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Impacts of Climate Change on Economics of Forestry and Adaptation Strategies in the Southern United States

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This article analyzes the impacts of different levels of forest productivity scenarios, disturbance risk, and salvageable rates resulting from climate change on the economics of loblolly pine in the southern United States. Potential adaptation strategies examined include reduction in planting density and use of slash pine instead of loblolly pine. Economic returns are most sensitive to changes in disturbance risk and productivity changes as compared with the salvage rate, planting density, or species selection. Loblolly pine with low planting density economically outperforms high-density loblolly pine. Slash pine is generally a less viable option compared with loblolly pine in most cases.

Key Words: adaptation strategies, climate change, disturbance risk, land expectation value, salvage

JEL Classifications: Q00, Q23, Q54

Climate change is expected to significantly affect growing conditions for forests in the southern United States. Climate models, which have seen tremendous advances in precision and predictive power, are unambiguously predicting that the Earth's temperature will increase in the 21st century (Christensen et al., 2007). Surface air temperatures are expected to rise between 2°C and 3°C in the southern United States and up to 5°C in the northern region in North America (Christensen et al., 2007). Average annual precipitation is also expected to change depending on location with the northern United States becoming wetter and the Southwest becoming drier (Karl, Melillo, and Peterson, 2009).

Persistent changes in temperatures, concentration of atmospheric carbon dioxide (CO_2), and precipitation patterns are likely to affect forest productivity and thus the supply of timber (Huang et al., 2011). The secondary effects of climate change, including increased severity of disturbances such as wildfires and pest outbreaks (McNulty, 2002; Stanturf, Goodrick, and Outcalt, 2007) and hurricanes (Nordhaus, 2010) are also expected to affect forest productivity and important forest-related ecosystem services.

The southern United States comprises 39% of U.S. timberland and provides 57% of total volume of roundwood products harvested nationally (Smith et al., 2009). Sixty-eight percent of private timberlands (49 million hectares)

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are owned by nonindustrial private forest (NIPF) landowners (Smith et al., 2009). Therefore, changes in climatic conditions may have a significant impact on the economics of timber production.

In light of climate change, attempts to model the economic implications on the overall southern United States' forest sector have been explored by Perez-Garcia et al. (2002) and White, Alig, and Haight (2010). At the forest landowner's level (hectare basis), information about changes in the land expectation value (net rents resulting from timber benefits) is limited. Climate change is likely to impact forest productivity, yet the direction and magnitude of change cannot be accurately determined because factors such as precipitation, temperature changes, and atmospheric conditions are changing simultaneously (Medlyn, Duursma, and Zeppel, 2011). Although increased atmospheric CO_2 levels increases photosynthesis rates favoring tree growth (Wertin, McGuire, and Teskey, 2010), other factors such as increased abiotic disturbances may likely affect forest productivity negatively (Chmura et al., 2011).

The purpose of this article is to assess some of the economics of forestry in loblolly pine (*Pinus taeda*) stands under the risk of disturbances resulting from climate change. Loblolly pine is a fast-growing species, widely distributed in the southern United States (Schultz, 1997). Specifically we explore: 1) the effect of potential changes in forest productivity coupled with increased disturbances resulting from climate change on the expected economic returns and optimal rotation age for southern NIPF landowners; 2) the impact of silvicultural strategies such as managing tree density to ameliorate the impact of natural disturbances on optimal forest management; and 3) the effect of more resistant tree species to natural disturbances on optimal forest management. Our approach focuses on maximizing economic revenues related to timber production because the majority of the southern U.S. forest landowners harvest trees for commercial purposes (Smith et al., 2009) and economic benefits obtained resulting from forest harvest motivates landowners to provide nontimber activities (Hanley et al. 2012).

Ecological Impacts of Climate Change on Forestlands

Carbon Dioxide and Temperature

Increased CO_2 concentrations and temperature would increase tree photosynthesis and growth (Ainsworth and Long, 2005). For example, Forest–Air–CO_2–Enrichment experiments in different sites worldwide predict an increase of 23–28% in tree productivity through 2050 in response to increased levels CO_2 (Kallarackal and Roby, 2012). However, elevated temperatures may cause increased respiration and limitations of the minerals in the soil leading to reduced responses in growth (Kallarackal and Roby, 2012).

In the southern United States, different studies have postulated an increase in pine forest productivity as a result of the effect of elevated atmospheric CO_2 but dissimilar results with elevated temperatures. Teskey (1997) found that net carbon (C) assimilation was enhanced, and branch growth and leaf area of 22-year-old loblolly pine increased under elevated CO_2 levels for a period of three years, but elevated temperatures had an insignificant impact on C assimilation and growth. Wertin, McGuire, and Teskey (2010) found that increased temperature and CO_2 would positively impact net photosynthesis of one-year-old loblolly pine seedlings, whereas increased temperature would have an insignificant impact on net photosynthesis. An increase in future forest productivity by approximately ten to 20% is expected in this region, although a substantial reduction in precipitation would definitely decrease forest productivity (Robert Teskey, personal communication, University of Georgia, June 2012).

Other studies have suggested that increased temperatures could negatively affect forest productivity (Chmura et al., 2011) or have negligible effects at the regional level (Huang et al., 2011). McNulty, Vose, and Swank (1996) claimed that increases in temperatures between 2°C and 7°C could dramatically decrease net primary productivity of loblolly pine across the southern United States by as much as 60% (Florida) and as little as 15% (Virginia).

