based on the estimated cost in 1995 of the equipment and installation. The capital was obtained with a 40:60 split of debt to equity, with the debt carrying a 9% interest expense for 10 years. A tax rate of 34% and a 15% discount rate were used.

To interpret the modeling results key assumptions and constraints made in developing the forest and mill models need to be defined. Table 1 describes the forest and Table 2 describes the kraft pulp and linerboard mill model assumptions and variables. For the base case, fiber costs account for ~40% of the total cost of linerboard manufacture. The second highest costs come from shipping and energy at 13.5% and 12.5%, respectively. All modeling was conducted with the following basic assumptions: 1) the mill owns all of the forestland needed for sustainable production of softwood logs (regulated forest), which come in as roundwood to the mill, reflected in the lack of transfer pricing for softwood logs; 2) hardwood (roundwood and chips) and recycled paper are purchased on the open market; and 3) mill linerboard production was held constant in terms of tonnage. Thus, all changes in mill costs and profit were taken in reduced wood costs.

An alternative modeling approach would have been to allow linerboard production at the mill to rise with increases in pulp yield or decreases in basis weight. This alternative approach in principal should lead to higher estimates of mill profitability for the wood and fiber traits than fixed production because the capital costs are spread out over more production. We decided to hold production constant not increased production because the mill model was designed to balance pulp and paper production and increasing production would require additional capital to an already new mill. A number of traits were expected to increased kraft pulp yields but the capacity of the paper machine wouldn't permit making much more linerboard without substantially more investment. Although the linerboard grade pulps could be sold on the open market, this is not currently a substantial market, and there is overcapacity in the global linerboard sector which may also affect the ability to sell the additional linerboard at our estimated price. Thus, the values that we estimated under the fixed production constraint are expected to be more conservative estimates for the value of forest biotechnology.

Overview of Modeling Approaches

The value of increased tree growth, estimated by increasing site index in the forest model, comes from reductions in the cost of the softwood logs delivered to the mill (Figure 1). The forest model estimates that one third of the total delivered wood cost comes from silvicultural inputs related to tree growth and the other two thirds of the cost come from harvesting and transportation of the logs to the mill. Harvesting represents the single greatest cost of delivered roundwood logs. Increased tree growth rates have only a minor impact on harvesting and transportation costs. The primary cost savings of planting genetically improved trees with faster growth comes from increased wood mass obtained for the same silvicultural cost.

The values for wood and fiber traits were modeled based on changes in pulp yield and linerboard basis weight (Figure 1). Specific gravity is a measure of the mass per unit volume of wood. Higher specific gravity wood yields more pulp than the same mass of wood with a lower specific gravity, due to less degradation of the carbohydrates in the wood (20). Differences in pulp yield due to changes in specific gravity were estimated with empirical equations obtained for loblolly pine (21). Consequently at a fixed level of linerboard production, increases in pulp yield decrease the amount of softwood required from the plantation and also reduce the production cost of softwood pulp.

Increases in the cellulose to lignin ratio affect both pulp yield and bioenergy recovery. These changes in pulp yield and recovered bioenergy were estimated from mass and energy balances respectively. The mill model contains a module that calculates the amount of energy recovered when black liquor solids amount and composition change (22). As the cellulose to lignin ratio increases the pulp yield rises thereby decreasing the amount of wood needed to produce the same amount of pulp. The decrease in lignin increases the cost of purchased energy, because the mill creates less of its own energy and must purchase more electricity. The value of cellulose microfibril angle was estimated by reductions in linerboard basis weight. Reductions in linerboard basis weight (mass per unit area) lower the amount of pulp fiber that is required to produce a given area of linerboard. In these decreased basis weight cases the mill still produced the same number of tons of linerboard but the increased profit to the mill was estimated by the standard up charges assigned to reduced basis weight high performance linerboard.

RESULTS & DISCUSSION

Base Case

When the growth rate and wood quality traits were altered, the impact on profitability was estimated relative to a base case. The base case scenario for the loblolly pine plantation establishment and management is summarized in Table 1. Table 3 contains a summary of the mill operating parameters, wood and pulp compositions, and outputs used in the base case operations for the softwood and hardwood pulps used to produce the top and bottom plies. The softwood and hardwood pulp yields were estimated based on Hatton's equations, using coefficients for Jack pine and aspen respectively (23). Table 4 summarizes the major outputs from the forest and mill models for the base case of growth rate, and wood and fiber properties using the thinned and unthinned models.

