For. Sci. 61(3):466–480
http://dx.doi.org/10.5849/forsci.14-089

economics

Projecting Potential Adoption of Genetically Engineered Freeze-Tolerant *Eucalyptus* in the United States

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Development of commercial *Eucalyptus* plantations has been limited in the United States because of the species' sensitivity to freezing temperatures. Recently developed genetically engineered clones of a *Eucalyptus* hybrid, which confer freeze tolerance, could expand the range of commercial plantations. This study explores how freeze-tolerant *Eucalyptus* might be adopted as a preferred land use based on comparative returns and a real options land-use switching model. Climate factors other than freezing are assumed to limit potential adoption to the southeastern region of the United States. Comparison of returns indicates that *Eucalyptus* would probably not compete with cropland but could be competitive with forest uses, especially planted pine. Real options analysis, using both geometric Brownian motion and mean reverting models of stochastic returns, indicates that switching could be expected on a portion of planted pine forestland. Models predict about 0.8–1.4 million acres of *Eucalyptus* plantations (5–9% of the current area of planted pine). Extending the analysis to also consider the current area of naturally regenerated pine results in as much as 2.8 million acres of *Eucalyptus*. Actual adoption will probably depend on uncertain future markets for cellulose, especially for bioenergy feedstock.

Keywords: real options, investment analysis, genetically modified organism (GMO), bioenergy

Planted forests provide an increasing share of fiber supply throughout the world, and their area expanded at a rate of 5 million ha yr^{-1} between 2000 and 2010 (Food and Agriculture Organization of the United Nations 2010). *Eucalyptus,* a highly productive genus native to Australia and Indonesia, has been planted across large areas of Asia, Africa, and South America, but its application in the United States has been limited by environmental factors, especially sensitivity to freezing temperatures. In the southeastern United States, the 16 million ha of planted forests are almost exclusively pines (*Pinus* spp.) and are an important source of softwood forest products. Hardwood forest products in the region are mostly sourced from natural stands and have become somewhat scarce, especially in some localized markets (Wear et al. 2007). As a result, a freeze-tolerant (FT) *Eucalyptus* established in plantations could have commercial application in the region for industries currently using hardwood forest products as an input and may make novel industrial applications economically viable.

Recent efforts to modify the genetics of *Eucalyptus* hybrids to confer freeze tolerance could expand the range of *Eucalyptus* in the United States. In particular, ArborGen LLC has developed two genetically engineered clones of a *Eucalyptus* hybrid: *Eucalyptus grandis* × *Eucalyptus urophylla,* with genetic modifications targeting freeze tolerance and male sterility. The company has petitioned the US Department of Agriculture (USDA) Animal and Plant Health Inspection Service (APHIS) for a determination of nonregulated status of this FT *Eucalyptus* under the authority of the Plant Protection Act of 2000 (regulations 7 CFR part 340; Public Law 106-224, June 20, 2000). In response to the ArborGen petition, USDA APHIS has decided to prepare an Environmental Impact Statement to consider the potential environmental effects of an agency determination of nonregulated status consistent with the National Environmental Policy Act of 1969 (NEPA) regulations and the USDA and USDA APHIS NEPA implementing regulations and procedures. If the petition is granted, it would allow ArborGen to plant these freeze-tolerant clones without permit in unconfined conditions. This study explores the potential adoption of these clones based on anticipated productivity and economics. The overarching question is how much land area might be occupied by FT *Eucalyptus* plantations if these clones receive nonregulated status. The answer would necessarily derive from the willingness of landowners to adopt this new land use in lieu of existing land uses. This article compares returns to existing land uses with those

Manuscript received May 19, 2014; accepted October 24, 2014; published online December 18, 2014.

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Acknowledgments: *We thank Dr. Bin Mei, University of Georgia, Warnell School of Forest Resources, Dr. Jeffrey Prestemon, USDA Forest Service, and Dr. Feng Song, Renmin University, Beijing, China, for helpful reviews of an early draft of this article.*

accruing to potential FT *Eucalyptus* management regimes within an anticipated viable range in the United States to determine where returns to *Eucalyptus* management could compete with existing land uses.

The analysis starts by examining the production technology and economics of *Eucalyptus* plantations to estimate potential returns and present net values of *Eucalyptus* adoption. These estimates depend on a full accounting of the costs, biophysical productivity, and revenues of management and are based largely on estimates from management of non-FT *Eucalyptus.* We construct implied historical returns by linking simulated profit functions to historical prices and compare these returns with returns to other land uses. Adoption of *Eucalyptus* would depend not only on expected returns but also on the relative return risk associated with all land uses. A real options land-use switching model compares FT *Eucalyptus* with existing major land uses to estimate adoption under modeled return and risk conditions. The analysis of several model variants allows us to explore how the expansion of *Eucalyptus* plantations could develop under various market futures.

This article is organized as follows: The next section describes land-use theory, first in a deterministic setting and then with a consideration of risk and uncertainty using real options and includes specific details regarding estimation of the land-use switching models. The data section describes the geographic region viable for FT *Eucalyptus* and the compilation of data on the extent and net returns for the existing agriculture and forestland uses within this region, as well as the predicted returns for *Eucalyptus* management. The third section describes the results of model estimation, comparisons of *Eucalyptus* returns with returns to existing land uses, and projections of potential *Eucalyptus* adoption in the future for a set of scenarios. The concluding section describes key findings and discusses important uncertainties associated with the analysis.

Land-Use Theory

Understanding the potential expansion of FT *Eucalyptus* plantations requires a model of switching between different possible land uses. For example, under a deterministic land-use switching model, the existing distribution of land uses is assumed to reflect profit-maximizing behavior on the part of private landowners so that the quasi-rent accruing to the selected land use exceeds the quasi-rents accruing to all other possible uses (e.g., Hardie et al. 2000)

$$R^* = \max(R^{*1}, \ldots, R^{*J}) \quad (1)$$

where $j = 1, \ldots, J$ represents the possible land-use categories. These quasi-rents are defined by profit functions that account for all the relevant costs of management as well as the returns to harvest for different rural land uses (we treat urban land uses as fixed). Anticipated rents therefore vary across demand futures; i.e., they depend not only on the prices of known and anticipated products but also on the qualities of the site that determine productivity and operating costs. If land is of homogeneous quality, then we would expect one land use to dominate all others everywhere; heterogeneous land quality accounts for a diversity of land-use outcomes within an analysis area. A more explicit accounting is as follows

$$R^{*j}(P,Q) = Px^{*j}(P,Q) \quad (2)$$

where quasi-rent for land use j depends on a vector of input and output prices (P) and the quality of the parcel indexed by Q. The product of prices with the vector of input/output quantities (x^{*j} which likewise depend on P and Q) define the profit associated with land use j. Equation 2 indicates that the rent accruing to any land use would change in response to exogenous changes in input (energy, labor, or capital) prices or in output (corn, wheat, other crops, or timber) prices and also implies that the ranking of rents for a given parcel may change in response. Rent reordering explains rural land-use changes in this formulation.

Introduction of a new land-use alternative, e.g., *Eucalyptus* plantations, would require a reevaluation of relationship 1 with $J + 1$ (rather than J) alternatives. Because the current distribution of land uses across an analysis area represents the optimal allocation of land across economic and land quality conditions, the potential for reallocation depends on comparing the quasi-rent for *Eucalyptus* plantations with the quasi-rent accruing to each land use currently occurring within the analysis area. With a deterministic model, once the returns to *Eucalyptus* have been estimated, this reduces to evaluating the following inequality

$$R^{*J+1} - C > R^* = \max(R^{*1}, \ldots, R^{*j}) \quad (3)$$

where C accounts for the one-time cost of converting to a *Eucalyptus* plantation. If the inequality holds, then the land use would be expected to switch from the current optimal alternative to a *Eucalyptus* plantation.

Landowners face uncertainty regarding future returns, and the structure of that uncertainty along with costs of conversion has been shown to influence switching decisions (e.g., Schatzki 2003). To address uncertainty and conversion costs, we apply real options methods to estimate the potential for adoption of *Eucalyptus.* In general, the inclusion of uncertainty and conversion costs in the decision model tends to reduce the likelihood of conversion compared with the predictions of the deterministic model (Dixit and Pindyck 1994, p. 7). The approach changes the switching calculus from an "all or nothing" proposition to one that accounts for portfolio balancing among uses.

A Real Options Land-Use Switching Model

Our switching model anticipates that a risk-neutral decision-maker chooses between retaining a current land use or (reversibly) adopting a new land use (*Eucalyptus*) based on a comparison of returns, conversion costs, and uncertainty regarding future returns. Modern investment theory highlights the limitations of discounted cash flow as a decision rule when returns are not known with certainty and investments are at least costly to reverse (Dixit and Pindyck 1994, p. 135–161). The ability to switch land use is an option that is lost when the decision is made; i.e., the landowner foregoes the option to further delay the timing of the investment and therein benefit from future information. The costs (as well as the benefits) of exercising the option factor into the decision, therein defining a real options problem. We adopt the modeling approach of Song et al. (2011) to define switching models to compare the *Eucalyptus* land use with current land uses. Their analysis addresses the potential adoption of perennial switchgrass over a corn-soybean land use in the midwestern United States and allows for two-way switching, a problem directly analogous to our research question.

Following Song et al. (2011), assume that a risk-neutral landowner is considering the current use of a unit of land, denoted by i, that can be converted to another use, j, at a lump sum cost of C_{ij}. The return to the current land use i ($\pi_i[t]$) in a given time period t is assumed to evolve by a stochastic process of the form

$$d\pi_i(t) = \alpha_i \pi_i dt + \sigma_i \pi_i dz_i \quad (4)$$

where α_i, the drift term, and σ_i, the variance term, are both constants and dz_i is the increment to a Wiener process. Equation 4 defines a geometric Brownian motion (GBM) model of the returns to the land use, which is nonstationary: a positive α indicates an upward drift in revenues.

To compare returns between two land uses requires estimating a GBM model for each and accounting for the correlation of the return series due to the influence of common factors (e.g., all land-based returns in a region may be similarly influenced by drought). The joint GBM models for both land uses can be expressed as follows

$$\begin{aligned} d\pi_1(t) &= \alpha_1(\pi_1, t)dt + \sigma_1(\pi_1, t)dz_1 \\ d\pi_2(t) &= \alpha_2(\pi_2, t)dt + \sigma_2(\pi_2, t)(\rho dz_1 + \sqrt{1-\rho^2}dz_2) \end{aligned} \quad (5)$$

where ρ is the correlation coefficient between the two return series and other variables are defined as above.