Water Availability

Forecasted precipitation is expected to vary significantly across the South (McNulty et al., 2013). Wertin, McGuire, and Teskey (2012) claimed that decreases in soil moisture resulting from changes in precipitation regimes may also eliminate the positive effects of increased CO_2, becoming the environmental limiting factor for C gain and tree growth. On the other hand, increased precipitation would result in increased forest growth of loblolly pine (Wertin, McGuire, and Teskey, 2012).

Forest Dynamics and Disturbance Events

Climate change is also a driver of other phenomena that are likely to impact forestlands, perhaps catastrophically. Rising CO_2 levels may affect long-term forest dynamics by changing composition in the understory community and accelerate successional development (Kallarackal and Roby, 2012). Elevated temperatures may exacerbate droughts that can leave trees highly vulnerable to damage by insects, pathogens, and wildfires further reducing forest productivity (Chmura et al., 2011)

Climate change is likely to lead to a higher frequency of intense hurricanes in the Atlantic basin (Nordhaus, 2010), which are one of the major natural disturbances to forest ecosystems in the southern United States (Wang et al., 2010). After a hurricane, approximately ten percent of the total annual C sequestered by affected forests in the United States can be lost as a result of downed biomass, and this, in turn, can increase wildfire hazard as a result of the accumulation of dead fuels (McNulty, 2002). Also, the likelihood and intensity of pest outbreaks would be exacerbated by tree damage and reduced tree vigor after a hurricane (Stanturf, Goodrick, and Outcalt, 2007).

Economic Impacts of Climate Change on Forestlands

Extant research suggests that the impacts of climate change on forest sectors will redound on consumers and producers dissimilarly (Hanewinkel, Hummel, and Cullmann, 2010; Perez-Garcia et al., 2002). Economic modeling of climate change has generally predicted an increase in timber production leading to lower timber prices (Kirilenko and Sedjo, 2007). As a result, forest landowners are likely to experience a decrease in land rents (Hanewinkel, Hummel, and Cullmann, 2010), whereas wood consumers are expected to see an increase in consumer surplus (Kirilenko and Sedjo, 2007).

In the United States, Alig, Adams, and McCarl (2002) indicated a reduction in forest landowners' welfare as a result of a reduction in timber prices, and economic gains for consumers, under climate change. Perez-Garcia et al. (2002) suggested an overall economic welfare gain in the southern United States' forest sector by 2040. They determined that timber prices will fall up to approximately 3.5%, producers' welfare losses will be between \$5.4 and \$4.2 billion (1993 U.S. dollars), and the consumer sector (mills) will expand their production and meet the higher demand generated by lower forest product prices, increasing consumer welfare between \$0.9 and \$9.7 billion. However, White, Alig, and Haight (2010) claimed that this region is projected to have total welfare losses.

Significant economic losses are caused by disturbance events on forests. For example, hurricanes Katrina and Rita caused a total loss of U.S. \$2–3 billion in 2005 in the United States (Stanturf, Goodrick, and Outcalt, 2007). Estimates of average annual hurricane damage are expected to increase to 0.08 percent of U.S. gross domestic product as a result of climate change (Nordhaus, 2010), implying similar increases in forest-related hurricane damages.

Model Specification

To conceptualize the impacts of climate change on forestland revenues, we apply a Faustmann framework. The Faustmann (1995) model has been widely used in different applications to determine the optimal rotation age of a forest stand (Buongiorno, 2001) despite its drawbacks. The basic Faustmann model does not account for stochastic disturbance events inherent to forestlands such as fire, hurricane, and pests. Although other approaches exist such as dynamic programming or optimal control theory to model the optimal rotation age problem or the impacts of natural disturbances on the optimal forest management regime resulting from climate change (Goetz et al., 2013), solving these complex stochastic problems would require one to know about future parameters such as timber prices, regeneration costs, disturbance risk, etc., which may be impractical (Chang, 1998). Thus, we use an extension of the Faustmann model that has captured how disturbance events arrive during a rotation and impact the forest landowners' harvest decision. This model was developed by Reed (1984) and has been extensively used in applied forest economics studies (Amacher, Malik, and Haight, 2005; Susaeta, Alavalapati, and Carter, 2009). Table 1 describes the different parameters used in the model.

Following Reed (1984), we assume that the disturbance event follows a homogenous Poisson process that occurs independently at the same average probability λ per unit of time. Let X denote a random variable that follows an exponential distribution. The probability that the forest stand is affected by a disturbance event before reaching the financially optimal rotation age T is $Pr(X < T) = 1 - e^{-\lambda T}$. At the optimal rotation age T, the forest stand is not affected by a disturbance event and the stand is harvested with a probability $Pr(X = T) = e^{-\lambda T}$.

The economic rents Y will depend on two states of the world. In the first state of the world (U_1), a disturbance events arrives at time X before the optimal rotation age of the forest stand and the forest landowner salvages a proportion $g(X)$ of the forest with mean .. and incurs the regeneration costs associated with the establishment of a new forest stand. In the second state of world (U_2), the landowner will harvest the forest stand at the optimal rotation age T without being affected by a disturbance event and replants a new forest stand with a regeneration cost X. Although the regeneration cost after a disturbance event might be higher than the regeneration cost when a disturbance event does not arrive, c is assumed, for simplicity, fixed and independent of salvage (Amacher, Ollikainen, and Koskela, 2009). Considering a forest stand that produces different forest products (i.e., for sawtimber, chip-and-saw, pulpwood, and biomass bioenergy markets; see Table 1), the current Y_n associated with a time X_n between successive stand harvest/destruction for n rotations for the first rotation are:

$$(1)\qquad Y_n = \begin{cases} U_1 = \bar{g}(X_n)\left[P_{sw}V_{sw}(X_n) + P_{cns}V_{cns}(X_n) + P_{pw}V_{pw}(X_n) + P_{bm}V_{bm}(X_n)\right] - c \;\forall\; X_n < T \\ U_2 = P_{sw}V_{sw}(T) + P_{cns}V_{cns}(T) + P_{pw}V_{pw}(T) + P_{bm}V_{bm}(T) - QUOTE\, c \quad iff \quad X_n = T \end{cases}$$