Table 4 also shows an additional set of scenarios that included the opportunity cost of the land in the computation of the cost of growing timber (Thin-LC and Unthin-LC). For each forest model the maximal bare land value (BLV) was calculated and used to indicate the optimal year of harvest. For all four forest scenarios the BLV was maximized at 18 years (Table 4). In the thinning models, age 10 was the earliest age at which all stems met the minimum pulpwood diameter and other constraints were a minimal removal volume of 20 tons/acre, 65 ft^2/acre as minimum residual basal area, and 6.5 in. as minimum quadratic mean diameter, stands were thinned to 50% of the trees per acre. The minimum age for harvesting solid wood products was 18 years, and initial planting densities less than 400 TPA were not considered saw timber due to more conic stems, broader crowns, and larger branches. The average specific gravity of the wood coming to the mill is estimated from forest tree biometric data and for the thinned cases is a weighted average of the specific gravities of the 10 and 18-year-old trees. Tree growth rate is indicated as mean annual increment (MAI) and the area of land required for a sustainable, continuous supply of 100% of the softwood needs for the mill is calculated. The MAI predicted in the forest model show that these growth rates are currently globally competitive (24). The land area includes set asides of 30% of the total area for roads, riparian zones and other buffers.

On the typical pine plantation in the southeastern U. S. A., trees are grown for multiple product classes, pulpwood, chip-n-saw and saw timber. Typically trees are planted at a high initial density and the stand is thinned once when competition for light, water and nutrients among trees substantially slows their growth. The trees remaining after thinning continue to grow; maximizing the proportion of stems that are large enough in diameter to become saw timber, the most valuable product class. In this work no attempt was made to estimate the increased profit to the stand that would result from selling a portion of the trees as higher value chip-n-saw and saw timber logs. Rather the work here looks at the forest from the perspective of the pulp and paper mill.

Table 4 shows that the typical thinning scenarios reduce pulp and paper mill profitability by ~20%. This decrease in profitability would be even greater if the mill paid additional transfer prices to the timberlands based on market prices. The large reduction in mill profit in the thinned scenarios is due to elevated roundwood costs incurred by greater forest production costs, greater land holdings and by increases in haul distance. Importantly, Brazilian companies that grow Eucalyptus trees specifically for hardwood pulp production have dramatically lower costs than other firms in the world. This cost advantage comes in large part from their use of genetically improved trees grown on high quality sites and short unthinned rotations. This analysis highlights a significant difference in the way U. S. southern softwood plantations are typically managed relative to hardwood plantations in Brazil.

Effect of Tree Growth Rate on Mill Profit

Growth rate is the most fundamentally important trait for land owners because they are paid principally on the tons of green (wet) wood harvested in each of the three different stem diameter classes (pulpwood, chip-n-saw, saw timber). Consequently tree genetic improvement programs have selected primarily for increases in growth rate, and silvicultural inputs are justified based on their ability to dramatically boost volume growth. To evaluate the potential of genetically improved trees, which grow faster with a fixed silvicultural input, on mill profitability, the delivered wood costs were estimated for differences in growth rate of -20% to +30%. Decreased growth was considered as potential tradeoffs between growth and wood quality are possible and increases of more than 30% were not considered as the growth and yield equations in the models were not considered valid above this. Decreased growth rate below the base case has a negative impact on mill profit as expected (Figure 2). Genetically improved trees that increase the site index by 30% (65 to 84.5) increase timber growth by ~ 25% and did not change the optimal 18 year rotation age. This increase in growth decreased delivered wood costs which increased mill profits by 5-10%, depending on the forest model scenario.

Effect of Specific Gravity on Mill Profit

Changes in wood specific gravity were modeled by changes in softwood pulp yield. Pulp yield increases for higher specific gravity wood based on experimental results with loblolly pine (21). Since the total yearly production of pulp was held constant, higher wood specific gravities decrease annual wood consumption, lower pulp mill costs and increase mill profit. Figure 3 shows the percentage profit change when specific gravity was varied from 0.30 to 0.80. Clearly, decreasing specific gravity below the base case of 0.47 is quite detrimental to the mill. Such decreases in specific gravity can occur on fast growing pine plantations where the wood is enriched in earlywood, a lower specific gravity type of wood, normally made in young trees and in older trees during the spring and early summer. Increased specific gravity arising from more latewood in older trees has substantial benefits, but specific gravities above 0.6 may have detrimental impacts on linerboard properties.

Effect of Wood Cellulose to Lignin Ratio on Mill Profit

The impact of processing wood with increased proportions of cellulose and reduced lignin contents on mill profit was modeled by increases in softwood pulp yield. Because no empirical data relates pulp yield with altered cellulose to lignin ratios, increases in softwood pulp yields were estimated with a mass balance approach by assuming a fixed chemical composition of the base and top ply pulps (Table 3). The mass balance approach assumed that the hemicellulose content of the wood was constant and that declines in wood lignin content were accompanied by increases in wood cellulose content. Figure 4 shows the effect on mill profit of increased cellulose and decreased lignin content in the softwood component of linerboard, at a fixed base case growth rate, specific gravity, and hardwood yield. The percentage profit change is presented as reductions in the wood lignin content from 29% to 15%. While there is a <1% increase in profit at a lignin content of 25% for all four scenarios, the two thinning scenarios show a 7% profit increase at a lignin content of 15%, half of the natural lignin content. Such dramatic reductions in wood lignin content lead to even greater increases in pulp yield than the elevated wood specific gravity cases (e.g., a lignin content of 20% uses 28,000 tons less wood/year than a specific gravity of 0.6). However, the value of these elevated pulp yields when lignin content is reduced are mitigated by the loss of biopower generation that comes from burning lignin and the consequent need to purchase more power from the open market.

