Fire Risk and the Economics of Sequestering Carbon in Forests

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Abstract

The impact of fire risk on slash pine (*Pinus elliottii*) plantations managed for the joint production of carbon and timber benefits was investigated. A Hartman model for determining the optimal rotation age and Land Expectation Value (LEV) for a stand with both carbon and timber benefits was extended to include the risk of fire. Information from this model was then used to determine optimal rotation age, LEV, carbon supply and timber supply as a function of fire risk and the price of carbon. The results indicate that fire risk reduces all of these variables and this reduction is greater for higher carbon prices. These results suggest that landowners' would respond less to a carbon market when the level of fire risk is relatively high.

Keywords: fire risk, carbon sequestration, optimal rotation age, slash pine, climate change

Introduction

There is growing concern over the accumulation of "greenhouse gasses", particularly carbon dioxide (CO_2), and associated global warming. As a result of global warming, sea levels may rise causing inundation of some coastal areas and the earth's environment may be altered affecting biodiversity and food security in many regions. Since the early 1990s, governmental and non-governmental organizations across the globe have been attempting to develop various strategies to mitigate atmospheric concentrations of greenhouse gasses (Hedger 1998). In 1997 the United Nations Convention on Climate Change adopted the Kyoto Protocol requiring developed countries to reduce their greenhouse gas emissions to approximately 5% below 1990 levels by 2008-2012. The details of the Protocol were worked out in November 2001 in

Marrakesh, Morocco and it appears likely that it will enter into force in the next couple of years. The current U.S. administration, however, has opted out of the Kyoto Protocol and has developed an alternative that it claims would be less harmful to the U.S. economy.

It is widely recognized that forests play an important role in the global carbon cycle by sequestering and storing carbon, enabling the switch from more energy-intensive materials such as steel to forest products, and facilitating substitution of biomass fuels for fossil fuels (Brand 1998). It is this role of forests in climate change that has influenced participants of the Kyoto Protocol to allow countries to count carbon sequestered in forests toward a country's emission requirements. As the U.S. has long been a proponent of this idea, the Bush administration has proposed over 3 billion dollars in its alternative climate change proposal for forestry and agricultural carbon sequestration activities (Bush 2002). Preliminary research indicates that carbon sequestration through forestry practices can be cost effective. For example, Dixon (1997) estimated that sequestration of carbon through silvicultural practices could cost between $2-56 per metric ton. Current projections by the Resources Planning Act assessment models show that through the year 2040 about 15 percent of projected U.S. carbon emissions will be sequestered by forests (Murray et al. 2000). These projections are based on current management trends such as decreased logging in the Pacific Northwest.

There is a problem, however, in capitalizing on the comparative advantage of producing an additional amount of timber and associated carbon. In the absence of markets for forest carbon, private timber producers consider carbon external to their production decisions. As a result, forest biomass production and associated carbon sequestration may be lower than is socially desirable. In the case of public lands, this problem can be resolved by manipulating government budget allocations. However, in the case of private lands, incentives may be necessary to stimulate landowners to consider carbon sequestration benefits in their production decisions (Alavalapati 1998). Consider forestry as a cycle of biomass production with a net CO_2 assimilation and biomass decay period with net CO_2 emission. If subsidies are given for net CO_2 assimilation and taxes are imposed on net CO_2 emission, this will generate a cash flow of positive net payments from regeneration to harvest followed by negative net payments following harvest because of carbon emissions (Hoen and Solberg 1997). If reforestation, afforestation, and the use of forest products can generate a net positive carbon balance, net subsidies may be justified for forest carbon sequestration.

There has been a considerable amount of work done on determining the impact of internalizing carbon benefits onto forest management decisions. The consensus from this research is that carbon benefits tend to lengthen the rotation and increase the Land Expectation Value (LEV) (Englin and Callaway 1993, van Kooten et al. 1995 and Alavalapati and Stainback 2002). All of these studies have treated the problem in a deterministic fashion. However the risk of catastrophic tree mortality due to fire is important to consider when making forest management decisions (Reed 1984). Forest fires can impact the outcome of policies to sequester carbon in forest biomass in at least two important ways. First, a fire releases some or all of the stored carbon back into the atmosphere. Second fire risk can significantly impact the optimal management of a forest stand.

In this paper, we first develop a modified Hartman model to determine the optimal rotation age, LEV, carbon supply and timber supply under risk of catastrophic fire from a forest stand that produces both timber and carbon benefits. Second, we apply this model to fast growing slash pine (*Pinus elliottii*) plantations in the southeastern United States. We finally discuss the implications of the results of this study and then suggest areas where future research is needed.

Model of Carbon and Timber Benefits

Faustmann (1995) is credited with correctly determining the rotation age for a forest stand that maximizes LEV from timber benefits. Hartman (1976) extended the Faustmann model to include the value associated with the standing forest in addition to timber benefits. These benefits can include environmental benefits such as water catchments and recreational benefits such as hunting and hiking. Several authors have adapted the Hartman model to investigate the impact of various forms of carbon payments on the optimal rotation age and the supply of sequestered carbon. Englin and Callaway (1993) investigated the impact of carbon payments on the optimal rotation age of Douglas Fir. Plantinga and Birdsey (1994) did a theoretical study to include carbon payments in the forest rotation problem. Hoen and Solberg (1997), van Kooten et al. (1995) and Enzinger and Jeffs (2000) did similar studies for Scandinavian forests, forests in western Canada and Eucalyptus plantations in Australia respectively. More recently, Stainback and Alavalapati (2002) investigated the impact of carbon payments on the optimal forest rotation age and the LEV of slash pine plantations in the U.S. south. These studies indicate that carbon benefits significantly increase the optimal rotation age, encourage the production of longer-lived products and significantly increase the LEV associated with forestry.