The first line of Equation (1) outlines the situation in which a landowner receives revenues from salvaging undamaged trees if the disturbance event arrives at time period X before the optimal rotation age and replants a new forest stand with a regeneration cost c. It represents the net economic returns with partial destruction of the forest stand assuming a risk of a disturbance event in every year. The second line of Equation (1) illustrates the case where the disturbance event does not arrive before harvest. Now the landowner obtains revenues from harvesting the stand at the optimal rotation age T and incurs the cost of replanting to start a new rotation. This process continues ad infinitum; thus, the sum of the expected net economic rents resulting from harvesting at the rotation age or salvaging the forest stand of equal successive rotations in perpetuity equals land expectation value LEV. As stated previously (Table 1 and Equation [1]), this model considers only timber benefits, i.e., different forest products such as sawtimber, chip-and-saw, and pulpwood, and the use of logging residues for biomass for bioenergy, each of them with different volume yields and prices. Other variations of this approach have also considered nontimber benefits such as payments for carbon sequestration (Stainback and Alavalapati, 2004),

Table 1. Description of the Different Parameters of the Reed Model

Parameters	Description
λ	Probability of arrival of a disturbance event in any given year
X	Time between successive disturbance events
$g(X)$	Proportion of the stand that is salvaged after a disturbance event at time X
V_{sw} (T)	Merchantable volume of sawtimber at time T
V_{cns} (T)	Merchantable volume of chip-and-saw at time T
V_{pw} (T)	Merchantable volume of pulpwood at time T
V_{bm} (T)	Merchantable volume of biomass for bioenergy at time T
P_{sw}[a]	Stumpage price for sawtimber
P_{cns}[a]	Stumpage price for chip-and-saw
P_{pw}[a]	Stumpage price for pulpwood
P_{bm}	Price for woody biomass for bioenergy
T	Optimal rotation age
c	Regeneration cost
r	Discount rate
Y	Forest landowner's net economic rent
$LEV(T)$	Land expectation value at time T

[a] Sawtimber (stem diameter breast height = 29.2 cm; top diameter = 17.8 cm), chip-and-saw (stem diameter breast height = 19.1cm; top diameter = 15.2 cm), pulpwood (diameter breast height = 11.4 cm; top diameter = 7.6 cm).

which is beyond the scope of this article. We can model *LEV* as:

$$LEV(T) = \frac{E(exp^{-rX}Y)}{1 - E(exp^{-rX})} \tag{2}$$

In Equation (2), Y represents the net revenues defined in Equation (1) and X—the waiting time between successive destruction of the stand resulting from stand harvest or disturbance event—is also the length of the rotation. We assume the same rotation length ($X_1 = X_2 = \ldots = X_n = X$) and expected present timber value for all rotations ($E(exp^{-rX_1}Y_1) = E(exp^{-rX_2}Y_2) = \ldots = E(exp^{-rX_n}\ Y_n) = E(exp^{-rX}Y)$) (Reed, 1984). Following Reed (1984), the expression for the expected term $E(exp^{-rX})$ in the numerator and denominator of Equation (2) can be described as:

$$\begin{aligned} E\left(exp^{-rX}\right) &= \int_0^X e^{-rX} dF_x(t) \\ &= \int_0^T exp^{-rX}\lambda exp^{-\lambda X}dX + exp^{-rT}exp^{-rT} \\ &= \frac{\lambda + rexp^{-(\lambda+r)T}}{(\lambda+r)} \end{aligned} \tag{3}$$

$$1 - E\left(exp^{-rX}\right) = \frac{r(1 - exp^{-(\lambda+r)T})}{r+\lambda} \tag{4}$$

The numerator in Equation (2) represents, for the first rotation, the sum of the net present economic returns when a forest stand is harvested at the optimal rotation age and salvaged after a disturbance event associated with their respective probabilities. Thus, the numerator in Equation (2) becomes:

$$E\left(exp^{-rX}Y\right) = exp^{-rT}U_2exp^{-\lambda T} + \int_0^T \lambda exp^{-rT}U_1exp^{-\lambda X}dX \tag{5}$$

Finally, substituting Equations (4) and (5) into Equation (2), we obtain Reed's land expectation value (Reed, 1984):

$$LEV(T) = \frac{\lambda + \mathrm{r}}{\mathrm{r}[1 - e^{-(\lambda+\mathrm{r})\mathrm{T}}]}\left\{exp^{-rT}U_2exp^{-\lambda T} + \int_0^T \lambda exp^{-rT}U_1exp^{-\lambda X}dX\right\} \tag{6}$$

Note that time T that maximizes the *LEV* in Equation (6) is the optimal rotation age. The mathematical proofs of the first-order conditions for the different parameters and their impacts on the optimal rotation age can be found in Amacher, Ollikainen, and Koskela (2009) and Reed (1984).