Effect of Reduced Linerboard Basis Weight on Mill Profits

Reduced linerboard basis weights (weight per 1000 ft^2) were analyzed because less damage to the fibers during pulping or decreases in cellulose microfibril angle should increase the tensile strength of pulp fibers which translates into increases in sheet tensile and compressive strengths. In this analysis up charges on linerboard sale prices commonly given to high performance linerboard grades produced by wet pressing (lower basis weight grades that perform as higher basis weight grades) were used with our base case wood prices and mill parameters. Figure 5 shows that reducing linerboard basis weight can dramatically affect the mill's profitability. As expected when total annual production is fixed, decreases in basis weight increase mill profitability for both the unthinned and unthinned scenarios but with greater effect for thinned forest scenarios as expected.

Comparison of the Value of Different Forest Tree Trait Changes

If we compare changes in the four different traits, growth, specific gravity, cellulose to lignin ratio and fiber tensile strength, then the greatest increase on mill profits are reduced basis weight followed by increased specific gravity, increased growth rate, and decreased lignin content (Figure 6). A 10% reduction in linerboard basis weight, from 42 lb. to 38 lb., shows an excellent potential profit increase of forty to fifty percent.

Survey of Southern Pine Tree Breeders to Assess what Technologies are Needed to Create Trees with Specific Growth and Wood Quality Traits

To assess which biological technologies, breeding, clonal selection or genetic engineering, will be needed to create within 20 years loblolly pine trees for widespread planting that have specific growth rates and wood qualities we surveyed southern pine tree breeders. Of the thirty active southern pine breeders from forest products companies and university tree breeding cooperatives identified, 45% returned the survey. The breeders were asked to decide on a Likert scale of whether they strongly disagree, disagree, don't know, agree or strongly agree with our base case and whether fourteen different examples of trees with specific growth rates and wood qualities could be developed through breeding, clonal selection or genetic engineering. It is known that some tradeoffs exist between fast growth and superior wood properties. The hypothetical trees for planting were categorized into ones with increased growth at constant wood properties, improved wood properties at constant growth, and increased growth and improved wood properties. The breeders were also asked to estimate what gains can be expected in the next twenty years in the various traits through breeding, clonal selection and genetic engineering.

The results of the survey are summarized in Figure 7. Ninety percent of the respondents agreed or strongly agreed that the base case growth and wood properties used in this study are achievable today. Slightly less than half of agreed that growth could be increased by 30% at constant wood properties with breeding but 80% believed that with clonal selection such trees could be obtained. The breeders think that developing a tree that grows as fast as the base case, but with ~20% higher specific gravity seems more likely through clonal selection and genetic engineering than by breeding. Decreasing MFA and increasing cellulose relative to lignin contents with constant growth seems mostly likely through genetic engineering, but equal numbers of breeders don't know if it can even be achieved with this technology.

Seedling Costs Reflect the Potential Return for Investments in Forest Biotechnology

In all of the above scenarios, seedling cost was fixed at the current market price of \$0.05. Table 5 shows what the maximum price for a genetically improved seedling could be, given the estimated decrease in linerboard cost. This maximum price was determined by increasing the seedling cost in the forest model to the point where the linerboard cost equaled that for the base case and all of the cost savings in the mill due to the wood improvement went into the seedling cost. Thus, these elevated seedling costs represent the total value predicted for such changes in growth or a wood property for linerboard production.

This higher seedling cost can be used to justify the magnitude of investment in forest tree biotechnology research and development. There are about a billion loblolly pine seedlings planted annually in the SE US. If 20% of this seedling market were genetically improved for the traits analyzed here, then the total potential value of the market based just on cost savings for linerboard would be $100-300 million annually depending on the trait. It should be noted that this is a minimal estimate of the market size because it does not include any additional value that would come from reduced production costs of other paper grades or of solidwood products. If these additional cost savings were included, the market size would be expected to be substantially greater.

Impact of Changes in Growth and Wood Quality Traits on Land Area Needed for Sustainable Production

Increases in growth rate, increases in pulp yield, and making the same area of linerboard with less fiber all increase the amount of linerboard that can be made from a hectare of land. Figure 8 shows that reducing lignin to 20% reduces the land area need for a sustainable wood supply to the mill by 15%; whereas increasing specific gravity of the wood to 0.6 reduces the land needs by 12%. Increasing growth produces more volume per land area in a given rotation and makes the largest percentage difference in the unthinned case. Interestingly the increasing growth in the thinned scenario has a lower percentage impact as a than the wood quality traits, because more trees go into nonpulpwood chip-n-saw and sawtimber.