The GBM model with positive drift implies increasing scarcity. In the case of renewable resources, long-term stability in commodity returns may be more consistent with theory. Accordingly, we also examine a mean reverting (MR) stochastic return model that allows for short-run fluctuations but anticipates a tendency for prices to be drawn back to a long-run mean value, consistent with a stock adjustment process (i.e., planting more or less crops) that responds to increasing or decreasing scarcity. This model is defined as

$$d\pi_i(t) = \eta(\bar{\pi}_i - \pi_i)\pi_i dt + \sigma_i \pi_i dz_i \quad (6)$$

where η is the speed of reversion back to the mean (and is expected to be positive) and the other parameters are as defined for the GBM model. Although the GBM model is more tractable and is the standard form applied to the real options analysis of financial instruments, the mean reverting (MR) model may be preferable for describing returns to land-based commodity production. It is difficult to select mean reversion or to allow for drift a priori. We instead investigate the implications of both formulations.

The expected present-value payoff in time period t due to the landowner following optimal conversion is a function of the returns to both possible land uses and is denoted as $V^i(\pi_{\text{cur}}(t), \pi_{\text{alt}}(t))$, with cur and alt denoting the current and alternative (e.g., *Eucalyptus*) land use, respectively. Letting r be the landowner's discount rate, the conversion decision is defined by

$$V^i(\pi_{\text{cur}}(t), \pi_{\text{alt}}(t)) = \max\left\{\begin{matrix} \pi_{cur}(t)dt + e^{-rdt}EV^{cur}(\pi_{cur}(t+dt), \pi_{alt}(t+dt)), \\ V^{alt}(\pi_{cur}(t), \pi_{alt}(t)) - C_{cur,alt} \end{matrix}\right\}, \quad (7)$$

The first term in the maximum operator is the return to the landowner from staying in the current land use i and is the sum of the immediate profits from the current land use and the discounted value of the expected profits at the end of the time period ($t + dt$). The second term in the maximum operator is the return from converting to the alternative use net of the switching cost $C_{\text{cur,alt}}$.

This present value function can be redefined to describe optimal decision rules incorporating the option value of the current land use based on different realizations of relative returns in the two possible land uses. Figure 1 shows a graphical representation of idealized switching boundaries for the current problem (Equation 7) with returns to current use and *Eucalyptus* use on the horizontal and vertical axes, respectively. Where relative returns occur above the upper switching boundary, returns to *Eucalyptus* exceed returns to the current use enough to justify switching from the current land use to *Eucalyptus.* Where relative returns occur below the lower switching boundary, returns to the current land use exceed *Eucalyptus* returns enough to justify switching from *Eucalyptus* back to the original use.

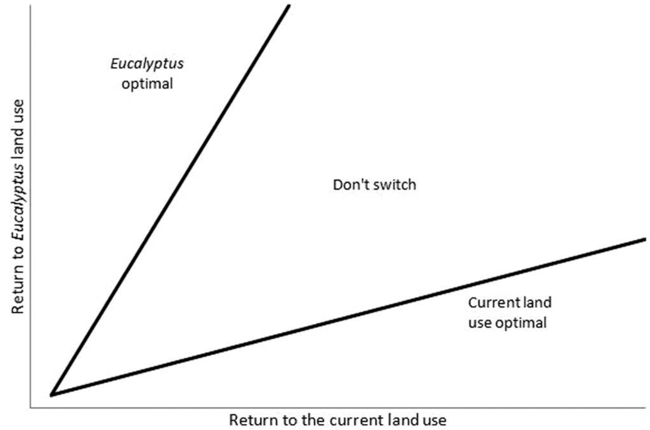

Figure 1. Idealized switching boundaries for a real options-based land-use switching model.

The region where relative returns fall between the two lines corresponds to the condition in which it is not optimal for the landowner to make a switch, even if current returns for the existing land use are lower than the alternative (because of conversion costs and/or risk). Note that land-use hysteresis is expected with this model specification, i.e., following a land-use switch, a return to a preswitch price pair may not induce switching back to the original land use. More information about the mathematical procedure and proofs underlying the conversion of the present value function to the optimality conditions can be found in Song et al. (2011) and Brekke and Øksendal (1994).

Model Specification

The land-use switching model described above is too complex to be solved analytically and is instead solved by numerical approximation. In this procedure, the model is reformulated as a series of piecewise linear basis functions and then solved for a subset of possible values by a process called collocation. This produces an approximation of the location of the switching boundaries between the two land uses demonstrated in Figure 1 (Miranda and Fackler 2002, p. 129, Fackler 2004). The probability of conversions through time may be estimated by simulating switching behavior over a large set of simulations for the return paths determined by Equations 5 and the correlation between returns. For each year in each simulation, switches to and from *Eucalyptus* are tallied to predict the total proportion of land that would be allocated to *Eucalyptus.* We construct pairwise comparisons of existing rural land uses with *Eucalyptus* management in each of several subregions for which distinct estimates of revenue time series can be constructed.

For each pairing between a current land use and the *Eucalyptus* land use, we use OSSOLVER, a MATLAB utility developed by Fackler (2004) for solving switching problems (to and from *Eucalyptus*) by numerical approximation, to solve for the optimality conditions and develop the conversion boundaries between land uses for

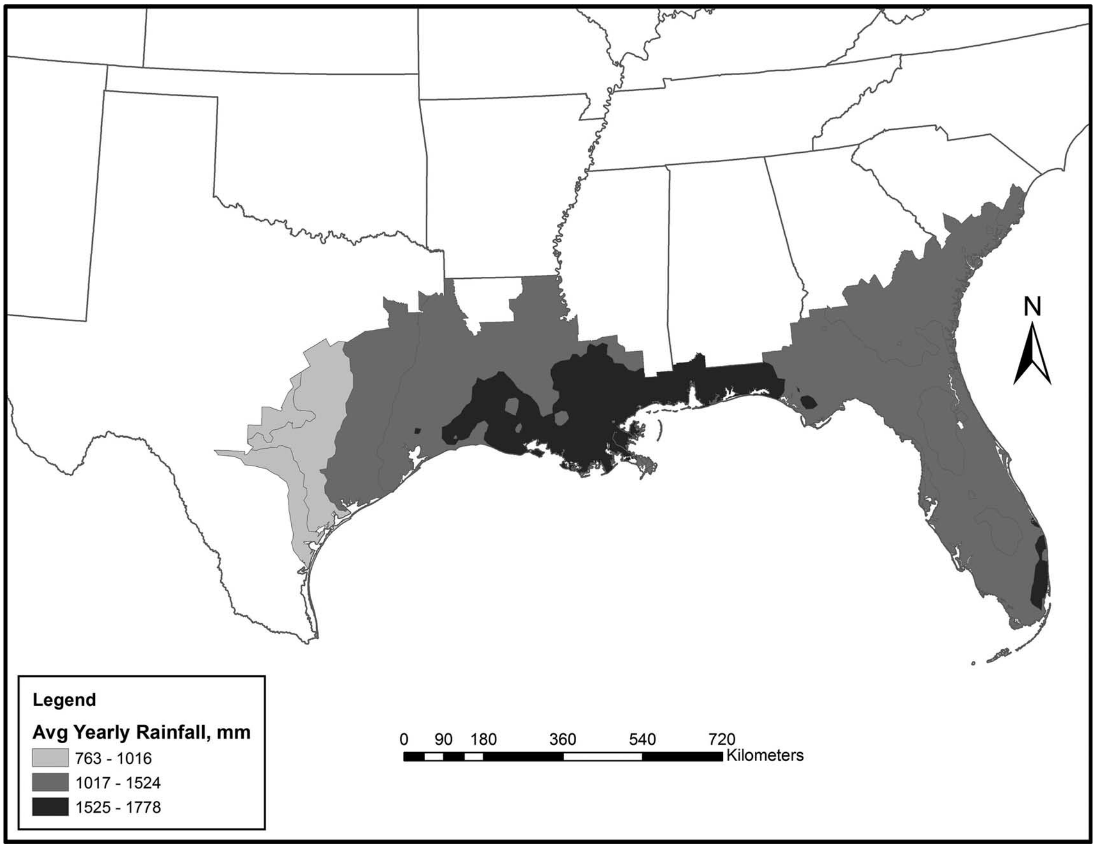

Figure 2. Study area defined by plant hardiness zones 8b and higher intersected with adequate precipitation for commercial plantings of *Eucalyptus* in the South.

each county. The switching boundaries estimated in this step define a mapping between revenue pairs and the optimal decision, incorporating the option value of the current land use and conversion costs between all pairs of land uses.

Monte Carlo simulations were done in the Python programming language, applying 100,000 realizations of Equations 4 over a 30-year time period and calculating the switching between the *Eucalyptus* and alternate land use based on the OSSOLVER switching boundaries. *Eucalyptus* adoption is examined initially for the existing market situation, i.e., with the estimated stochastic revenue functions for existing land uses and a constructed *Eucalyptus* revenue function based on production of hardwood for the pulpwood market. To address altered demands for cellulosic fiber, for example, from anticipated thermal and biochemical bioenergy uses, we also consider scenarios with higher initial prices for both *Eucalyptus* and other wood-producing land uses.

Study Area and Data

The study area is limited initially by USDA plant hardiness zones 8b and higher as shown in Figure 2. This is defined by the parameters of the environmental analysis conducted by USDA APHIS and implicitly assumes that an effective frost tolerance is conferred on the *Eucalyptus* hybrid through genetic modification. This zone encompasses a large area of the southeastern United States and also includes much of the southwestern United States and California along with coastal areas of Oregon and Washington. Intolerance to cold (freeze damage) has restricted the small area of commercial plantings of non-FT *Eucalyptus* to zone 9 (generally zone 9a), and FT hybrids could expand the range to this broader area. USDA plant hardiness zones are defined by bands of average annual minimum temperatures and can be useful for defining limits based on frost or cold tolerance. Commercial *Eucalyptus* plantings would be limited not only by cold sensitivity but also by potential productivity, which is influenced by the availability of water inputs and solar insolation. This eliminates areas in the southwestern United States where plantations would require irrigation, which we deem cost prohibitive. We define the areas where *Eucalyptus* could be a viable crop by screening out areas based on the range of water and solar inputs observed in other parts of the world. Based on a review of literature, we screen out areas with average annual precipitation of <800 mm/year as unsuitable for plantings in the United States. We define the mean annual daily temperature cutoff as $>15°$ C (about 60° F) and a solar insolation cutoff as 4 kwh/m^{-2} per day. These screens eliminate from consideration the small section of plant hardiness zone 8b contained in Oregon and Washington. Our study area is therefore limited to the southeastern United States from east-central Texas to South Carolina as shown in Figure 2.