For a forest stand producing two outputs sawtimber and pulpwood, merchantable timber volume can be presented as:

$$v(t) = v(t)_{pulp} + v(t)_{saw} \tag{1}$$

Where $v(t)$ is the total merchantable volume which in this case is the pulpwood volume $v(t)_{pulp}$ plus sawtimber volume $v(t)_{saw}$ and t is stand age in years. The present value of carbon benefits $pv(t)_c$ over one rotation period can be represented by:

$$pv(T)_{carbon} = \int_0^T \alpha\beta p_c v'(t) e^{-rt} dt - dec(T)_{saw} e^{-rt} - dec(T)_{pulp} e^{-rt} - dec(T)_{slash} e^{-rt} \tag{2}$$

Here α is a conversion factor to convert wood volume to metric tons of carbon, β is the ratio of merchantable timber volume to total tree volume including roots, bark, leaves and branches, p_c is the price of a metric ton of carbon, $v'(t)$ is the derivative of equation (1) with respect to t and r is the discount rate. The terms $dec(t)_{saw}$, $dec(t)_{pulp}$ and $dec(t)_{waste}$, respectively, represent the carbon emissions from harvest due to the decay of sawtimber, pulpwood and wood waste left at harvest and are represented by equations (3), (4) and (5).

$$dec(T)_{saw} = \left(\frac{p_c \alpha v(t)_{saw}}{100} \left[1 - (1+r)^{-100} \right] \right) \tag{3}$$

$$dec(T)_{pulp} = \left(\frac{p_c \alpha v(t) pulp}{5} \left[1 - (1+r)^{-5} \right] \right) \tag{4}$$

$$dec(T)_{waste} = p_c \alpha \left(\beta v(t) - v(t)_{saw} - v(t)_{pulp} \right) \tag{5}$$

The decay of sawtimber and pulpwood represented by equation (3) and (4) is modeled to be a linear process where an equal amount decays each year until all of the carbon pool is released back into the atmosphere. Sawtimber is modeled to decay over 100 years and pulpwood over 5 years. The decay of wood waste, which is simply all of the wood volume not sold as sawtimber or pulpwood, is represented by equation (5) and is modeled to decay immediately after harvest.

The value of timber *val(t)* can be represented as:

$$val(t) = p_s v(t)_{saw} + p_p v(t)_{pulp} \tag{6}$$

Where p_s and p_p represent the price of sawtimber and pulpwood respectively. The net present value of timber benefits over one rotation can now be represented by equation (7):

$$pv(t)_{timber} = \left(val(t) - g\right)e^{-rt} \tag{7}$$

Where *g* represents the planting cost. Equation (7) simply states that the present value of timber benefits is the discounted value of sawtimber and pulpwood produced minus the planting cost. If the land is used to produce timber and carbon perpetually then the bare land value *LEV(t)* can be represented as:

$$LEV(t) = \frac{pv(t)_{carbon} + pv(t)_{timber}}{1 - e^{-rt}} \tag{8}$$

If the value of carbon is zero then equation (8) reduces to the original Faustmann model.

Using the above equations the amount of carbon sequestered can be represented by the following equation:

$$s(t)_{carbon} = \alpha\left(\sum_{n=1}^{T}\frac{v(n)}{T} + \frac{100v(T)_{saw} + 5v(T)_{pulp}}{T}\right) \tag{9}$$

The first term on the right hand side of equation (9) represents the average volume in a stand during the rotation period. At some point the emissions of carbon from the decay of products is equal to the amount of carbon entering the product pools from harvests. When this occurs a steady-state equilibrium is achieved which is represented by the second part of the right-hand side of equation (9). Finally the supply of sawtimber and pulpwood can is represented by:

$$s(T)_{saw} = \frac{v(T)_{saw}}{T} \qquad s(T)_{pulp} = \frac{v(T)_{pulp}}{T} \tag{10}$$

Model of Carbon and Timber Benefits with Risk

Consideration of the risk of catastrophic fire can significantly change the optimal management regime of a forest stand (Reed and Errico 1985). In addition, with carbon sequestration as one of the management objectives, there is a concern about the sequestered carbon being prematurely released back into the atmosphere (Enzinger and Jeffs 2000). Martell (1980) and Routledge (1980) include fire risk in their analysis of the optimal rotation in a discrete time framework. Reed (1984) expands the Faustmann formula to take into account fire risk in a continuous time framework. The conclusion from these studies is that fire risk reduces both the optimal rotation age and LEV. Englin et al. (2000) expand this model to include recreational benefits and find that rotation age decreases with increasing fire risk but recreational benefits increase the optimal rotation age at every level of risk. Unlike other amenity benefits such as recreation, when carbon benefits are internalized, a landowner must pay for carbon emissions emitted due to a fire. Thus there is an additional cost associated with fire in a carbon market in addition to the lost revenue from the timber and not being able to carry the stand to the end of the rotation.

We expand the Reed (1984) model to include both timber and carbon benefits. In this model the probability of fire occurring is assumed to have a Poisson distribution.