CONCLUSIONS

Forest biotechnological improvements of loblolly pine growth and wood properties have the potential to substantially increase the profitability of linerboard mills in the southeast U. S. A. The decision to manage forest plantations with thinning for multiple products, rather than not thinning and using all of the wood for pulp production has a substantial negative impact on mill profit. Percentage increases in incremental mill operating profit from improved growth and wood properties were generally greater for thinned than the unthinned forests due to the higher wood costs for thinned forests. The greatest profit potential came from reductions in linerboard basis weight, which can be achieved by decreases in cellulose MFA. Increases in wood specific gravity followed by increases in the growth rate also provided strong potential profit increases. An increase in wood cellulose and a concomitant reduction in wood lignin content provided the lowest but still positive benefit to an integrated kraft linerboard mill. In contrast, increases in cellulose to lignin ratio due reduced the land area needed for sustainable production the most because of the large predicted increases in pulp yield. Surveys of pine tree breeders' show that while tradeoffs between growth and wood properties are expected; breeding, clonal selection and mass vegetative propagation are likely to lead to find trees with normal growth and increased specific gravity, but genetic engineering will probably be needed for substantial changes in cellulose to lignin ratio and reductions in MFA if this is possible.

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FIGURE LEGENDS

Figure 1 Overview of approach to cost modeling of traits, increased tree growth decreases delivered wood prices, increased specific gravity and increased cellulose to lignin ratio increased pulp yields and reduce wood consumption, and decreased microfibril angle permits basis weight reductions so that less pulp is used to make the same amount of paper.

Figure 2 Percentage change in mill profit relative to the base case with changes in tree growth rate. The growth rate was varied from -20 % to + 30% for each of the four forest cost scenarios.

Figure 3 Percentage change in mill profit relative to the base case (0.47) with changes in tree specific gravity. The average specific gravity of the wood was varied from 0.3 to 0.8 for each of the four forest cost scenarios.

Figure 4 Percentage change in mill profit relative to the base case with changes in tree cellulose to lignin ration. The average lignin content of the wood was reduced from the base case of 29% to 15% for each of the four forest cost scenarios.

Figure 5 Percentage change in mill profit relative to the base case (42 lb.) with changes in linerboard basis weight. The basis weight was varied from 42 lb. to 32 lb. for each of the four forest cost scenarios. The percent change in profitability for the with land costs and without land costs scenarios were same, because up charges for the decreased basis weights were used.

Figure 6 Comparison of increased growth and the improved wood quality traits at the base case growth on mill profit. The changes in the traits depicted were chosen to because they are plausibly attainable biological changes that may not adversely affect tree growth or linerboard production. Basis weight 10% = 38 lb., -50% lignin = wood lignin of 15%, +30% specific gravity = 0.6

Figure 7 Responses from survey of pine tree breeders for the need for whether they agreed to disagreed with whether different breeding (B), clonal selection (CS), or genetic engineering (GE), can be used to attain trees with increased specific gravity, growth, cellulose content and decreased microfibril angle.

Figure 8 The impact trait changes on land needed for sustainable supply of softwood to the mill for the thinned and unthinned scenarios.

Table 1

Forest Cost Model Description, Assumptions, Prescriptions and Input Variables

Plantation comprises solely Loblolly Pine	The cost of a seedling is fixed at \$0.05 Initial planting density is 605 trees per acre
Land is located in the lower coastal plain of the southeastern USA	Base site index is 65 (max height in ft. at 25 yrs)
Intensive management improves SI from 65 to 78 for the unthinned scenario and 80 for the thinned scenario Silvicultural components of the model are constructed in MS-Excel with input variables of site index, trees per acre, cost per seedling, regeneration costs, stumpage prices, discount rate, and land cost.	*Site Prep:* Shear, rake, pile, bed and hardwood pretreatment *Herbicide Treatments*: at planting and year 2 for unthinned scenario and brush control at age 11 for thinned scenario *Fertilizer Treatments*: Years 1, 6, and 10 for unthinned scenario and Years 1, 6, and 12 for thinned scenario
The land value is fixed and all land is owned by the mill for the sole purpose of supplying wood to the mill.	For all rotations the opportunity cost associated with the land is assessed at a real discount rate of 8%.
Growth and yield equations for lower coastal plain	Equations were obtained from the Plantation Management Research Cooperative at the University of Georgia
Tree diameter classes are estimated with the Weibull distribution function (PDF)	
Harvesting outputs (efficiencies) are estimated with the Auburn Harvest Analyzer	The harvesting components have multiple input variables
Transportation is estimated as a function of the distance and a derived hauling rate of \$2/mile/load	The transportation components have multiple input variables
The forest cost model optimizes the bare land value (BLV) of the plantation	***Input Variables For Cost Modeling*****:** per acre land cost, specific gravity, trees per acre, growth (site index), and seedling cost

Table 2

Pulp and Paper Mill Model Description, Assumptions and Input Variables

Hypothetical, vintage-1995, Greenfield Kraft linerboard mill located in Southeast U.S.	The single paper machine produces about 590,000 MT/y (metric tons per year; 6.5% moisture) of 42 lb linerboard. *Top ply* is 50% softwood and 50% hardwood *Bottom ply* is 58% softwood, 10% hardwood and 32% recycled
Pulp mill produces 483,000 air dried metric tons ADMT/y unbleached Kraft pulp per year.	337,000 ADMT/yr of softwood Kraft pulp (70% of virgin fiber needs) at 70 Kappa for top ply and 105 Kappa for bottom ply.
Mill also produces 127,000 ADMT/yr of recycled paper pulp	Produces 146,000 ADMT /yr of hardwood kraft pulp (30% of virgin fiber needs) at 60 Kappa
Capital is depreciated over 20 years for all equipment	Black liquor solids and heating values are estimated separately for each pulp
Model is constructed in MS-Excel as an integrated set of worksheets with a base and proposed case format.	***Input Variables For Cost Modeling*:** All significant input prices and machine variables can be changed manually to determine the effect on production costs and mill profitability