Model Application to the Southern U.S.' Forests

Loblolly pine is the most important commercial species native to the southern United States occupying more than 13 million ha (Schultz, 1997). Loblolly pine is naturally distributed from the east of Texas through the Gulf States to Florida, and northward to Delaware, and also found in southeastern Oklahoma, central Arkansas, and southern Tennessee (Schultz, 1997). We assume that the following forest products are obtained from a hectare of loblolly pine stand: sawtimber, chip-and-saw, pulpwood, and woody biomass for bioenergy (harvest residues such as branches, tops, and foliage). A growth and yield model developed by the University of Georgia Plantation Management Research Cooperative (Harrison and Borders, 1996) is used to generate merchantable volume and woody biomass for bioenergy of managed loblolly pine stands. The presence of bioenergy markets has been shown to shorten modestly the optimal rotation age (shorter) and increase the profitability of forest lands (Susaeta, Alavalapati, and Carter, 2009). Tree planting density and intrinsic site index are, respectively, 1600 trees/ha^{-1} and 20 m at base age 25 years.

We simulate different scenarios to account for potential changes in forest productivity resulting from climate change. Given the imperfect knowledge of climate dynamics, risk of disturbances, and how ecosystems respond to changes, the uncertainty of climatic risk makes it difficult to give highly accurate estimates. We assume a ten percent to 20% increase in future forest productivity if water availability is not limited; otherwise, a negative impact on forest growth is expected (Robert Teskey, personal communication, University of Georgia, June 2012). The scenarios that cover the potential benefits or negative effects of climate change on forest growth are defined in Table 2. Our estimate of 20% increase in forest productivity is close to the projections postulated by Kallarackal and Roby (2012). Equation (6) is applied to each scenario to gauge the effect of climate change on land values and optimal rotation ages. Because the forest stand is harvested when the land value reaches its maximum value, and this is continuously affected by the arrival of a catastrophic event, we do not impose any restriction on the optimal rotation age.

Table 2. Different Forest Productivity Scenarios under Climate Change and Values for Parameters of the Reed Model

Scenario	Description
Scenario A	No changes in forest productivity.
Scenario B	20% increase in loblolly pine growth
Scenario C	10% increase in loblolly pine growth
Scenario D	20% decrease in loblolly pine growth
Scenario E	10% decrease in loblolly pine growth
P_{sw}	\$29/m^{-3}
P_{cns}	\$19/m^{-3}
P_{pw}	\$11/m^{-3}
P_{bm}[a]	\$2/ton^{-1}
c[b]	\$1025/ha^{-1}
r	0.04
λ	0.01, 0.02, 0.03, 0.04, 0.05
g	0.2, 0.3

[a] Typically, the commercialization of forest biomass is in metric tons.
[b] Site preparation = \$647/ha–1, weed control = \$163/ha–1, planting = \$135/ha–1 (\$0.06/plant–1, 1600 trees/ha–1), seedling = \$80/ha–1 (\$0.05/plant–1, 1600 trees/ha–1).

Table 2 also shows the different values for all parameters used in our analysis. Southern average stumpage prices for sawtimber (P_{sw}), chip-and-saw (P_{cns}), and pulpwood (P_{pw}) are obtained from Timber Mart South (2013). Woody biomass for bioenergy is a nascent market and is considered a low-value material (Jeuck and Duncan, 2009). Furthermore, the demand for woody biomass for bioenergy has fallen as a result of steady fossil fuel prices (Florida Forestry Association—Pines and Needles, 2013). The price for biomass for bioenergy (P_{bm}) is in the range used by other studies such as Dwivedi et al. (2012). Regeneration costs associated with the establishment of loblolly pine stands are procured from Barlow and Dubois (2011). These costs at the moment of stand establishment include site preparation, weed control, planting, and seedling. For simplicity we have not included fertilization or weed control activities after planting.

The probability of disturbance risk λ encompasses catastrophic disturbances likely to increase as a result of climate change such as hurricanes, wildfires, and pest outbreaks. The probability of risk can also be interpreted as the arrival rate of a disturbance event. We assume that the expected rate of disturbance disturbances in forests is 0.01 annually such that the disturbance arrives every 100 years. This assumption is consistent with extant research (e.g., Amacher, Malik, and Haight, 2005; Parisi and Lund, 2008; Stainback and Alavalapati, 2004). For example, Amacher, Malik, and Haight (2005) assumed an initial fire arrival rate of 0.02. Stainback and Alavalapati (2004) assume a generic disturbance arrival rate between 0.00 and 0.04. The location-specific arrival rate based on historic major hurricanes (i.e., category three or greater) ranges from 63 years ($\lambda = 0.016$) and 265 years ($\lambda < 0.01$) (Parisi and Lund, 2008) in the United States and between 23 years ($\lambda \approx 0.04$) and 37 years ($\lambda \approx 0.03$) in the southern United States. For our analysis we consider a range between 0.01 and 0.05 for the probability of disturbance risk (Table 2), reflecting the influence of climate change on increased disturbance risk.

Our model also allows for postdisturbance timber salvage. The proportion of salvaged timber will depend on the severity of damage, access to the forest stand, and value of the timber (McNulty, 2002). Our range of simulation is consistent with recent literature. Stanturf, Goodrick, and Outcalt (2007) report a salvage rate of 37% of the timber volume after hurricane Hugo struck South Carolina as a category four storm in 1989. Prestemon and Holmes (2004) have also reported salvage rates between 20% and 30% after a hurricane event.

Adaptation Strategies

Forest landowners are expected to play an important role in the adaptation of climate change impacts (D'Amato et al., 2011). Adaptation strategies include options that help ecosystems assimilate to changing climatic conditions (Millar, Stephenson, and Stephens, 2007). These strategies include creating resistance, promoting resilience, and enabling forests to respond to change (Millar, Stephenson, and Stephens, 2007). Adaptation strategies consider the creation of structurally complex forest ecosystems such as mixed forest species stands and tree sizes (D'Amato et al., 2011). They also include options such as planting forest species more resistant to climate change, consideration of stock quality and timber salvage, and relocation of plantations (Sedjo, 2010). Particularly in the southern United States, internalizing the monetized social benefits of climate change adaptation strategies becomes critical for landowners to adequately plan forest management activities. We have defined two climate change adaptation strategies for increased disturbance events, which are defined subsequently.