Thus the risk of fire is modeled to be equal in each year. If the time between successive stand destructions (through fire or harvest) is represented by $x_1, x_2 \ldots x_n$ and λ represents the probability of a fire occurring in one year then the cumulative distribution of the probability of the stand being destroyed can be represented as:

$$prob(x \le T) = F_x(t) = \begin{cases} \lambda e^{-\lambda x} & if\, x < T \\ e^{-\lambda x} & if\, x = T \end{cases} \tag{11}$$

When a fire does occur usually some portion of the stand is salvageable. If the portion that is salvageable is on average *k* then the net revenue from a stand over one rotation can be represented as:

$$Y_x = \begin{cases} \begin{bmatrix} val(T) - g + e^{rT}\int_0^T \alpha\beta p_c v'(t)dt \\ -dec(T)_{saw} - dec(T)_{pulp} - dec(T)_{waste} \end{bmatrix} & if\, x < T \\ \\ \begin{bmatrix} kval(T) - g + e^{rT}\int_0^T \alpha\beta p_c v'(t)dt \\ -kdec(T)_{saw} - kdec(T)_{pulp} - kdec(T)_{waste} \\ -\int_0^T (1-k)\alpha\beta v'(t)dt \end{bmatrix} & if\, x = T \end{cases} \tag{12}$$

The terms e^{rT} and e^{rx} discount the carbon benefits to the end of the rotation. The Land Expectation Value with fire risk *LEVr(x)* associated with carbon and timber benefits can now be written as:

$$LEVr(x) = E\left[\sum_{n=1}^{\infty} e^{-r(x_1+x_2+\ldots x_n)} Y_n\right] \tag{13}$$

Because fire events follow a Poisson distribution, x_n is independent and equation (13) can be written as follows:

$$\begin{aligned} LEVr(x) &= \sum_{n=1}^{\infty} E\left[e^{-r\left(x_1+x_2+\ldots X_{n-1}\right)}\right] E\left(e^{-rx_n} Y_n\right) \\ &= E\left(e^{-rx_n} y_n\right) \sum_{n=1}^{\infty} \prod_{i=1}^{n-1} \left[E\left(e^{-rx_i}\right)\right] \\ &= \frac{E\left(e^{-rx} Y\right)}{1-E\left(e^{-rx}\right)} \end{aligned} \tag{14}$$

In addition:

$$\begin{aligned} E\left(e^{-rX}\right) &= \int_0^{\infty} e^{-rt} dF_x(t) \\ &= \int_0^{T} e^{-rt} \lambda e^{-\lambda t} dt + e^{-rT} e^{-\lambda T} \\ &= \frac{\left(\lambda + re^{-(\lambda+r)T}\right)}{\left(\lambda+r\right)} \end{aligned} \tag{15}$$

Using equations (11) and (12) it is now possible to write:

$$E\left(e^{-rx} Y_x\right) = \left[\begin{array}{l} e^{-\lambda T}\left[val(T)-g\right]e^{-rT} + e^{-\lambda T}\left(e^{rT}\int_0^T p_c \alpha\beta v'(t) e^{-rt} dt\right)e^{-rT} \\ -e^{-\lambda T} dec(T)_{saw} e^{-rT} - e^{-\lambda T} dec(T)_{pulp} e^{-rT} \\ -e^{-\lambda T} dec(T)_{waste} e^{-rT} + \int_0^T \lambda e^{-\lambda t}\left(kval(t)-g\right)e^{-rt} dt \\ +\int_0^T \lambda e^{-\lambda t}\left(\int_0^t p_c \alpha\beta v'(z) dz\right)e^{-rt} dt - \int_0^T \lambda e^{-\lambda t} kdec(t)_{saw} e^{-rt} dt \\ -\int_0^T \lambda e^{-\lambda t} kdec(t)_{pulp} - \int_0^T \lambda e^{-\lambda t} kdec(t)_{waste} e^{-rt} dt \\ -\int_0^T \lambda e^{-\lambda t}\left(1-k\right) p_c \alpha\beta v'(t) e^{-rt} dt \end{array}\right] \tag{16}$$

Equation (16) is just the addition of the two possible outcomes from equation (12) multiplied by their probabilities of occurring. Substituting equations (16) and (15) into equation (14) and rearranging terms yields:

$$
\begin{aligned}
LEVr(T) = {} & \frac{\lambda + r}{r\left(1 - e^{-(r+\lambda)T}\right)} \\
& \left\{
\begin{aligned}
& \left[val(T) - g\right]e^{-(\lambda+r)T} + e^{rT}\int_0^T p_c \alpha\beta v'(t) e^{-rt}\,dt\,e^{(\lambda+r)T} \\
& - dec(T)_{saw}\,e^{-(\lambda+r)T} - dec(T)_{pulp}\,e^{-(\lambda+r)T} - dec(T)_{waste}\,e^{-(\lambda+r)T} \\
& + \int_0^T \lambda k val(t) e^{-(\lambda+r)t}\,dt + \int_0^T \lambda e^{rt}\left[\int_0^t p_c \alpha\beta v'(z) e^{-rz}\,dz\right] e^{-(\lambda+r)t}\,dt \\
& - \int_0^T \lambda k dec(t)_{saw}\,e^{-(\lambda+r)t}\,dt - \int_0^T \lambda k dec(t)_{pulp}\,e^{-(\lambda+r)t}\,dt \\
& - \int_0^T \lambda k dec(t)_{waste}\,e^{-(\lambda+r)t}\,dt - \int_0^T \lambda(1-k) p_c \alpha\beta v'(t) e^{-(\lambda+r)t}\,dt
\end{aligned}
\right\} \\
& - \frac{\lambda g}{r}
\end{aligned}
\tag{17}
$$

Note that if λ is 0 then equation (17) reduces to equation (8). The value of *T* that maximizes *LEVr(T)* is optimal rotation age.