Examination of the potential adoption of *Eucalyptus* plantations in zone 8b requires data on the current rural land-use distributions across forest management types and crop types, returns accruing to each of these existing land uses, the costs of converting from existing land uses to *Eucalyptus* and vice versa, and the potential returns accruing to *Eucalyptus.* Data were compiled at the county and subregional levels. Returns data are organized by the one or two Timber Mart-South (TMS) subregions within each state. Crop returns are compiled by crop and for broader regions defined by the USDA and were linked to TMS subregions. Where more than one crop return region is associated with the TMS subregion, an average return is constructed by weighting the respective crop returns by crop acreage. Data (land uses, conversion costs, and returns) are assembled for each subregion from the following sources.

Area of Land Uses

Cropland by crop type and pastureland area are taken from the 1997, 2002, and 2007 Census of Agriculture (USDA 2007) as reported by the National Agricultural Statistics Service[1]; forest areas by forest management type are taken from the USDA Forest Service Forest Inventory and Analysis databases for each state (e.g., Miles et al. 2001, Smith et al. 2009). Because farmers use a variety of crop rotation patterns (which we cannot identify a priori) and rarely employ monocultures, we treat cropland as a single use and assign the portfolio of six major crops produced within the subregion based on cropland acreages. Forests are divided between intensively managed planted pine and four other, naturally regenerated forest types. We consider switching options for the former but not for the latter because currently planted forests have demonstrated economic feasibility for tree plantations. This logic limits our analysis to areas already identified as "operational" in terms of drainage and access, and we revisit the implications of this assumption in the Discussion and Conclusions section by also considering naturally regenerated pine.

Returns to Land Uses

Net returns to land uses are derived from annual return and cost estimates or from secondary sources and are expressed in real terms using the implicit GDP price deflator with a base year of 2005. Forestland returns are developed for each county using substate timber (stumpage) prices linked to simulated outputs and costs associated with a specified management regime. For cropland returns we use reports of annual net returns to each major crop type for each subregion but had to make adjustments for a change in the definition of returns occurring in 1996. For the earlier time series of crop returns, years 1975–1996, we defined the net return as the reported gross value of production net of variable cash expenses. To most closely match the definition of crop returns with the most recent time series (years 1996–2011), we had to subtract the interest on operating capital from the reported value of production less operating costs and hired labor. We constructed an acreage-weighted average return to cropland for each subregion using individual crop acreages for 1997, 2002, and 2007. We assume that the 1997 acreages apply to years prior to 1997 and then interpolate crop acreages between data points to estimate acreages for 1997–2007. Acreages are held at 2007 levels for 2007–2011. Comparable data were not available for pasture, and we have not included this land use in our analysis.

Historical net returns accruing to *Eucalyptus* plantations are simulated using cost and productivity data from recent published work related to *Eucalyptus* grown in the southeastern United States (especially Gonzalez et al. 2011a, 2011b). These are linked to historical hardwood pulpwood prices to simulate the pseudohistorical revenue series used to estimate the stochastic revenue functions. The same approach is used to construct a return series for planted pine forests. To produce return data comparable to annual crop returns, we calculated an annualized return for forestry uses based on a valuation using each year's stumpage prices for a given region. This approach is consistent with the landowner basing the decision to switch on anticipated returns for woody crops and that switching from the current woody crop would occur only after a harvest. That is, we do not directly address the issue of changing the harvest timing for existing woody crops in response to other options.

Predictions of land-use switching are based on return processes (GBM or MR model) estimated for the various land uses. We started with base scenarios that use the estimated models applied to starting conditions defined by 2011 prices. Alternative futures were constructed by adjusting the rates of return growth in the GBM models, adjusting the variability and correlations of returns in the MR or GBM models, or changing the starting conditions. We also constructed a sensitivity analysis of these models to examine the influence of *Eucalyptus* establishment costs and starting prices on eventual adoption of *Eucalyptus* across the southeastern United States.

Results

Rural land in the region reflects a diversity of uses. The 2007 Census of Agriculture (USDA 2007) indicates that 7.7 million acres of land were dedicated to six major crop uses, down from 9.3 million acres in 1997 (Figure 3A). Most of the decline between 1997 and 2007 is explained by declines in cotton acreage (−0.85 million acres) and soybean acreage (−0.98 million acres) coupled with a moderate expansion in corn acreage (+0.43 million acres). Peanut and wheat acreages are relatively small (0.5 million acres) but stable over this period. Forest uses dominate the rural landscape in the study area at 59.3 million acres. Forest uses similarly show strong diversity in this region (Figure 3B). Pine forest types account for 27 million acres or 46% of total forest area, with 16 million acres (27%) in a planted forest condition. Hardwood forest types account for 25 million acres (42%) with a majority (15 million acres) in lowland hardwood forest types.

Returns to *Eucalyptus* Management

To estimate returns to *Eucalyptus* management we start by assuming that removals will be sold in a hardwood pulpwood market and simulate management using a 16-year management regime based on Gonzalez et al. (2011a) and Dougherty and Wright (2012). Conversion costs include mechanical and chemical site preparation, seedlings, and planting. An initial harvest occurs at age 8 followed by coppice regeneration and a final harvest at age 16. Management costs include fertilization applied at year 2 and at year 10, herbicide treatments at years 1 and 9, and annual management costs (generally consistent with management regimes described in Dougherty and Wright 2012). All cost estimates are shown in Table 1. Revenues depend on biophysical production and prices. FT *Eucalyptus* productivity is uncertain, so we consider three different levels of productivity based on the published literature (Table 2). We define a baseline level of expected productivity (mean annual increment) as 12 green tons/acre/year and examine returns at 8 and 16 green tons/acre/year as lower and upper cases. Throughout this study, we adopt a discount rate of 8%.

To simulate what the returns to the *Eucalyptus* management regime would have been over the historical period, we apply historical hardwood pulpwood prices to *Eucalyptus* output and calculate the net present value of perpetual management of *Eucalyptus* using the cost and revenue components described above. This is the bareland value (BLV) for *Eucalyptus* management. An ordinary least squares regression between net annual returns and hardwood pulpwood prices was developed using return estimates generated for each productivity level and a sequence of hardwood pulpwood prices between minimum and maximum historical values. This regression

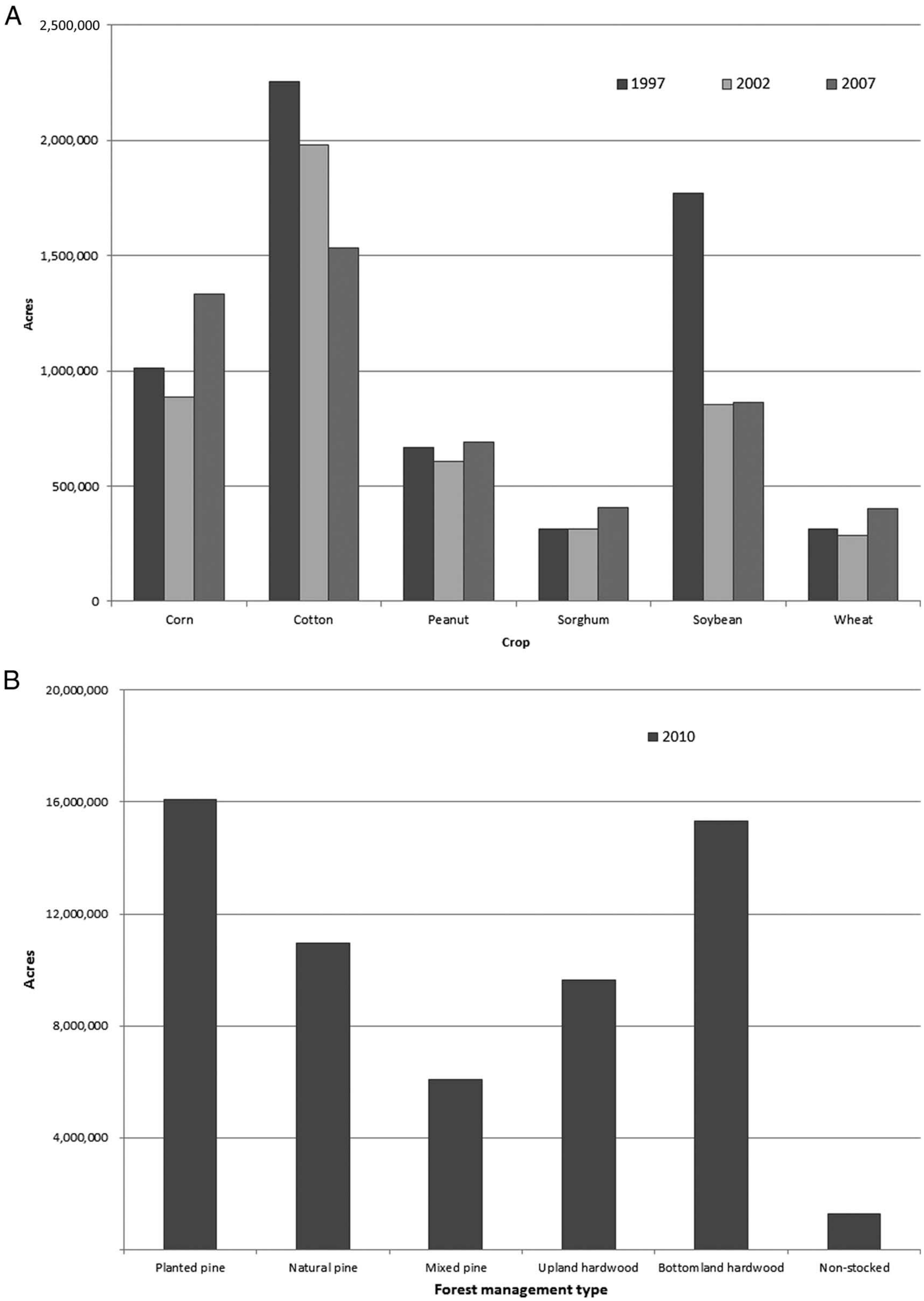

Figure 3. Distribution of rural land uses in the study area for crop types in 1997, 2002, and 2007 (A) and for forest types in 2010 (B). (Sources: USDA Census of Agriculture and Forest Inventory and Analysis.)

model (adjusted $R^2 = 0.999$) was used to define the series of anticipated returns given the hardwood price series of each state-subregion and the specified productivity levels. Reflecting a sustained growth in hardwood pulpwood prices over this period, *Eucalyptus* BLV increased from exclusively negative values between 1977 and the early 1990s to strongly positive values in the latter part of the series (2005–2011). Values are highly variable across the region ($173–$698/acre in 2011) with the highest values in 2011 found in the western part of the region (Texas, Mississippi, and Louisiana) and lowest values found in Florida. The rankings of values by state have not been constant over time.