Table 3 Base Case Wood Properties and Pulping Conditions

Scenario	SW Wood Lignin Comp. (%)	SW Wood Density (BD kg/green m^3)	SW BS Pulp Kappa	SW Wood Comp.: Cellulose/ Hemi/ Lignin/ Extr (%)	SW BS Pulp Comp.: Cellulose/ Hemi/ Lignin/ Extr (%)	SW BS EA, as Na_2O (% on wood)	Sulfidity (%)	SW BS Pulp Yield (%)	SW BS HHV (BTU/ lb BLS)
Thin Unthin Thin-LC Unthin-LC	29	470	105	39 / 23 / 29 / 9	63 / 17 / 16 / 4	10	25	60.3	6705.663

Scenario	SW Wood Lignin Comp. (%)	SW Wood Density (BD kg/green m^3)	SW TS Pulp Kappa	SW Wood Comp.: Cellulose/ Hemi/ Lignin/ Extr (%)	SW TS Pulp Comp.: Cellulose/ Hemi/ Lignin/ Extr (%)	SW TS EA, as Na_2O (% on wood)	Sulfidity (%)	SW TS Pulp Yield (%)	SW TS HHV (BTU/ lb BLS)
Thin Unthin Thin-LC Unthin-LC	29	470	70	39 / 23 / 29 / 9	68 / 17 / 13 / 3	13	25	53.5	6490.115

Scenario	HW Wood Lignin Comp. (%)	HW Wood Density (BD kg/green m^3)	HW Pulp Kappa	HW Wood Comp.: Cellulose/ Hemi/ Lignin/ Extr (%)	HW Pulp Comp.: Cellulose/ Hemi/ Lignin/ Extr (%)	HW EA, as Na_2O (% on wood)	Sulfidity (%)	HW Pulp Yield (%)	HW HHV (BTU/ lb BLS)
Thin Unthin Thin-LC Unthin-LC	20	515	60	51 / 27 / 20 / 2	68 / 25 / 7 / 0	12.5	25	58	5592.102

TABLE 4. Summary of Forest Cost Model for the Base Case Data

Forest Cost Model	Rot. Age (Yr)	SG	MAI (m3/hec/yr)	Land (Hec)	Wood Cost ($/grn ton)	Liner Cost ($/MT)	Op. Profit (Mil. $)
Thin	18	0.465	21.55	246,342	15.30	274	27.95
Unthin	18	0.471	21.51	85,688	13.27	267	34.23
Thin–LC	18	0.465	21.55	246,342	16.73	278	25.79
Unthin-LC	18	0.471	21.51	85,688	14.67	271	31.67

Table 5. Breakeven Seedling Costs for Growth, Wood Composition, and Specific Gravity within the Thinned Land Cost Scenario

Growth Rate	Breakeven Seedling Cost ($/seedling)	Lignin Content	Breakeven Seedling Cost ($/seedling)	Specific Gravity	Breakeven Seedling Cost ($/seedling)
0	0.05	29%	0.05	0.458	0.05
+10%	0.25	25%	0.09	0.50	0.52
+20%	0.48	20%	0.29	0.55	1.09
+30%	0.63	15%	0.47	0.60	1.67