Carbon supply with risk can be represented as:

$$
s_r(T)_{carbon} = \left[
\begin{aligned}
& \frac{\sum_{n=1}^{T} e^{-\lambda n} v(n)}{\sum_{n=1}^{T} e^{-\lambda n}} + \frac{100\left(e^{-\lambda T} v(T)_{saw} + \int_0^T k\lambda e^{-\lambda t} v(t)_{saw}\,dt\right)}{T} \\
& + \frac{5\left(e^{-\lambda T} v(T)_{pulp} + \int_0^T k\lambda e^{-\lambda t} v(t)_{pulp}\,dt\right)}{T}
\end{aligned}
\right]
\tag{18}
$$

Equation (18) is just equation (9) adjusted for fire risk. The first part of the right hand side of the equation represents the average volume of the stand during the rotation. To understand this part of the equation it is useful to visualize fire as occurring on a portion of the stand every year equal to the to the level of risk. For instance if the risk of fire occurring is 2% then 2% of the stand burns each year. When a portion of the stand burns it is replanted and this replanted portion faces the same fire risk as the rest of the stand. The numerator in the first part of the right hand side of the equation is divided by the sum of the portion of the stand that remain unburned each year instead of T to adjust for the replanting on the burned portions. The last two parts of the right-hand side of the equation represent the steady-state equilibrium of the product pools as in equation (9). Sawtimber and pulpwood volume are represented in similar fashion by:

$$s_r(T)_{saw} = \frac{e^{-\lambda T} v(T)_{saw} + \int_0^T k\lambda e^{-\lambda t} v(t)_{saw}\, dt}{T}$$

$$s_r(T)_{pulp} = \frac{e^{-\lambda T} v(T)_{pulp} + \int_0^T k\lambda e^{-\lambda t} v(t)_{pulp}\, dt}{T} \tag{19}$$

Application to Slash Pine Plantations in the southeast U.S.

In the warm temperate climate of the lower coastal plain of the U.S. intensely managed pine plantations or fiber farms with very short rotations are becoming increasingly popular to meet the growing demand of timber products from this region (Yin et al. 1998). In these plantations unthinned stands can produce both pulpwood and sawtimber on rotations typically around 25 years. Because of the importance of this region in timber production, the fast growth rates associated with managed pine plantations and the availability of marginal agricultural land, this region may prove cost effective in sequestering carbon.

In our analysis we use a growth and yield model developed by Pinaar and Rheney (1993) for intensely managed unthinned slash pine plantations with even-aged harvest cycles. To develop this model the authors used data collected at 16 locations over a period of 18 years in north Florida and south Georgia by the Management Research Cooperative at the University of Georgia. In this model both sawtimber and pulpwood volume is estimated as a function of planting density, site index and stand age. Using taper functions, the amount of sawtimber is estimated as the volume of trees with a diameter at breast height (dbh) of 8 inches or greater to a 6 inch diameter top and the amount of pulpwood is estimated as the volume of trees with a dbh of 4 inches or greater to a 2 inch top. Sawtimber yields a higher price then pulpwood so it is assumed that all timber volume that can be sold as sawtimber is sold as such and the remainder that can be sold as pulpwood is sold as pulpwood.

The taper equations associated with this growth and yield model do not possess the required mathematical properties, such as being integratable, to be used in the present economic analysis. To solve this problem we fitted the output from the original taper equations from years 15 to 60 to the following functional form that does posses the desired properties:

$$v(t)_{saw}, v(t)_{pulp} = at^{b}e^{-ct} \tag{20}$$

Where $v(t)_{saw}$ and $v(t)_{pulp}$ represent the volume of sawtimber and pulpwood, respectively, in cubic feet per acre and a, b and c are parameters to be estimated. Using nonlinear least squares regression a, b and c were determined to be 0.023(5.6), 3.0(44.9) and 0.018(6.8) respectively for sawtimber and 1.8(6.1), 3.0(45.4) and 0.087(46.4) for pulpwood where the numbers in parentheses are t-ratios. The growth and yield function assumes tree density to be 600 trees per acre at age 2 and the site index to be 60feet at a base age of 25 years. The management regime was assumed to consist of mechanical site preparation and tree planting and a broadcast burn before planting. The original and fitted sawtimber and pulpwood functions are shown in figure 1.