We next constructed an annualized return series based on the discounted cash flow described above, excluding the conversion costs (initial site preparation and planting), which are incorporated

Table 1. *Eucalyptus* management regime for producing hardwood pulpwood.

Description	Timing	Value	Unit	Value	Unit
Mechanical site preparation	Establishment	247	$/ha	99.96	$/ac
Chemical site preparation	Establishment	116	$/ha	46.94	$/ac
Planting density	Establishment	1,250	trees/ha	505.86	trees/ac
Planting cost	Establishment	133	$/ha	53.82	$/ac
Seedling cost	Establishment	0.25	$/seedling	0.25	$/seedling
Fertilizer	Midrotation (years 2 and 10)	247	$/ha	99.96	$/ac
Herbicide	Midrotation (years 1 and 9)	124	$/ha	50.18	$/ac
Management	Yearly	25	$/ha	9.98	$/ac
Growth rate	Yearly	30	tons/ha/year	12	tons/ac/yr
Discount rate		0.08		0.08	
Harvest age		8	yr	8	yr

Table 2. Estimates of *Eucalyptus* productivity from various published studies.

Author	Region	Productivity (green tons ac^{-1} yr^{-1})	Methods
Dougherty and Wright (2012)	Southern United States	High: 15* Medium: 11 Low: 8	Assumption
Gonzalez et al. (2011a)	Southern United States	Range for pulpwood management: 8–16 Range for energy crops: 10–18	Assumption
Kline and Coleman (2010)	Southeastern United States	Range: 8–11 Most likely: 9.8	Survey of forest industry experts
Stape et al. (2010)	Brazil	Average (current silviculture): 11* Irrigated: 14 Maximum: 19	Measured plots across 1,000+ km gradient
Langholtz et al. (2007)	Central Florida	Range: 15–28*	Model fit to field trial data

* Converted from Mg ha^{-1} yr^{-1}, assuming 1.1023 tons/Mg and 2.47 acres/ha.

directly in the switching decision. The annualized return series is used to construct the stochastic return models. Consistent with the BLV estimates, annualized returns to *Eucalyptus* have trended upward since the late 1980s. In 2011, they ranged from between $16/acre and $66/acre across the subregions with an average return of about $48 for the entire region (Figure 4).

Returns to Pine Management

Jones et al. (2010) conducted a financial analysis of intensive loblolly pine plantation management, and our pine plantation management regime is based on their work. To obtain yield by product class, we reproduced a portion of their study using the simulation model LobDSS. Table 3 lists all of the management activities and costs. Regional averages of annual management costs and herbaceous weed control are from Barlow and Dubois (2011). Table 3 also lists the assumed yields by product class by harvest event.

To examine the returns to planted pine over the historical period, we apply this management and cost regime and calculate implied BLVs in each year for the observed pine pulpwood and sawtimber prices. BLVs have been positive throughout the region except for those for five subregions in the western part of the region during a short period (1985–1988) and for Texas subregions in 1990 and 2009. BLVs reached peak values in the late 1990s but then fell substantially between 1998 and 2001 and have trended slightly downward since. The variability of BLVs across subregions fell along with the level of values during the latter period. The annualized return series (Figure 5) follows the same pattern. The average BLVs and returns to planted pine were at historically low values between 2009 and 2012.

Returns to Cropland Management

Returns to individual crops have been quite variable across the regions since the 1970s. The returns to peanuts, for example, trended downward between 1977 and 2005 but increased between 2005 and 2011. Returns to all crops have trended upward since 2005, and this is reflected in the returns to the composite crop index for each subregion (Figure 6). For most regions, the real return to cropland nearly tripled between 2005 and 2011, reflecting increased returns to corn as well as shifts in crop acreages toward corn and other higher valued crops.

Return Comparisons

Figure 7 compares annual returns between *Eucalyptus,* planted pine, and crops for the years 1977–2011. Crop returns dominate the other two uses across the time series with the exception of 2003, during which returns to crops were slightly less that the annualized returns to planted pine. Returns to pine peaked in the late 1990s and have declined to about $40/acre, while implied returns to *Eucalyptus* have increased over the period, becoming positive in the early 1990s, and are now comparable to pine returns (slightly exceeding average returns to pine in the last year of the time series). Returns to pine are linked to the progression of real prices for pine pulpwood, sawtimber, and chip-n-saw products. Pulpwood prices moved upward from the 1970s through the late 1990s and then dropped substantially, consistent with a strong expansion in pine pulpwood supplies (see Wear et al. 2007). Sawtimber prices are generally cyclical and strongly affected by demands from the housing sector; recent declines in returns have been strongly influenced by the post-2007 recession. Returns to *Eucalyptus* are driven by the dynamics of hardwood pulpwood prices, and strong price increases are consistent with an overall tightening of hardwood pulpwood supplies (see Wear et al. 2007). Because crop returns in 2010 and 2011 were about 5 times higher than both the *Eucalyptus* and pine returns, we assume that land-use switching from crops to *Eucalyptus* would be highly unlikely. We focus exclusively on switching between planted pine and *Eucalyptus.*

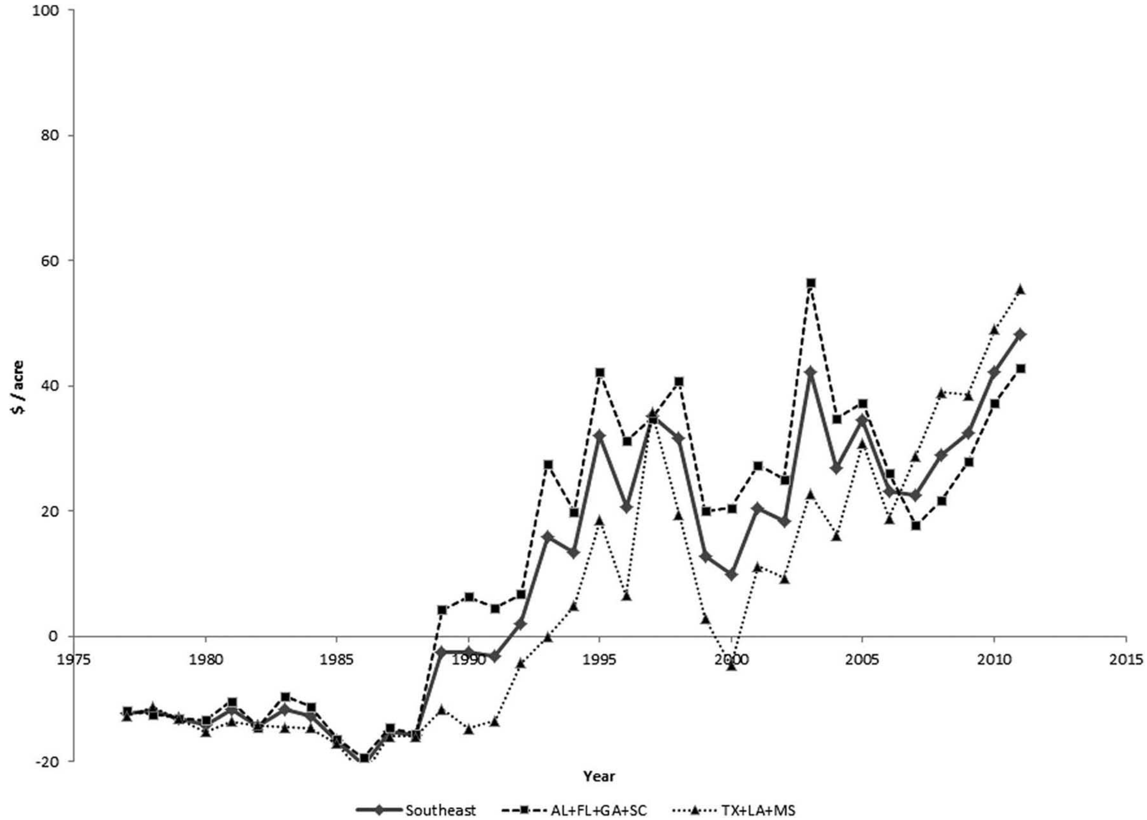

Figure 4. Real returns to *Eucalyptus* management by subregions defined by multistate aggregates (2005 = 100; 1977–2012).

Table 3. Planted pine management regime.

Management activities	Year	Value	Unit	Value	Unit
Mechanical site preparation	0	370.65	$/ha	150.00	$/ac
Chemical site preparation	0	286.31	$/ha	115.87	$/ac
Planting and seedlings	0	156.66	$/ha	63.40	$/ac
Weed control, banded	0	89.57	$/ha	36.25	$/ac
Weed control, broadcast	1	84.51	$/ha	34.20	$/ac
Fertilizer	1	74.13	$/ha	30.00	$/ac
Management costs	1–24	25	$/ha	9.98	$/ac
Discount rate		0.08			
Harvest events and yields		*Pulpwood*	*Chip-'n-saw*	*Sawtimber*	
First thinning	11	35.5			Tons/ac
Second thinning	18	7.4	17		Tons/ac
Final harvest	24	18	9.4	61.3	Tons/ac

To examine the possibility of land-use switching between *Eucalyptus* and planted pine, we first examine the difference between their respective BLVs. The differences have changed from a range of −$1,300 to −$800 acre in the 1970s to a range of −$400 to +$200 /acre in 2012 (based on moderate *Eucalyptus* productivity), again reinforcing the observation that returns to the two technologies have become comparable in the recent past and supporting a careful analysis of potential switching. Note as well that the most positive differences are found for the western part of the study area (Texas, Louisiana, and Mississippi).

Stochastic Return Models

The GBM model of returns as described by Equation 4,

$$d\pi_i(t) = \alpha_i \pi_i dt + \sigma_i \pi_i dz_i \tag{8}$$

requires estimates of the drift parameter (α) and the variance parameter (σ) for each return series. After discretizing the series and rearranging terms, the parameters can be derived as functions of the first difference of the ln(π) series: $\alpha = m + 0.5\, s^2$ and $\sigma = s$, where m and s are the mean and SD of the series $\ln(\pi_t)$-$\ln(\pi_{t-1})$ and ρ defines the simple correlation coefficient between the differenced return series for *Eucalyptus* and the alternative land use. Because the GBM model estimates derive from the logarithm of the returns, the parameters are undefined when revenues are negative. In addition, in the context of the switching problem described in Equation 7, explosive returns result when the drift parameter exceeds the discount rate (0.08 in this case).