FIGURE 1

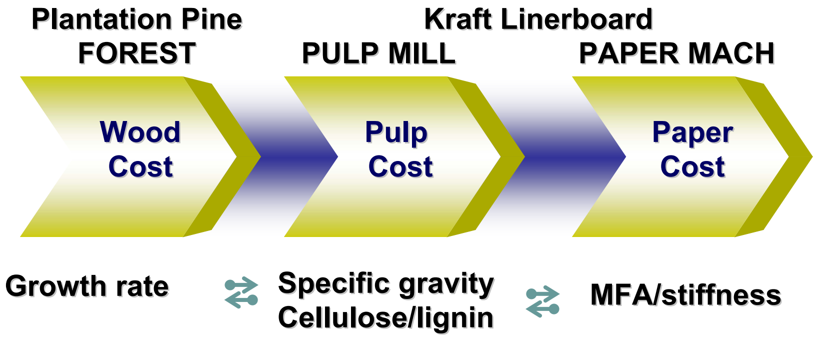
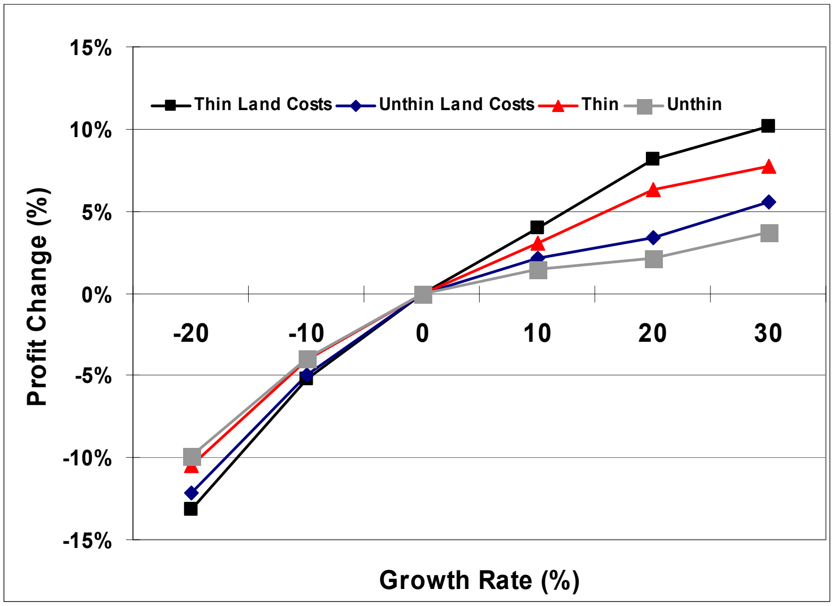

Plantation Pine
FOREST
Kraft Linerboard
PULP MILL
PAPER MACH
Wood Cost
Pulp Cost
Paper Cost
Growth rate
Specific gravity
Cellulose/lignin
MFA/stiffness

Figure 2



15%
10%
5%
0%
-5%
-10%
-15%
Thin Land Costs
Unthin Land Costs
Thin
Unthin
-20
-10
0
10
20
30
Profit Change (%)
Growth Rate (%)

Figure 3

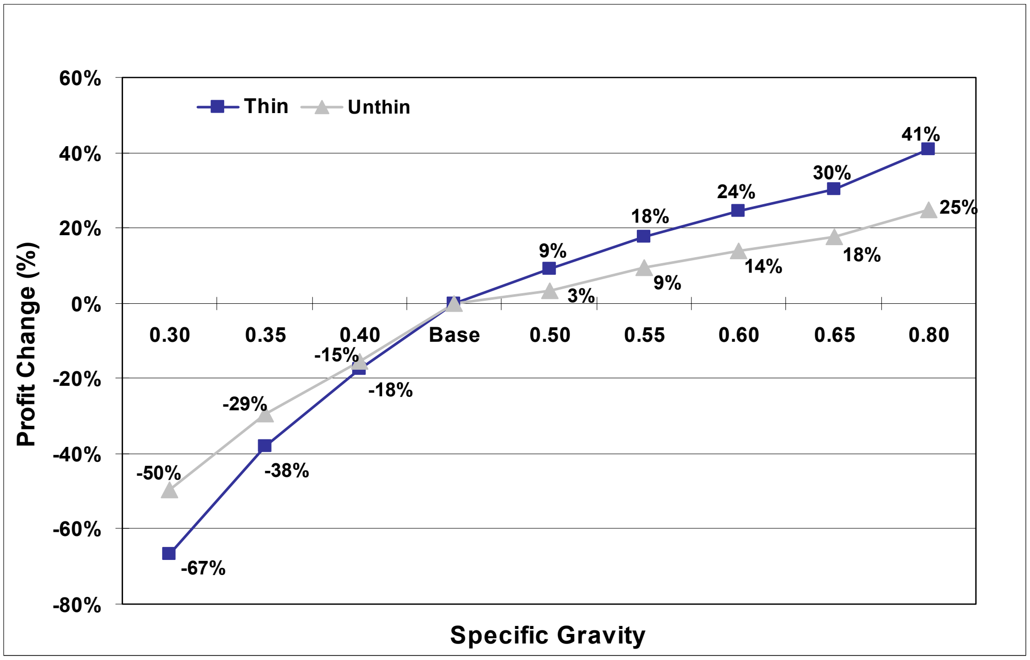

60%
40%
20%
0%
-20%
-40%
-60%
-80%
Profit Change (%)
Thin
Unthin
41%
30%
24%
18%
9%
25%
18%
14%
9%
3%
0.30
0.35
0.40
Base
0.50
0.55
0.60
0.65
0.80
-15%
-18%
-29%
-38%
-50%
-67%
Specific Gravity