Stand Density Management

Reduced tree density decreases the accumulation of forest fuels that influence wildfires and tree mortality (e.g., Amacher, Malik, and Haight, 2005; Stephens, Collins, and Roller, 2012). It also reduces susceptibility to insect attacks (Sala et al., 2005). The reduction of forest fuels not only decreases the damage of a fire, but also increases timber salvage (Amacher, Malik, and Haight, 2005). We consider a decrease in tree planting density to 1111 trees/ha^{-1} (vs. the 1600 trees/ha^{-1}, spacing of 2.5 m), which reflects a range of tree spacing between 3.5 and 3.6 m and 3.3 and 3.4 m for loblolly pine stands at ages 25 and 20 years, respectively. By reducing the tree density, we postulate that the severity of wildfires may be reduced, and more undamaged timber can be salvaged. Despite the fact that lower tree density may favor the susceptibility of a forest stand to hurricane damage (Krista et al., 2010), we remain in a range of tree spacing pointed out by Stanturf, Goodrick, and Outcalt (2007) in which a loblolly pine stand is not damaged by hurricanes. They reported that 20-m tall loblolly pine stands with spacings of 2.5, five, and 7.5 m and 25-m tall stands with spacing of 2.5 m were undamaged with winds up to 128 km/hour^{-1}.

Tree Species Selection

Different tree species have different levels of resistance to hurricane damage. Slash pine is less susceptible than loblolly pine to breakage, uprooting, salt damage, and deterioration by insect and diseases (Barry et al., 1998). The use of slash pine allows forest landowners/managers to salvage more timber after a hurricane.

We postulate a change in planted species from loblolly to slash pine (*Pinus elliotti*). It is also a commercially fast-growing species native to the southern United States that occupies more than 4.2 million ha and is naturally distributed from eastern Texas to southern North Carolina to south–central Florida (Barnett and Sheffield, 2004). Similar to loblolly pine, we use stand growth and yield models developed by Pienaar, Shiver, and Rheney (1996) to simulate merchantable volume (sawtimber, chip-and-saw, and pulpwood) and biomass for bioenergy for slash pine stands. In general, slash pine only grows better than loblolly pine on less productive sites (site index < 18 m), whereas loblolly pine outperforms slash pine on high productivity sites (site index > 21 m) (Fox, 2004). Between site index of 18 m and 21 m, the growth between both species is equivalent (Fox, 2004).

The same stumpage prices, discount rate, level of risk, and forest productivity scenarios are assumed for both adaptation strategies. The costs of both adaptation options differ by their respective regeneration costs, which for loblolly pine with low planting density are $960/ha^{-1} (site preparation = $647/ha^{-1}, weed control = $163/ha^{-1}, planting = $93/ha^{-1}, seedling = 55/ha^{-1}) and for slash pine are $1025/ha^{-1}, the same as the initial loblolly pine management scenario. For both adaptation cases, we conduct the economic analysis initially used for a loblolly pine stand using the following forest productivity scenarios: no change in forest productivity (Scenario A), 20% increased forest productivity (Scenario B), and 20% decreased forest productivity (Scenario D) to make the reporting of significant results more manageable.

We emphasize two keys assumption of our model: 1) probability of arrival of a disturbance is not affected by density management or species selection; and 2) only undamaged timber after a disturbance event can be salvaged. In practice, intermediate silvicultural activities or changes in forest management are unlikely to have a significant effect on the probability of hurricane landfall, lightning strikes on a forest stand, or flying ashes from adjacent fires (λ remains unchanged, and increases in λ are the result of climatic changes). The use of more resistant tree species can reduce hurricane damage. Likewise, an adequate level of tree spacing can reduce fire damage. Strategies oriented to a reduction of damage resulting from a disturbance event (fewer trees will be destroyed) have a positive impact on timber salvage (greater salvageable rate) (Amacher, Ollikainen, and Koskela, 2009). Thus, we consider higher salvageable portions in the case of both adaptation strategies: g = 0.2, 0.3, 0.4, and 0.5. We assume the same site index for loblolly pine and slash pine (20 m at age 25 years). Comparisons of relative productivity between both species using growth and yield models is considered appropriate when a site index of between 18 and 21 m is chosen (Fox, 2004).

Results and Discussion

The *LEV* s for all loblolly pine scenarios are shown in Table 3. *LEV* s are very sensitive to the increased disturbance risk. Recall that the baseline level of disturbance rate is set to λ = 0.01, which exogenously affects the timber volume. Our simulation results illustrate the relationship among disturbance rate (negative relationship), forest productivity (positive relationship), and salvage portion (positive impact) on *LEV*s.

Holding $\lambda = 0.01$ and $g = 0.2$, a ten percent decrease in productivity (Scenario E) significantly reduces *LEV* by 59% compared with the baseline and a 20% decrease (Scenario D) leads to net economic losses for forest landowners. Reduction in land values resulting from disturbance risk from climate change were also reported by Hanewinkel, Hummel, and Cullmann (2010). A negative *LEV* implies that investing in timber production in itself does not become a viable economic option for forest landowners. However, a word of caution is merited. For example, after the arrival of a catastrophic event, there are stumpage price dynamics through time (for example, a long-term price enhancement resulting from inventory shortages) that can positively affect timber revenues (Prestemon and Holmes, 2010).