As shown in Figure 4, returns to *Eucalyptus* are negative until the last 10–15 years of the time series (depending on the subregion), leaving only a short time period over which to calculate the parameters of the GBM model. During this period, *Eucalyptus* returns rose steadily to the point where they have converged with pine returns, and this is reflected in high drift parameters (ranging from 0.07 to 0.592) (Table 4), with a variance parameter ranging from 0.27 to 0.90. In nearly all cases, the growth in *Eucalyptus* returns

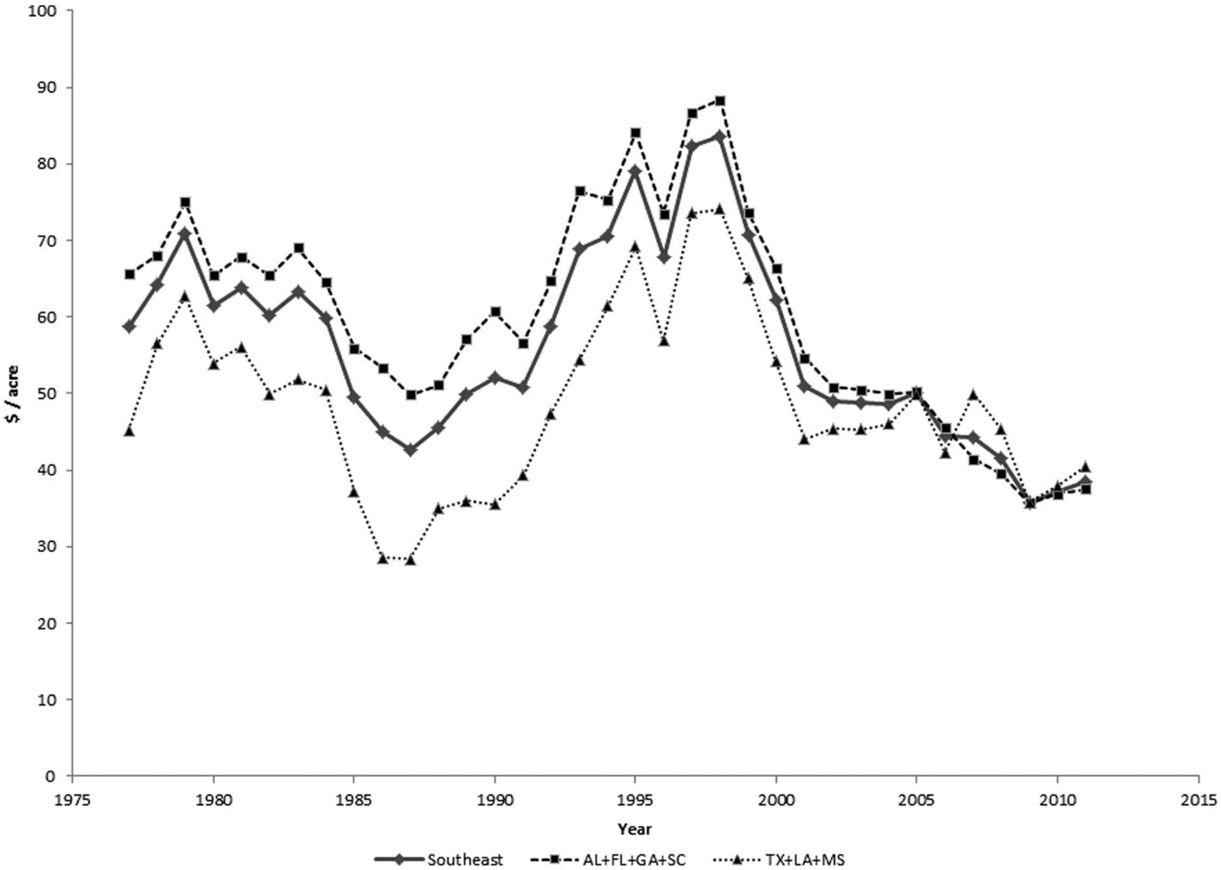

Figure 5. Returns estimates for planted pine management by subregions defined by multistate aggregates (2005 = 100; 1977–2012).

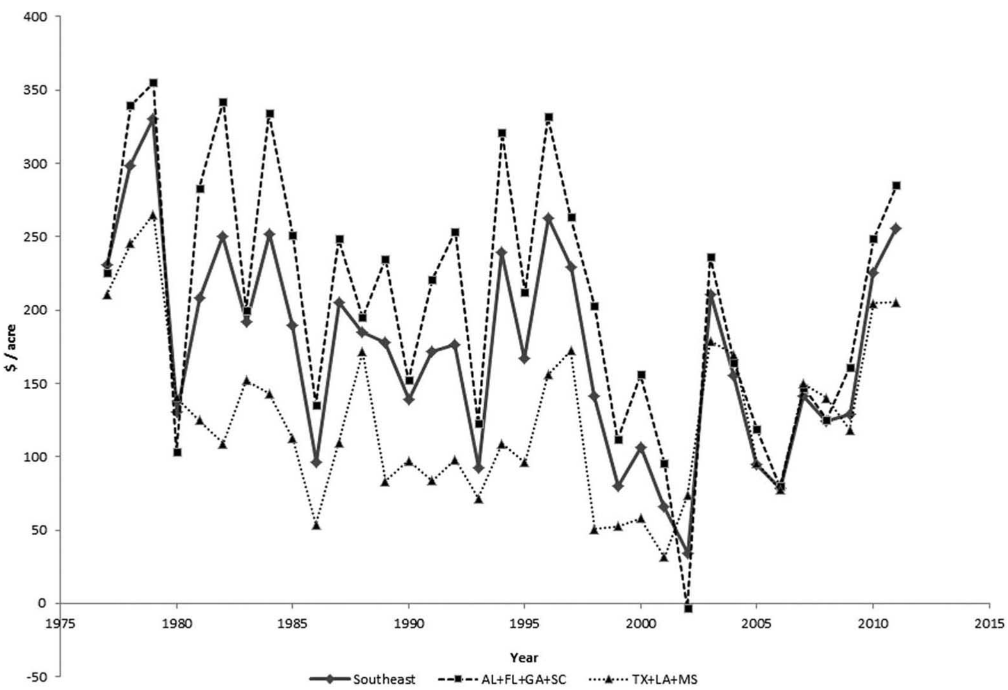

Figure 6. Real returns to cropland by subregions defined by multistate aggregates (2005 = 100).

exceeds the discount rate. In contrast, returns to planted pine exhibited relatively small drift rates ranging from negative (−0.02) to slightly positive (0.008) and fairly consistent variance parameters (from 0.09 to 0.16). The high drift parameters for *Eucalyptus* may indicate either a transition period where the scarcity of hardwood products increased substantially or that the short time series of positive *Eucalyptus* returns does not provide enough information to precisely discern drift from variance from the data.

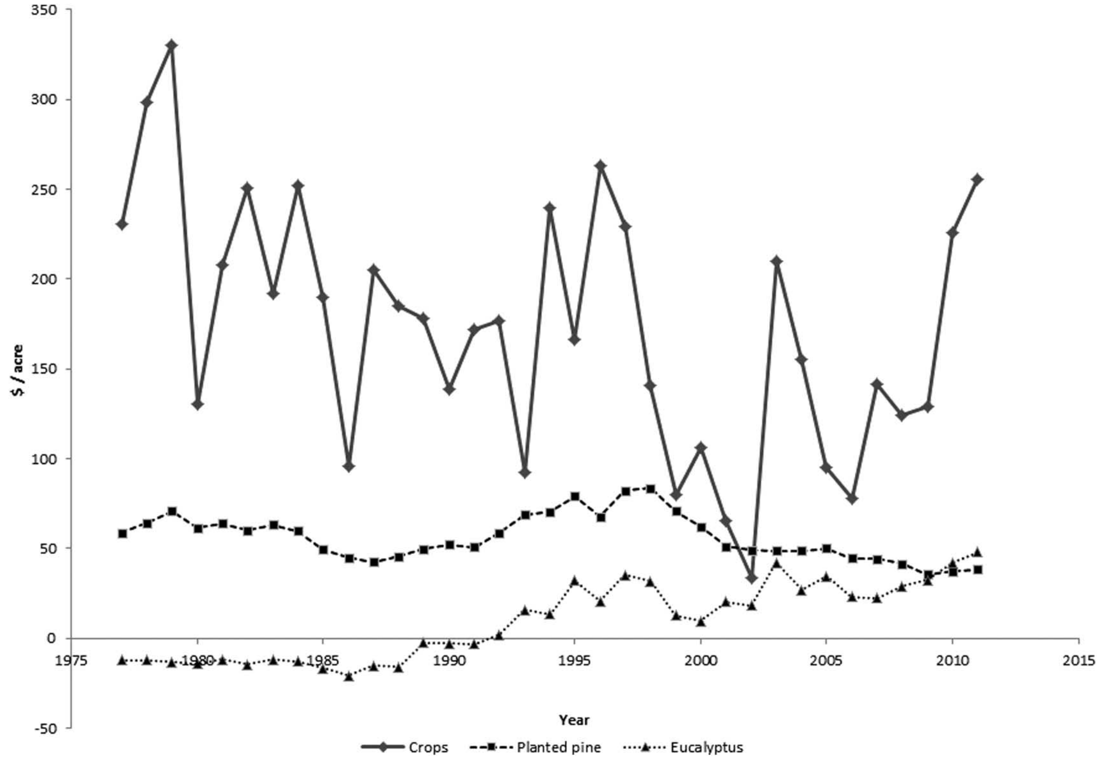

Figure 7. Southeast-wide regional average returns for *Eucalyptus*, planted pine, and crop composite (1977–2011).

Table 4. Estimates of parameters of the GBM model of pine and *Eucalyptus* returns by TMS zone.