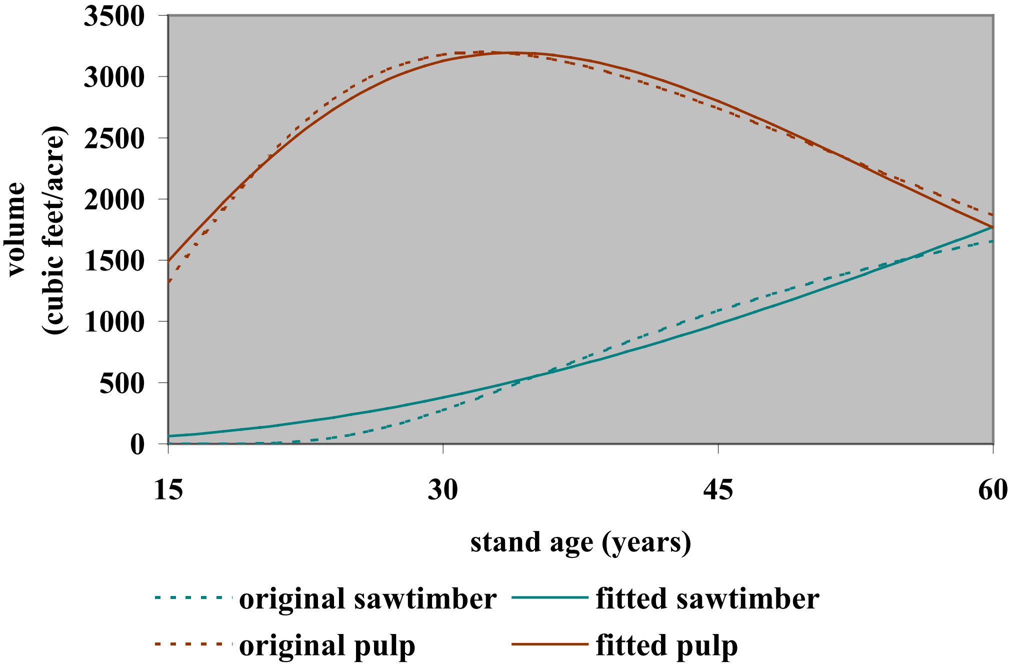

Figure 1. Original sawtimber and pulpwood functions compared to the estimated functions.

In the economic model timber prices were assumed to be $1.09 per cubic foot for sawtimber and $0.20 per cubic foot for pulpwood (Timber Mart-South 2001). The interest rate was set at 6%. The conversion factor α is 0.0081 metric tons of carbon per cubic foot and β is 1.7 (Birdsey 1996). Both α and β are specific for slash pine grown in the southeastern U.S. The value of carbon varies in the literature but usually ranges from

$0 to $200 per metric ton. We do the analysis at carbon prices of $0, $40 and $160 per metric ton. The carbon price of $0 represents the Faustmann scenario.

The optimal rotation age was determined for a range of risk levels from 0.01 occurrences a year to 0.04 occurrences a year. In addition two scenarios were investigated concerning the salvageable portion of the stand after a fire occurs. One scenario consists of the entire stand being destroyed and none of the timber being salvageable and in the other 70% of the stand is salvageable. As can be seen in figure 2 the optimal rotation age decreases as fire risk increases for both scenarios of salvage. As the price of carbon increases the optimal rotation age increases for all levels of risk. Two implications of this can be inferred from figure 1. First as the rotation age increases more carbon will be sequestered in the stand. In addition a greater portion of the harvested

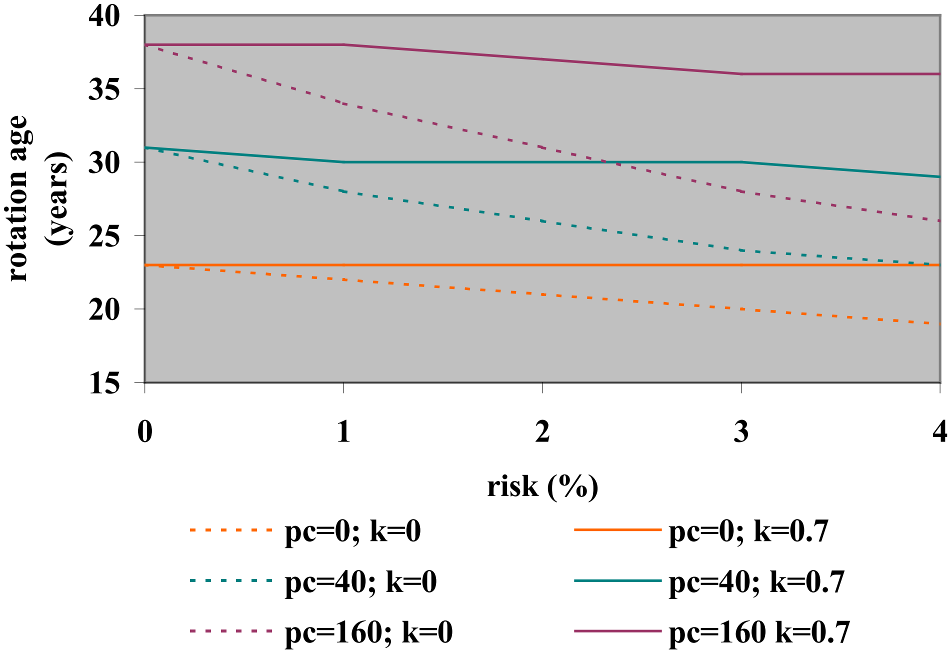

Figure 2. Rotation age as a function of fire risk. The price of carbon in dollars per metric ton is represented by pc and the portion of the stand salvageable after a fire is represented by k.

biomass will be put into sawtimber, with a longer life span, as opposed to pulpwood. However as the price of carbon increases the decline in the optimal rotation age as a result of fire risk is greater. Therefore, at higher risk levels the optimal rotation ages converge suggesting that the impact of a carbon subsidy and tax policy would be less under high levels of risk. With a carbon subsidy and tax policy, when a fire occurs the land owner not only loses some or all of the timber benefits associated with the stand but also must pay for all of the carbon emissions released from the stand due to the fire. Thus when the portion of the stand salvageable after a fire is 0 the optimal rotation age decreases faster with increasing fire risk as compare to when the salvageable portion is 0.7.