Figure 4

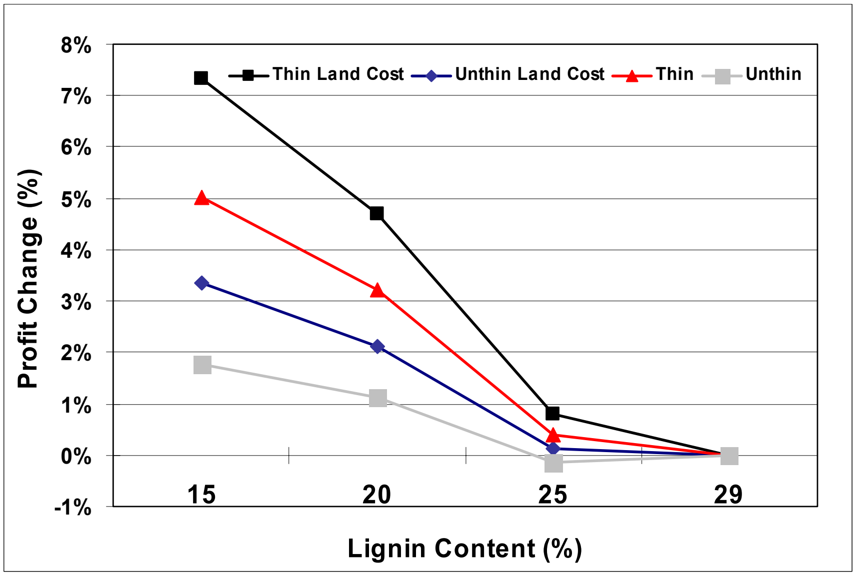

Thin Land Cost
Unthin Land Cost
Thin
Unthin
8%
7%
6%
5%
4%
3%
2%
1%
0%
-1%
Profit Change (%)
15
20
25
29
Lignin Content (%)

Figure 5

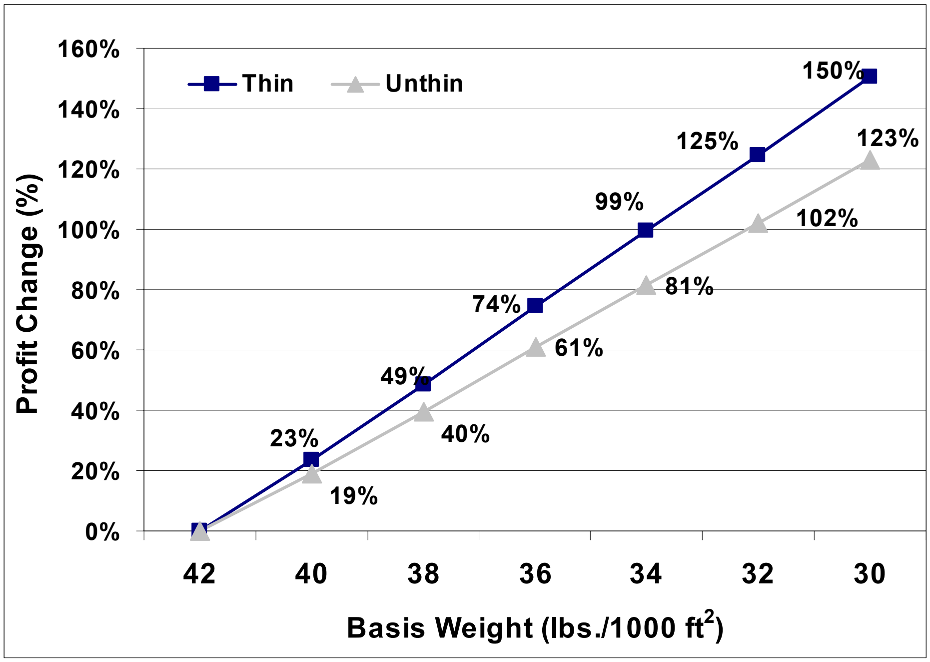

160%
140%
120%
100%
80%
60%
40%
20%
0%
Profit Change (%)
Thin
Unthin
150%
125%
99%
74%
49%
23%
123%
102%
81%
61%
40%
19%
42
40
38
36
34
32
30
Basis Weight (lbs./1000 ft2)

Figure 6

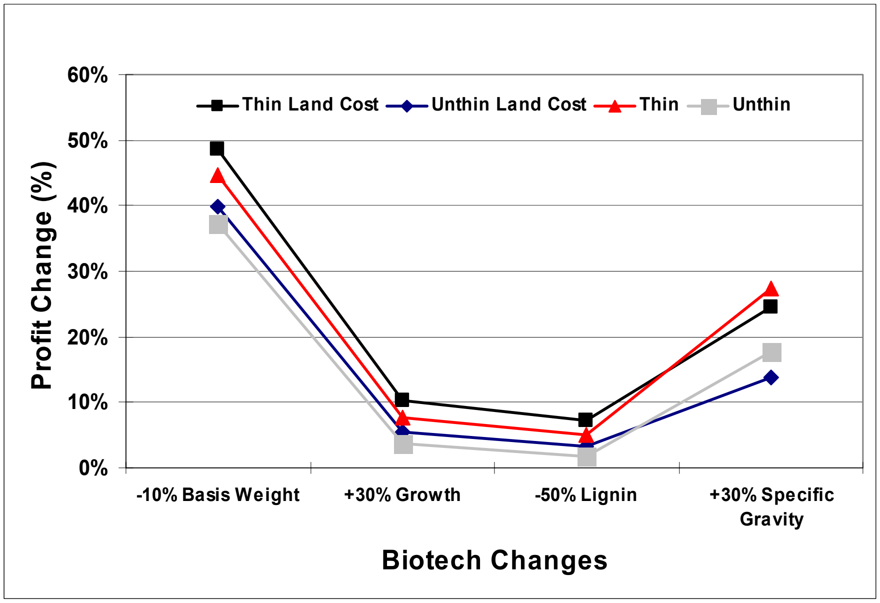

60%
50%
40%
30%
20%
10%
0%
Profit Change (%)
Thin Land Cost
Unthin Land Cost
Thin
Unthin
-10% Basis Weight
+30% Growth
-50% Lignin
+30% Specific Gravity
Biotech Changes