	Pine		*Eucalyptus*		
TMS zone	Drift term	Variance term	Drift term	Variance term	Correlation coefficient
AL2	−0.005	0.102	0.150	0.370	0.610
FL1	−0.020	0.090	0.007	0.432	−0.300
FL2	−0.011	0.095	0.332	0.784	0.480
GA2	−0.009	0.103	0.056	0.309	0.340
LA1	0.008	0.139	0.080	0.267	0.210
LA2	0.005	0.164	0.401	0.454	0.070
MS2	0.007	0.143	0.592	0.895	0.420
SC2	−0.012	0.088	0.024	0.281	0.140
TX1	0.006	0.104	0.074	0.326	0.84
TX2	0.003	0.098	NA	NA	NA
Minimum	−0.020	0.088	0.007	0.267	−0.300
Maximum	0.008	0.164	0.592	0.895	0.840
Mean	−0.004	0.114	0.191	0.458	0.312
Median	−0.005	0.103	0.080	0.370	0.340
All Southeast	−0.007	0.100	0.139	0.494	0.260
TX-LA-MS	0.006	0.134	0.191	0.458	0.410
AL-FL-GA-SC	−0.013	0.088	0.049	0.334	0.380

Estimates for pine returns are based on the full times series (1977–2012), whereas estimates for *Eucalyptus* returns are based on the series over the period for which returns are positive (1993–2012). NA, not applicable.

A MR model described by Equation 6 provides a plausible alternative to the GBM model for describing stochastic returns

$$d\pi_i(t) = \eta_i(\bar{\pi}_i - \pi_i)\pi_i dt + \sigma_i \pi_i dz_i \qquad (9)$$

where n is the speed of reversion back to the mean (and is expected to be positive), $\bar{\pi}$ is the mean return, and the variance parameter (σ) is directly comparable to the value from the GBM model.

Following Dixit and Pindyck (1994), the MR models were estimated in pairwise fashion using a seemingly unrelated regression (SUR) model of differenced returns

$$\pi_{i,\,t} - \pi_{i,\,t-1} = a_i + b_i \pi_{i,\,t-1} + \sigma_i \epsilon_i, \qquad i = \text{pine, eucalyptus} \qquad (10)$$

Estimates for reversion speed are defined as $\eta_i = -b_i$, the long-run revenue mean of revenue is defined as $\pi_i = -a_i/b_i$, and σ_i is defined as the SE of the regression. The model anticipates a positive reversion speed (otherwise the revenue series would be explosive). The correlation coefficients between return series are defined using the cross-equation covariance from the SUR estimation. Inspection of product price and return values for forest products indicates a structural break at the end of the 1990s (prior to this time, softwood pulpwood prices grew steadily and afterward dropped substantially). After examination of MR models for a variety of time frames, only the post-1999 series provided significant positive reversion speeds across all commodities (Table 5). Model estimates indicate that reversion speeds are higher for *Eucalyptus* than for other commodities, i.e., there is a stronger tendency to return to the mean for *Eucalyptus*, and the correlation between pine and *Eucalyptus* returns is estimated to be 0.17.

Real Options Land-Use Switching

To construct the real options model for land-use switching using the GBM model, we start with the parameter estimates in Table 4 and modify them to reflect a set of scenarios. We adopt the average estimate of return variance parameter from the estimated models (0.11 for pine and 0.46 for *Eucalyptus*) showing a substantially higher return variance for *Eucalyptus.* The drift parameter is set at 0 for pine returns, assuming that markets have adjusted to the point where plantation returns will no longer drift downward (recall that

Table 5. Estimates of MR stochastic return model processes for Eucalyptus versus crop and *Eucalyptus* versus planted pine returns using data for 2000–2011.

	Eucalyptus versus crop composite				*Eucalyptus* versus planted pine			
	Symbol	*Eucalyptus*	Symbol	Crops	Symbol	*Eucalyptus*	Symbol	Pine
Long-run production profit	π_e	32.66	π_c	146.14	π_e	34.15	π_p	39.84
Reverting speed	η_e	0.0467*	η_c	0.021*	η_e	0.036*	η_p	0.0059*
Variance parameter	σ_e	0.40	σ_c	1.48	σ_e	0.404	σ_p	0.064
Correlation parameter	ρ	0.81			ρ	0.17		

* Significant at 5% level.

the estimated mean value for the drift parameter was slightly negative). We assume that *Eucalyptus* returns continue to drift upward but at a more moderate rate of 0.02. The correlation coefficient is set at the mean value for the TMS zones (0.31), reflecting a positive but relatively low correlation between the returns to these two forestry options.

The base model, with drift parameters of 0.00 and 0.02 for pine and *Eucalyptus*, respectively, yields the switching boundaries displayed in Figure 8A. Landowners are motivated to switch from pine to *Eucalyptus* only where the latter's returns are substantially higher than those for pine (the upper switching boundary in Figure 8A). For example, with pine returns at \$50.00/acre, *Eucalyptus* returns would need to exceed about \$200.00/acre to result in switching. Hysteresis is clearly indicated with these switching boundaries. For example, if land use switched to *Eucalyptus* at the *Eucalyptus*:pine return pair of \$210:\$50, a subsequent reversal of land use would only result if *Eucalyptus* returns fell to nearly 0 (Figure 8A). When the return variance term for *Eucalyptus* is decreased to 0.11 (the value of the pine return variance term), the switching boundaries are much closer, as shown in Figure 8B, indicating that higher return certainty would lead to more frequent switching to *Eucalyptus.*

Switching simulations based on 100,000 Monte Carlo simulations of the stochastic return series are played out against the switching boundaries in Figure 8A, and land-use switches are recorded for each realization. A summary of switching for all 100,000 realizations yields the proportion of land managed for *Eucalyptus* at each time step. We constructed simulations across several alternative GBM models: (A) the base case described above, (B) higher initial returns for *Eucalyptus* consistent with the high *Eucalyptus* productivity case, (C) increased correlation between *Eucalyptus* and planted pine returns, (D) a reduced variance term for *Eucalyptus* returns (equal to the variance term for planted pine), and (E) a 50% reduction in the drift term for *Eucalyptus* returns (0.01). Cases A and B can be simulated based on the switching boundaries from the base model, whereas cases C, D, and E require estimating alternative models (i.e., parameters of the switching model are altered by these scenarios). The *Eucalyptus* proportion of the planted pine area for these five scenarios is shown in Figure 9, and the total area converted is shown in Figure 10.

Switching results, summarized in Figure 9, show that for the base case (scenario A), the area of *Eucalyptus* grows steadily to about 5% of planted pine area in year 10 (2022) and remains between 4 and 5% through year 30 (2042). The percentage of *Eucalyptus* remains low despite the upward drift in returns. The low percentage reflects the high upper switching boundary in Figure 8A, which reflects the high return variance associated with *Eucalyptus.* With a higher starting price for *Eucalyptus* (scenario B), switching occurs earlier in the time series, peaks at about 10% at year 8, and then drifts back toward levels simulated under the base case. Higher early adoption reflects the higher likelihood of observing price pairs above the upper switching boundary, but the higher return variance for *Eucalyptus* dominates over time. A higher correlation between the two return series (scenario C) causes simulated price pairs to be closer to the 45° line in Figure 8A, thereby reducing the probability of price pairs being outside the switching boundaries. By year 30, only about 2% of pine land is planted in *Eucalyptus* under this scenario. Lowering the variance term for the *Eucalyptus* returns (scenario D) results in a strong upward trend in the area of *Eucalyptus,* exceeding

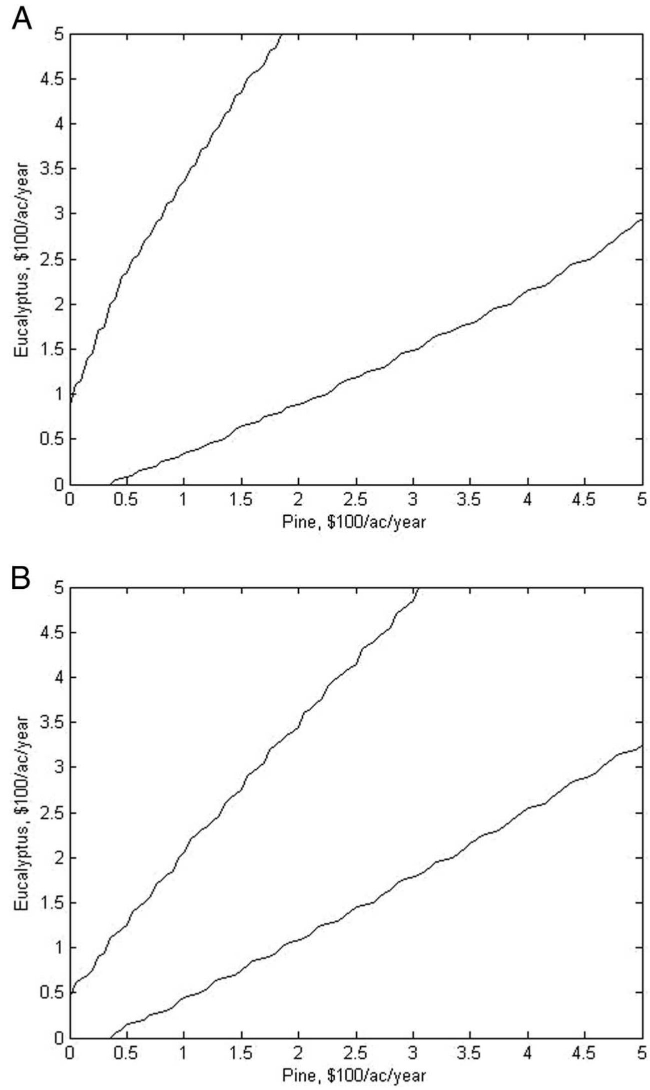

Figure 8. Switching boundaries for *Eucalyptus* and pine for the base model (A) and with the variation in *Eucalyptus* returns reduced by 50% (B).