Table 3. *LEV*s and Rotation Ages (T) for all Loblolly Pine Productivity Scenarios, Disturbance Risks, and Salvageable Portions

		Scenario A Current Situation		Scenario B +20% Increased Productivity		Scenario C +10% Increased Productivity		Scenario D –20% Decreased Productivity		Scenario E –10% Decreased Productivity	
g	λ	LEV $/ha^{-1}	T years	LEV $/ha^{-1}	T years	LEV $/ha^{-1}	T years	LEV $/ha^{-1}	T years	LEV $/ha^{-1}	T years
0.2	0.01	544	23	1211	22	862	23	**91**	25	224	24
	0.02	**178**	22	432	21	113	22	**755**	24	**469**	23
	0.03	**875**	21	**315**	20	**607**	21	**1401**	23	**1140**	22
	0.04	**1548**	21	**1035**	20	**1303**	20	**2030**	22	**1793**	22
	0.05	**2204**	20	**1731**	19	**1980**	20	**2645**	22	**2428**	21
0.3	0.01	573	23	1246	22	896	23	**66**	25	251	24
	0.02	**126**	23	493	22	171	22	**712**	24	**422**	23
	0.03	**804**	22	**233**	21	**532**	21	**1345**	24	**1077**	23
	0.04	**1467**	21	**937**	20	**1214**	21	**1963**	23	**1717**	22
	0.05	**2113**	21	**1624**	20	**1880**	20	**2571**	22	**2346**	22

Note: Negative values in bold.

Our results indicate that when productivity increases by ten percent (Scenario C), *LEV* increases by 59%. A 20% productivity increase (Scenario B) raises *LEV* by 123%. Increasing the salvage rate from 0.2 to 0.3 but holding the disturbance at 0.01 only slightly impacts *LEV* at all productivity levels. Similar findings regarding the minimal impact of salvage portion on economic rents of loblolly pine after hurricane Hugo struck South Carolina were found by Haight, Smith, and Straka (1995).

LEV is highly sensitive to disturbance rates. All scenarios have negative *LEV*s when $\lambda > 0.02$, and only the productivity increase scenarios (B and C) show positive *LEV*s when $\lambda = 0.02$ (Table 3). The positive *LEV*s for Scenarios B and C (20% and ten percent increase in forest productivity, respectively) suggest that increases in forest productivity somewhat offset the negative effect of increased probability of risk of disturbance events resulting from climate change. For example, with no changes in productivity (Scenario A), the *LEV* decreases by 133% when λ increases from 0.01 to 0.02. In the case of Scenarios B and C, this decrease is lower: 64% and 87%, respectively. However, worse economic conditions will occur with lower forest product prices, a plausible assumption resulting from increased supply of timber resulting from better productivity conditions (Alig, Adams, and McCarl, 2002; Perez-Garcia et al., 2002) and salvage (Sohngen, Alig, and Solberg, 2010).

In general, we find lower optimal rotation ages when disturbance rates increase for the same level of salvageable portion. Similar to Stainback and Alavalapati (2004) who modeled the effect of risk on slash pine plantations in the southeast United States, increased arrival rates of disturbances lead to earlier harvest to avoid potential future damages. Also consistent with expectations, increased forest productivity leads to a shorter optimal rotation age for the same level of disturbance risk.

Loblolly Pine with Low Planting Density

The *LEV* s for loblolly pine with low planting density under different forest productivity scenarios are shown in Table 4. Higher positive *LEV* s are obtained with loblolly pine with low planting density for the same level of salvageable portions and productivity scenarios compared with those for original loblolly pine management. On average, 16% and six percent higher *LEV* s are obtained with $g = 0.2$ or 0.3 and $\lambda = 0.01$ for Scenarios A (no changes in productivity) and B (20% increase in forest productivity), respectively. With $\lambda = 0.02$, this difference becomes larger for Scenario B (23%).

Table 4. *LEV*s and Rotation Ages (T) for Loblolly Pine with Low Planting Density for Different Forest Productivity Scenarios, Disturbance Risks, and Salvageable Portions

		Scenario A		Scenario B		Scenario D	
g	λ	LEV $/ha^{-1}	T years	LEV $/ha^{-1}	T years	LEV $/ha^{-1}	T years
0.2	0.01	632	23	1283	22	14	24
	0.02	**54**	22	537	21	**615**	23
	0.03	**715**	21	**176**	20	**1225**	22
	0.04	**1354**	20	**860**	20	**1819**	22
	0.05	**1974**	20	**1520**	19	**2399**	21
0.3	0.01	662	23	1319	23	38	24
	0.02	**3**	22	599	22	**573**	24
	0.03	**647**	22	**93**	21	**1169**	23
	0.04	**1273**	21	**763**	20	**1753**	22
	0.05	**1886**	20	**1415**	20	**2327**	22
0.4	0.01	692	24	1357	23	63	25
	0.02	51	23	664	22	**529**	24
	0.03	**576**	22	**9**	21	**1112**	23
	0.04	**1190**	22	**664**	21	**1685**	23
	0.05	**1792**	21	**1304**	20	**2252**	22
0.5	0.01	724	24	1394	23	88	25
	0.02	105	23	729	23	**486**	25
	0.03	**503**	23	79	22	**1053**	24
	0.04	**1103**	22	**560**	22	**1615**	24
	0.05	**1694**	22	**1187**	21	**2172**	23

Note: Negative values in bold.

Decreased tree planting density favors the production of larger trees produced by the forest stand (more production of sawtimber and chip-and-saw than pulpwood), which in turns generates higher economic revenues for forest landowners.