Land Expectation Value, *LEVr(T)*, is shown in figure 3. As expected land value decreases with increasing fire risk. As with the optimal rotation age, the decrease in land

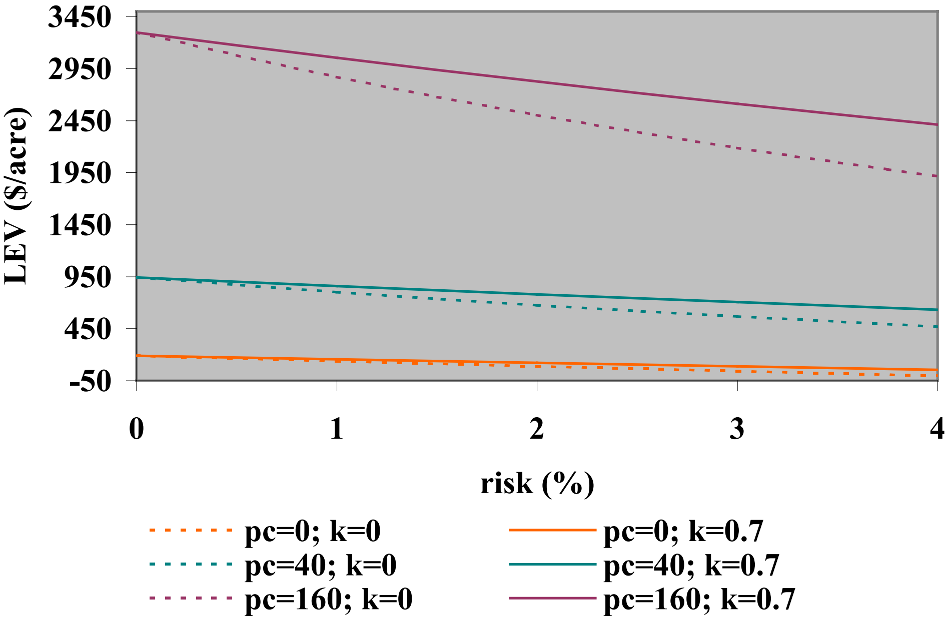

Figure 3. LEVr(T) as a function of stand age. The price of carbon in dollars per metric ton is represented by pc and the portion of the stand salvageable after a fire is represented by k.

value due to fire risk is greater for higher values of carbon. Thus as carbon prices increase there is a greater incentive for landowners to engage in management practices that reduce fire risk. Also, consistent with expectations, the land value drops faster when the salvageable portion after a fire is lower. However, as can be seen from the figure, land value always increases with higher carbon prices regardless of the risk level. Thus landowners would financially benefit from participating in a carbon market even when the risk of fire releasing all or part of the stored carbon is significant.

The carbon supply is shown in figure 4. Again as expected, the amount of carbon sequestered is greater for higher carbon prices but declines with increasing fire risk.

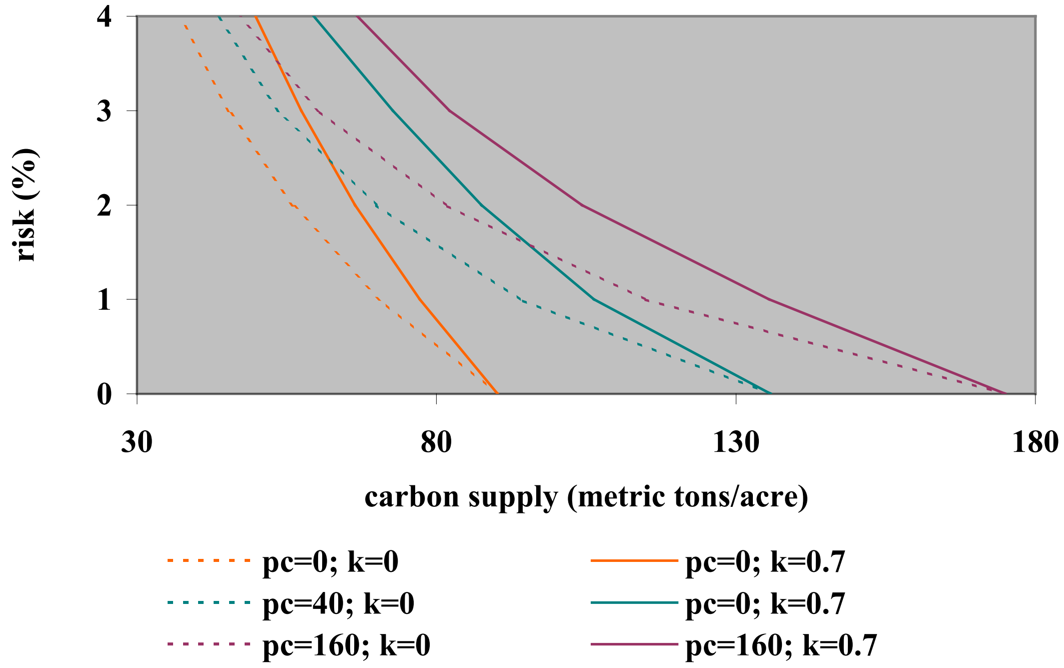

Figure 4. Supply of carbon as a function of fire risk. The price of carbon in dollars per metric ton is represented by pc and the portion of the stand salvageable after a fire is represented by k.

However the decline with risk is much greater for higher carbon prices meaning that for high levels of risk there is a much smaller gain in stored carbon with a carbon subsidy and tax policy. Again as expected the decline in the supply of carbon is much greater when the there is no salvageable portion of the stand.

The supplies in sawtimber and pulpwood are shown in figures 5 and 6 respectively. The supply of sawtimber and pulpwood both decrease with increasing fire risk. Furthermore, as expected from figure 1, sawtimber supply increases with increasing carbon prices and pulpwood supply increase with a carbon price increase of $0 to $40 dollars per metric ton but decrease with a carbon price increase from $40 to $160 per metric ton.