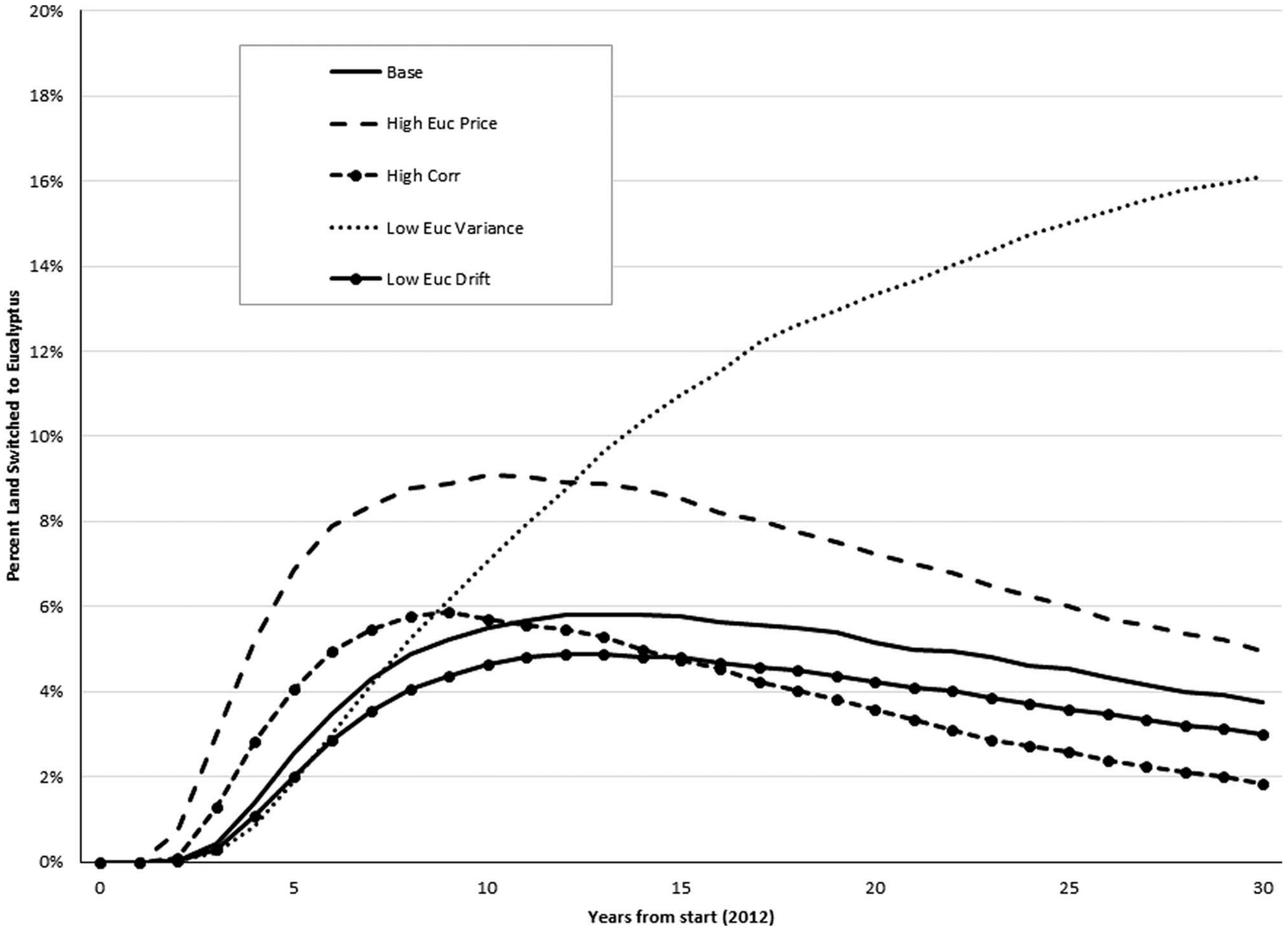

Figure 9. Projected proportion of planted pine land that switches to *Eucalyptus* from year 1 through year 30 for several scenarios using the GBM model: the base case (Base), with an elevated starting return for *Eucalyptus* (High Euc Price), a higher correlation coefficient between planted pine and *Eucalyptus* returns (High Corr), a reduced variance of *Eucalyptus* returns (Low Euc Variance), and a reduced drift term for *Eucalyptus* returns (Low Euc Drift).

15% by year 30. Recall that *Eucalyptus* is modeled with a positive drift term (0.02), whereas the pine trend term is set to 0; thus, lowering the variance term for *Eucalyptus* returns allows the trend, i.e., an increasing spread between *Eucalyptus* and pine returns, to be more dominant in the projected return series, resulting in an increasing rate of land-use switching. Reducing the drift term by 50% lowers adoption of *Eucalyptus* by about 20%.

We also simulated switching with the MR model, first using the base case defined by parameters in Table 5 and then a set of model variants. Switching behavior is much less variable with the MR model (Figure 11). With use of average return values (pine = \$40 and *Eucalyptus* = \$34) and parameters from Table 5, about 9% of the planted pine area converts to *Eucalyptus*, and this proportion is maintained throughout the simulation period. When the *Eucalyptus* average return is increased to \$40 (the same as for pine), about 30% of the planted pine forest area switches to *Eucalyptus*. Model variants with higher return correlations do not lead to substantial departures from the base MR model in terms of total area converted.

A mapping of potential adoption, which is based on the conversion proportions from the GBM switching model and the current distribution of prices and land uses (Figure 12), indicates that conditions are most favorable for *Eucalyptus* in the western part of the study area. The projected area of *Eucalyptus* exceeds 20,000 acres for several counties stretching from coastal Alabama through Louisiana. Another area of high adoption is projected for the upper coastal plain in Georgia.

Discussion and Conclusions

Our comparison of returns to *Eucalyptus* with those of other rural land uses indicates potential for the commercial adoption of FT *Eucalyptus* in the southeastern United States. FT *Eucalyptus* could provide returns comparable to those of planted pine forests, especially in the western part of the Southeast (Texas, Louisiana, and Mississippi). This competitive position derives from strong growth in real hardwood pulpwood prices over the past two decades. In contrast, high returns to cropland would generally preclude transition to *Eucalyptus*: current crop returns currently exceed *Eucalyptus* returns by an order of 3–5 times.

Although hardwood prices and potential returns to *Eucalyptus* plantations have grown, real softwood pulpwood prices and returns to pine plantations declined from peak levels in the late 1990s and have leveled off, making returns to the two uses comparable. A decision to convert from pine to FT *Eucalyptus* would depend not only on these return comparisons but also on the conversion costs and the return risk associated with the two land uses. The implied return variance for *Eucalyptus* has been higher than that for pine, and our real options analysis indicates that land-use switching estimates

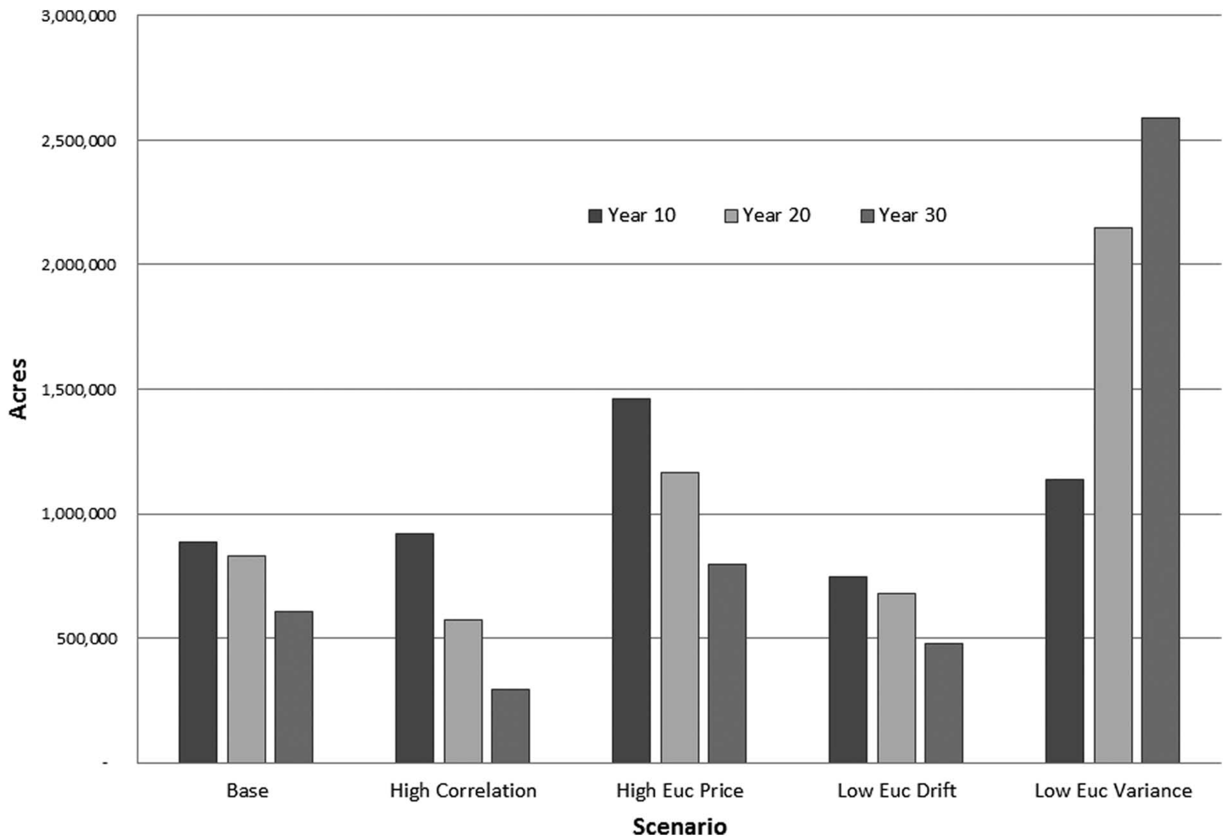

Figure 10. Projected area of *Eucalyptus* plantations by GBM scenario: (A) base case (Base), (B) higher initial returns for *Eucalyptus* (High EUC Price), (C) increased correlation between *Eucalyptus* and planted pine returns (High Correlation), (D) reduced variance term for *Eucalyptus* returns (equal to variance term for planted pine) (Low EUC Variance), and (E) 50% reduced drift term for *Eucalyptus* returns (Low Euc Drift).

are sensitive to the model used to characterize future returns and variances.

Simulations based on the GBM model, which allows for a continued upward drift in *Eucalyptus* returns, results in a conversion of about 5% of planted pine forest area (about 0.8 million acre) to *Eucalyptus* in year 30. Reflecting differences in its formulation, the MR model generates different projections: for the base case, about 9% of planted pine area would switch to *Eucalyptus* (roughly 1.4 million acres). The MR model defines a higher degree of certainty regarding future returns, and this is reflected in the higher rates of land-use switching over time. Variants of both models indicate that adoption of *Eucalyptus* is sensitive to return variance: lowering return variance parameters for *Eucalyptus* strongly increases adoption, especially with the GBM model formulation, but is less sensitive to estimates of return correlations between pine and *Eucalyptus*.