Greater salvageable portions resulting from this adaptation strategy also generate greater economic returns compared with those for the original loblolly pine management. In the case of Scenario A, for $g = 0.4$, the *LEV* s are 27% and 21% greater than the *LEV* s for $g = 0.2$ and 0.3, respectively ($\lambda = 0.01$). For $g = 0.5$, the *LEV* s are 33% and 26% greater than the *LEV* s associated with $g = 0.2$ and 0.3.

Increased forest productivity conditions resulting from climate change (Scenario B) led to 12% and nine percent ($g = 0.4$) higher economic returns compared with $g = 0.2$ and 0.3, respectively ($\lambda = 0.01$). Likewise, 15% and 12% greater *LEV* s are obtained with $g = 0.5$. In relative terms, planting fewer trees under increased forest productivity conditions and with higher salvageable portions accentuates the differences in profits with higher levels of risk. In the case of $g = 0.4$ and with $\lambda = 0.02$, 54% and 35% greater *LEV* s are obtained compared with *LEV* s with $g = 0.2$ and $g = 0.3$, respectively. In the case of $g = 0.5$, 69% and 48% greater *LEV* s are obtained, respectively, compared with *LEV* s under initial parameter levels: $g = 0.2$ or 0.3.

Decreased tree planting density allows loblolly pine management to be financially attractive for landowners for higher levels of disturbance risk. Positive land values are obtained with salvageable portion $g = 0.3$–0.5 for $\lambda = 0.03$ for Scenario B (20% increase in forest productivity). Regardless of the salvageable portion, investing in loblolly pine does not become a feasible option for landowners when $\lambda > 0.01$ and forest productivity is decreased by 20% (Scenario D).

There is not a clear trend regarding the effect of increased salvageable levels on the optimal rotation age for both types of forest management, although it generally tends to delay the harvest of the forest stand (Amacher, Ollikainen, and Koskela 2009). For example, marginally longer optimal rotation ages are found when $g = 0.3$ and $\lambda = 0.02$ for loblolly pine with high planting density (compared with $g = 0.2$) and $g = 0.4$ and $\lambda = 0.02$ for loblolly pine with low planting density (compared with $g = 0.3$).

Slash Pine

Planting slash pine results in a less profitable option than loblolly pine with high planting density for the same forest productivity scenarios, hurricane risk, and salvageable portion assumptions (Table 5). In the case of Scenario A (no changes in forest productivity), 26% lower *LEV* s for slash pine are found for $\lambda = 0.01$ and $g = 0.2$ or 0.3 compared with those for loblolly pine. With better future climate conditions, the forest productivity of slash pine and loblolly pine are expected to be higher. In terms of profitability, this difference is reduced: five percent lower *LEV* s, for the 20% increased forest productivity scenario (Scenario B). Depending on the type of management and soil (for example, poorly drained soils), slash pine is expected to perform better than loblolly pine (Fox, 2004).

Higher salvageable portions ($g = 0.4$) slightly increase economic returns compared with loblolly pine with high planting density and $\lambda = 0.01$. In the case of Scenario B, with $g = 0.4$, the *LEV* is greater by one percent for slash pine compared with the *LEV* for loblolly pine with high planting density when $g = 0.2$. On the other hand, the land value for slash pine is two percent lower compared with the land value for loblolly pine when $g = 0.3$ ($\lambda = 0.01$). In the case of $g = 0.5$, the economic returns are increased by three percent and remain unchanged, respectively, compared with those for loblolly pine when $g = 0.2$ and 0.3. Likewise, with increased hurricane risk ($\lambda = 0.02$), landowners are better off planting slash pine than loblolly pine realizing 14% and 28% ($g = 0.4$ and $g = 0.5$) greater economic rents than those for loblolly pine with high planting density ($g = 0.2$). Similar ($g = 0.4$) and

Table 5. *LEV*s and Rotation Ages (T) for Slash Pine Forest for Different Forest Productivity Scenarios, Disturbance Risks, and Salvageable Portions

		Scenario A		Scenario B		Scenario D	
g	λ	LEV $\$/ha^{-1}$	T years	LEV $\$/ha^{-1}$	T years	LEV $\$/ha^{-1}$	T years
0.2	0.01	400	23	1152	22	**282**	24
	0.02	**310**	22	372	22	**924**	24
	0.03	**995**	22	**375**	21	**1552**	23
	0.04	**1665**	22	**1101**	21	**2166**	23
	0.05	**2314**	21	**1801**	20	**2770**	23
0.3	0.01	427	23	1185	22	**260**	25
	0.02	**261**	23	433	22	**885**	24
	0.03	**931**	22	**297**	21	**1500**	24
	0.04	**1586**	22	**1005**	21	**2105**	23
	0.05	**2228**	22	**1697**	21	**2699**	23
0.4	0.01	454	23	1218	22	**238**	25
	0.02	**211**	23	493	22	**846**	24
	0.03	**865**	23	**217**	22	**1446**	24
	0.04	**1506**	22	**908**	21	**2040**	24
	0.05	**2137**	22	**1586**	21	**2628**	24
0.5	0.01	481	23	1251	22	**216**	25
	0.02	**161**	23	554	22	**807**	25
	0.03	**796**	23	**132**	22	**1393**	24
	0.04	**1425**	23	**809**	22	**1975**	24
	0.05	**2046**	22	**1474**	21	**2554**	24

Note: Negative values in bold.

12% higher ($g = 0.5$) *LEVs* for slash pine are found compared with those for loblolly pine ($g = 0.3$). We also found that slash pine is not profitable if its productivity decreases by 20% (Scenario D) for any level of salvageable portion and risk.