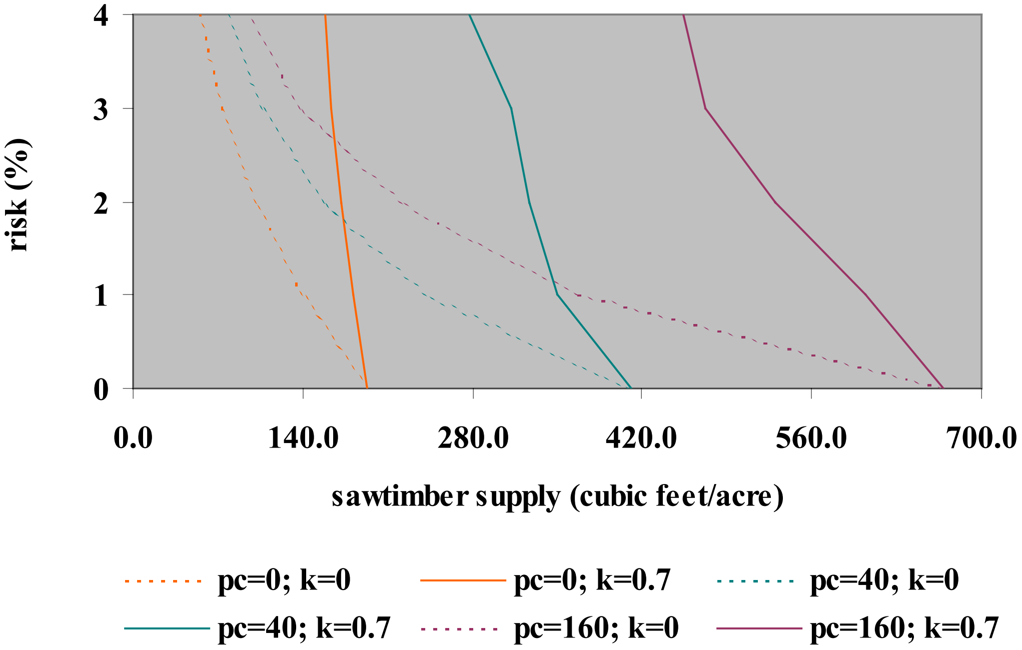

Figure 5. Sawtimber supply as a function of fire risk. The price of carbon in dollars per metric ton is represented by pc and the portion of the stand salvageable after a fire is represented by k.

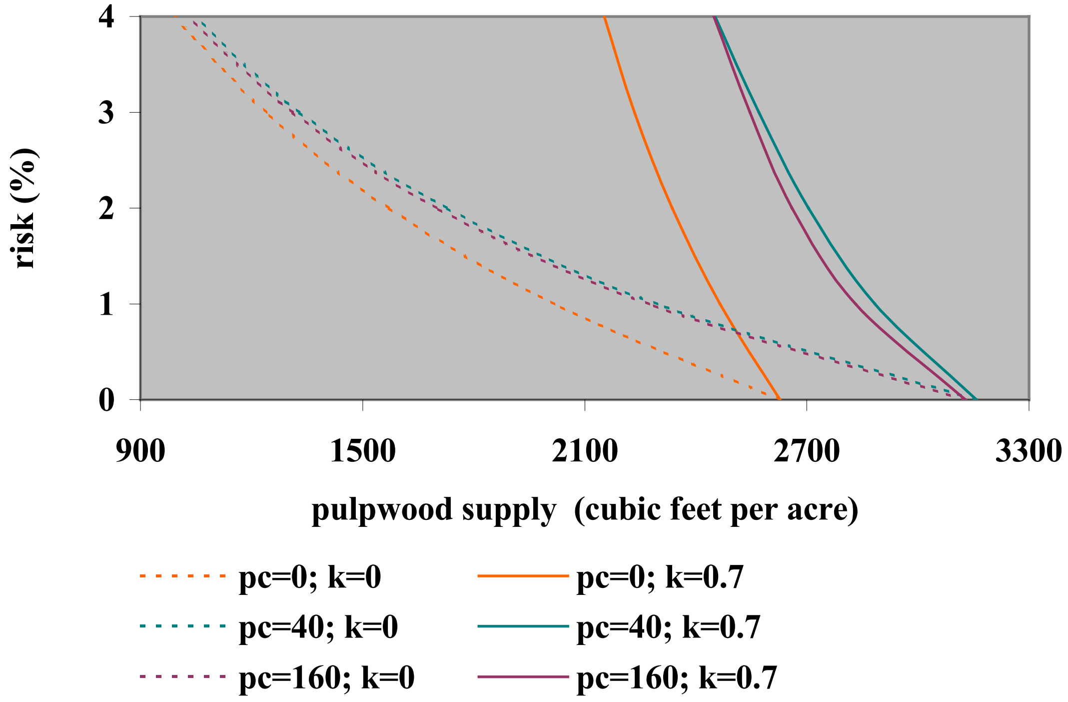

Figure 6. Pulpwood supply as a function of fire risk. The price of carbon in dollars per metric ton is represented by pc and the portion of the stand salvageable after a fire is represented by k.

Conclusions

Fire risk decreases the rotation age and land value for all carbon prices investigated. Furthermore these decreases were greater for higher carbon prices suggesting that fire risk would have the effect of dampening the impact of a carbon subsidy and tax policy. Conversely internalizing carbon benefits onto forest management increases the rotation age and land value at all levels of risk investigated. These results are consistent with previous studies (Englin et al. 2000). The much greater decrease in land value due to risk when carbon benefits are internalized indicates that there would be a greater incentive for landowners or forest managers to reduce fire risk or purchase insurance at a higher premium in a carbon market.