Figure 7

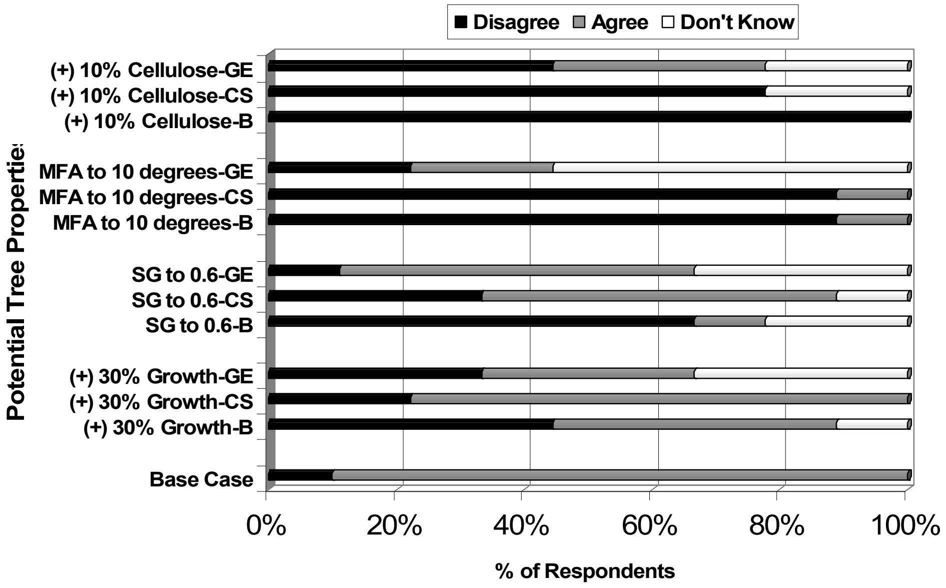
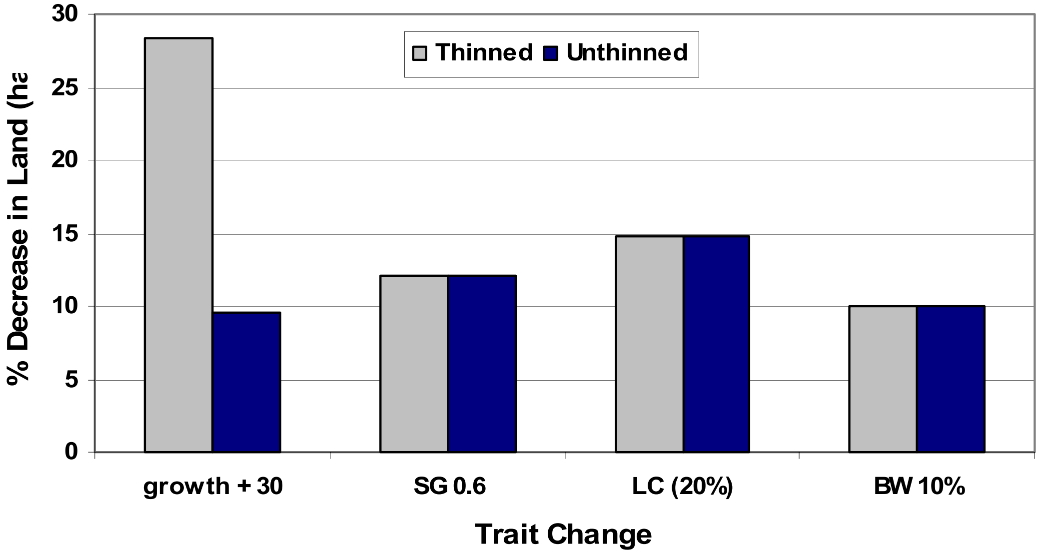

■ Disagree
▨ Agree
☐ Don't Know
(+) 10% Cellulose-GE
(+) 10% Cellulose-CS
(+) 10% Cellulose-B
MFA to 10 degrees-GE
MFA to 10 degrees-CS
MFA to 10 degrees-B
SG to 0.6-GE
SG to 0.6-CS
SG to 0.6-B
(+) 30% Growth-GE
(+) 30% Growth-CS
(+) 30% Growth-B
Base Case
Potential Tree Propertie
0%
20%
40%
60%
80%
100%
% of Respondents

Figure 8



% Decrease in Land (ha
30
25
20
15
10
5
0
Thinned
Unthinned
growth + 30
SG 0.6
LC (20%)
BW 10%
Trait Change