Overall, our findings suggest that maintaining forestlands with loblolly pine and planting fewer trees is preferred to changing forest composition to slash pine for all levels of salvageable portions. On average for $g = 0.2$–0.5 and with positive changes in forest productivity as a result of climate change, loblolly pine with low planting density economically outperforms slash pine by 11% ($\lambda = 0.01$) and 37% ($\lambda = 0.02$). Similar to the previous section planting fewer trees, coupled with greater forest growth results in a higher proportion of high value-added trees produced by the forest stand, generating increased financial revenues to forest landowners.

In our previous analysis, we assumed static regeneration costs after a natural disturbance. The regeneration costs after a disturbance are vital to reflect the economic returns for landowners. In general, they are higher than those in the absence of a disturbance event as a result of large amounts of residual vegetation (Marsinko, Straka, and Baumann, 1996). Cost increases ranging between six percent to 60% and five percent 12% were obtained for site preparation and chemical control activities, respectively, after hurricane Hugo struck the southern United States (Marsinko, Straka, and Baumann, 1996). As such, we considered a 25% increase in the site preparation and weed control costs resulting in regeneration costs after a disturbance event of \$1221/ha^{-1} for loblolly pine with high planting density and slash pine and \$1162/ha^{-1} for loblolly pine with low planting density.

With the new levels of costs and for Scenario B and $\lambda = 0.02$, the *LEV* s for loblolly pine with high planting density are lower by 23% (\$331/ha^{-1}; $g = 0.2$) and 20% (\$392/ha^{-1}; $g = 0.3$) lower compared with land values for the same forest management with constant regeneration costs. In relative terms, higher regeneration costs have a greater impact on the profitability of slash pine compared with loblolly pine with low planting density. The *LEV* s for slash pine are reduced by 20% (\$396/ha^{-1}; $g = 0.4$) and 18% (\$457/ha^{-1}; $g = 0.5$), whereas in the case of loblolly pine with a low planting density, the *LEV* s decrease by 15% (\$563/ha^{-1}; $g = 0.4$) and 14% (\$628/ha^{-1}; $g = 0.5$).

Conclusions

This article analyzes the effects of different levels of disturbance risk, implicitly considering "what if" climate change scenarios on the economics of forestlands in the southern United States. Increased (decreased) forest productivity scenarios lead to higher (lower) economic returns for forest landowners. Increased levels of disturbance risk resulting from climate change worsen the profitability of forestry regardless of the forest productivity scenario. Particularly in the case of decreased forest productivity scenarios, continuing to invest in forestry may result in economic losses for landowners; and changes in disturbance risk and productivity changes are the most critical determinants for economic returns.

We simulated several adaptation strategies for forest landowners and found that planting fewer loblolly pine/ha to reduce damage caused by increased wildfire events generates higher land values than those for the original (high-density) loblolly pine management under increased forest productivity conditions. Slash pine is a less economically viable option compared with both loblolly pine forest managements in most cases. Under certain conditions (high salvageable portions), NIPF landowners will be better off planting slash pine instead of loblolly pine with high planting density. Thus, the selection of adequate forest species and management (e.g., silvicultural efforts aim to increase the amount of undamaged timber that can be recovered after a natural disturbance) become crucial to capture the benefits and mitigate the negative effects resulting from climate change. Furthermore, specific salvage harvest policies, for example subsidies, must not be driven by tree mortality but the type of disturbance (Sims, 2013). Higher regeneration costs after a natural disturbance have a negative impact on the economic returns for landowners, and in relative terms, the profitability of slash pine is more eroded than loblolly pine with low planting density.

Findings of our study help inform landowners about the feasibility of alternative climate change adaptation strategies; however, we note limitations of this study. We recognize that our study did not account for the influence of other factors that drive revenues such as stumpage prices, costs, and returns to alternative land uses may also change in response to climate change. These shortcomings also inform future research, and we believe that this study can be extended in several ways. The use of ecophysiological models becomes critical to determine future forest growth with forecasted temperatures and precipitation for the next 100 years in the southern United States. For example, the Pine Integrated Network: Education, Mitigation, and Adaptation project—led by 11 southeastern land grant universities and awarded by the USDA National Institute of Food and Agriculture—aims to develop sustainable forest practices under variable climates to increase C sequestration by 15% by 2030. As part of this project, researchers are currently adapting a 3-PG model (Landsberg and Waring, 1997) to gauge changes in net primary productivity by modifying climatic variables at the county level in the southern United States. Similar to Lesage (2011), the use of panel data with a spatial dimension is an excellent tool to determine the effect of climate change on the profitability of forestlands. Thus, with this level of information, it will be possible to conduct multiscale policy and economic analyses of forest benefits through different climate scenarios and propose alternative forest management approaches for NIPF landowners.

The assessment of forest landowners' preferences is an area of further research, given the role that preferences may play in management decisions under uncertainty of the impacts of climate change. Forecasts of future stumpage and C prices are also an area for further research because they will affect the harvest decision and supply of forest products and C under climate change. With changing climatic conditions, increasing demand for forest biomass for bioenergy will likely play a pivotal role with regard to policies oriented to ameliorate the emission of CO_2. Further understanding of C markets and payments for C sequestration may also be included to reflect NIPF landowners' views regarding the optimal harvest timing, supply of C, and forest product (Stainback and Alavalapati, 2004). Defining NIPF landowners' preferences at the regional level in light of subsidies for C markets will help elucidate the best policies to reduce greenhouse gas emissions. Finally, the use of other species more resistant to natural disturbances such as longleaf pine is also a subject of further research.

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