How should these results be interpreted in terms of plausible future conditions? First, our analysis indicates that *Eucalyptus* is potentially competitive with planted pine management over a range of future conditions. Results further indicate that although *Eucalyptus* may be competitive in terms of expected returns, return variance and conversion costs will limit the degree to which land is actually converted. Our two empirical models that simulate future returns under base case conditions, project between 0.8 million acres (the GBM model) and 1.4 million acres (the MR model) of *Eucalyptus* in year 30. The GBM base model describes a case in which returns to *Eucalyptus* drift upward, whereas returns to planted pine follow a random walk, consistent with a future in which the demand for hardwood material continues to grow relative to the supply (i.e., hardwood scarcity increases). This might be consistent with a scenario in which mild expansion in demands for bioenergy feedstocks steadily increased the demand for hardwoods. However, under such a scenario, we might also expect the return variance for hardwoods to decrease as demand strengthened. If this were the case, then a more substantial switching to *Eucalyptus* could result. This is clearly demonstrated by the doubling of *Eucalyptus* adoption with the variant of the GBM model for which the return variance for *Eucalyptus* is reduced by 50%. Other variants of the models that adjust starting returns and variance indicate that plausible shifts in key market parameters could lead to strong shifts in land-use outcomes.

Our analysis assumes that forest areas likely to switch would be limited to the current area of planted pine because this is the portion of the region's forests that has demonstrated economic feasibility for tree plantations. Although this is the largest forest management type in the study area, the estimate of available area may be conservative. If we assumed instead that the eligible area also included the area of naturally regenerated pine (Wear et al. 2013 find high probabilities of planting after harvests of this forest type), then the total eligible area would shift from about 16 million acres to about 27 million acres. Applying the proportions of switching from our two base models would shift the projected

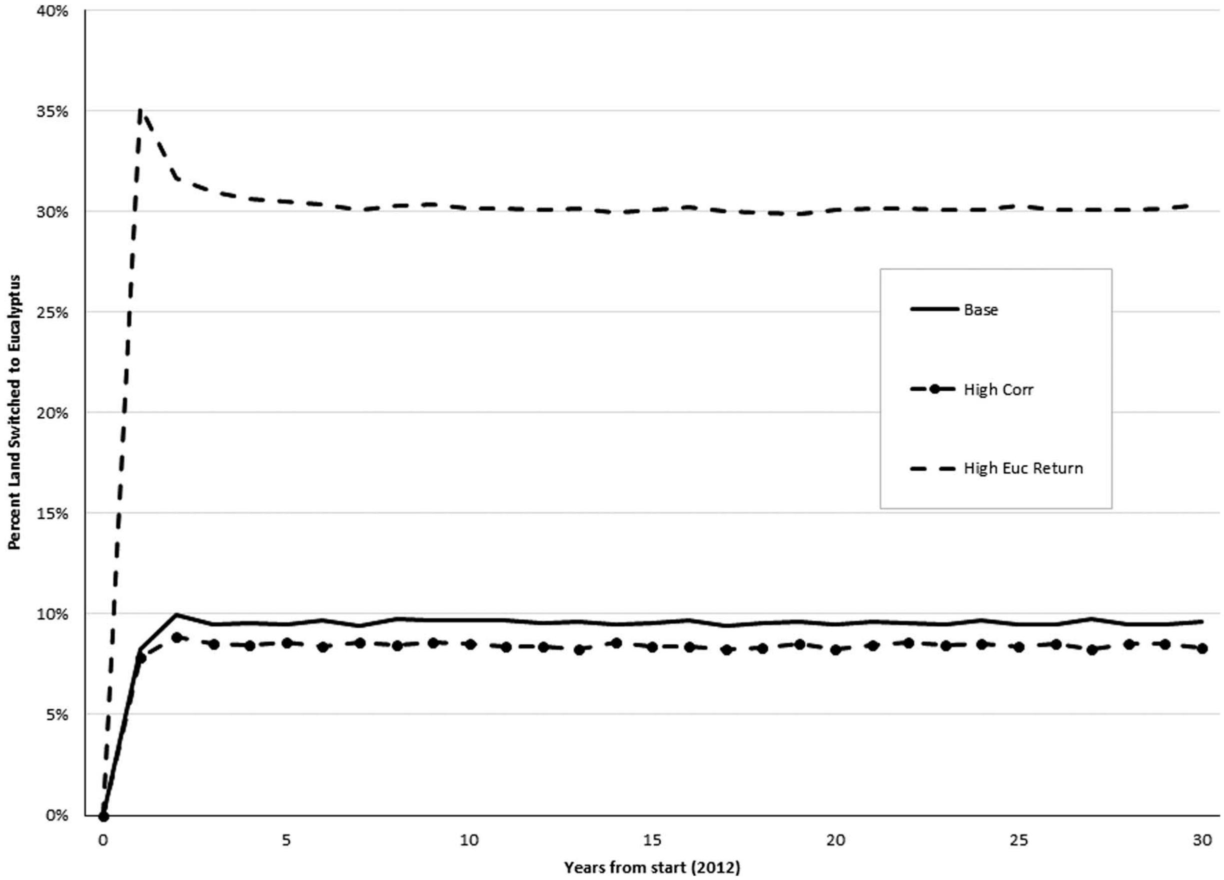

Figure 11. Projected proportion of planted pine land that switches to *Eucalyptus* from year 1 through year 30 for several scenarios of the MR model: the base case (Base), with an elevated starting return for *Eucalyptus* (High Euc Return), and a higher correlation coefficient between planted pine and *Eucalyptus* returns (High Corr).

area of adoption from a range of 0.8–1.4 million acres to between 1.35 and 2.75 million acres.

Our analysis is based on several assumptions about market futures and risk that influence return variances. One especially important assumption is that the freeze tolerance conferred by the FT *Eucalyptus* will be successful in preventing substantial freeze damage to planted trees within the study area (plant hardiness zone 8b and higher). If, instead, FT *Eucalyptus* damage rates prove higher than those for pine, then *Eucalyptus* return variances would be higher. A higher return variance would reduce adoption of *Eucalyptus* as demonstrated by our sensitivity analyses. In addition, this study assumes that productivity is essentially uniform across the southeastern United States. This seems appropriate given the novelty of FT *Eucalyptus,* but incorporating location-specific productivity and damage functions could provide additional insights into the likely location of future *Eucalyptus* plantations. Another unknown is the actual cost of the FT *Eucalyptus* seedlings. According to our analysis, the conversion costs between land uses could have a discernible effect on the area that would ultimately switch. An additional source of risk and one that extends well beyond the scope of this study is the risk of some public backlash against the planting of genetically modified trees. This societal risk could affect investment choices in the same fashion as biophysical risk; i.e., increased return variance would reduce the rate of adoption.

In addition to its treatment of risk, our analysis adopts assumptions regarding landowner decisionmaking and market structure that should be considered when one evaluates the results. Landowners are modeled as risk-neutral decisionmakers evaluating options that address uncertainty about future returns. Whereas this seems appropriate for a sector-wide analysis, alternative risk preferences could be imposed. For example, risk aversion might lead to less investment in *Eucalyptus* due to its inherent risk attributes, although more diversification among land uses could result as a risk hedging strategy. In addition, the analysis applies landowner choice models to a region's forestry sector, assuming exogenous pricing. This seems reasonable for relatively low levels of adoption, especially given the degree of uncertainty surrounding the novelty of FT *Eucalyptus,* but as adoption increased, price feedbacks through shifting fiber supplies would arise. Both risk treatment and market-level (price-endogenous) analysis of return generation define areas for additional research.

Whereas our projections are not meant to be precise predictions of the area of *Eucalyptus* adoption, they do demonstrate that under current conditions, a risk-neutral and profit-maximizing landowner could choose to adopt *Eucalyptus* as a preferred land use. The extent of that adoption will depend on the future of market prices for various timber products and on the demonstrated productivity and certainty of production from available *Eucalyptus* seedlings. An important unknown is the extent to which wood-based bioenergy production might grow in the United States, and the implications for future demands for all timber products. Our findings indicate that FT *Eucalyptus,* if granted nonregulated status, could play a role in the development of future markets.

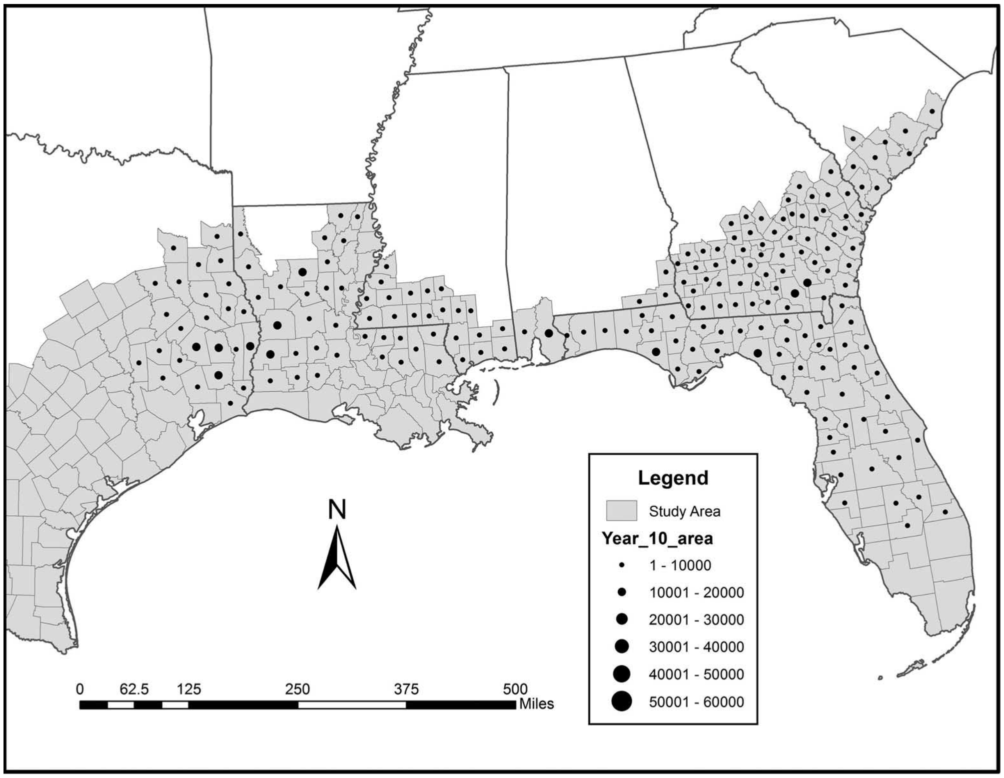

Figure 12. Forecasted area of *Eucalyptus* in the southeastern United States at year 10 using the base GBM model and separate starting returns of each TMS region.

Endnote

1. For more information, see www.nass.usda.gov/.

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