As expected carbon supply decreases with increasing fire risk. Furthermore this decrease is greater for higher carbon prices. Thus at high levels of risk, internalizing carbon benefits would have a smaller positive impact on the amount of carbon sequestered. The inclusion of fire risk decreases the amount of carbon sequestered in two ways. First, when a fire occurs all or part of the stored carbon is released back into the atmosphere. Second, risk induces shorter rotations thereby decreasing both the amount of carbon stored on the stand and increasing the proportion of pulpwood produced, which has a shorter life span then sawtimber. For these reasons it would be more efficient to focus carbon sequestration policies on forestland with a smaller risk of fire.

Fire risk reduces the supply of both sawtimber and pulpwood. However, at all levels of risk sawtimber supply is positively correlated with carbon prices while pulpwood supply is negatively correlated with carbon prices at high price levels. It should be stressed, however, that if the land area devoted to forest production increases, due to higher land values, then sawtimber and pulpwood supply could both decrease. These changes in sawtimber and pulpwood supplies could impact the price of timber products. A decrease in the price of sawtimber and an increase in the price of pulpwood could dampen the effect of a carbon subsidy and tax policy by encouraging shorter rotations and more pulpwood production. Similarly, a decrease in price for both sawtimber and pulpwood could dampen the impact of a carbon policy on the extensive margin.

There are some limitations associated with this study. First, fire risk may not be the same for all stand ages. For instance, the susceptibility of southern pines to fire usually decreases with age. However, changing the cumulative distribution of risk would not likely change the general conclusions from the results. Second, rotation age is only one of the many key inputs in timber production. We did not address other changes in forest management that could result from a carbon subsidy and tax policy. For instance, it is probable that carbon taxes and subsidies would have an impact on the amount of fertilizer, pesticides and stocking density used by landowners. Finally, as mentioned earlier, the change in timber supply caused by changes in the optimal rotation age and land values will inevitably influence the market price of sawtimber and pulpwood. This price change will in turn influence forest management decisions. Investigations of these issues in future studies may help formulate effective forest carbon sequestration policies.

References

Alavalapati, J. R.R. 1998. Why not incentives for forest carbon sequestration? Florida Forests Fall:27-29

Alavalapati, J.R.R., G.A. Stainback and D.R. Carter. 2002. Restoration of the longleaf pine ecosystem in the U.S. South: An ecological economic analysis. Ecological Economics. 40:411-419.

Birdsey, R. A. 1996. Carbon storage for major forest types and regions in the conterminous United States. P. 1-25 *in* Forest and global change: Vol. II, Forest management opportunities for mitigating and adapting to climate change, Sampson, R.N., and D. Hair (eds.). American Forests, Washington, DC.

Brand, D. 1998. Opportunities generated by the Kyoto Protocol in the forest sector. Commonwealth Forestry Review 77:164-169.

Bush, G.W. 2002. Global Climate Change Policy Book. The White House, Washington DC.

Dixon, R.K. 1997. Silvicultural options to conserve and sequester carbon in forest systems: preliminary economic assessment. Critical Reviews in Environmental Science and Technology 27(Special):S139-S149.

Englin, J. and J.M. Callaway. 1993. Global climate change and optimal forest management. Natural Resource Modeling 7:191-202.

Englin, J., P. Boxall and G. Hauer. 2000. An empirical examination of optimal rotations in a multiple-use forest in the presence of fire risk. Journal of Agricultural and Resource Economics. 25:14-27.

Enzinger, S. and C. J. Jeffs 2000. Economics of forests as carbon sinks: An Australian perspective. Journal of Forest Economics 6:227-249.

Faustmann M. 1995. Calculation of the value which forestland and immature stands possess for forestry (Republication of original article – 1849). Journal of Forest Economics 1:7-44.

Hartman, R. 1976. The harvesting decision when a standing forest has value. Economic Inquiry 14:52-58.

Hedger, M.M. 1998. Making Kyoto Work - the Complex Agenda of Forestry. Commonwealth Forestry Review 77(3):172-180.

Hoen, H. F.and B. S. Solberg. 1997. CO_2-taxing, timber rotations, and market implications. Critical Reviews in Environmental Science and Technology 27(Special Issue):S151-S162.

Martell, D.L. 1980. The optimal rotation of a flammable forest stand. Canadian Journal of Forest Research. 10:30-34.

Murray, B. C., S. P. Prisley, R. A. Birdsey and R. Neil Sampson. 2000. carbon sinks in the Kyoto Protocol: Potential relevance for US forests. Journal of Forestry 98:6-11.

Plantinga, A. J., and R. A. Birdsey. 1994. Optimal forest stand management when benefits are derived from carbon. Natural Resource Modeling 8: 373-387.

Pienaar, L.V. and J.W. Rheney. 1993. Yield prediction for mechanically site-prepared slash pine plantations in the southeastern coastal plain. Southern Journal of Applied Forestry 17:163-173.

Reed, W.J. 1984. The effects of the risk of fire on the optimal rotation of a forest. Journal of Environmental Economics and Management. 11:180-190.

-----. 1986. Optimal harvesting models in forest management – a survey. Natural Resource Modeling. 1:55-79.

Routledge, R.D. 1980. The effect of potential catastrophic mortality and other unpredictable events on optimal forest rotation policy. Forest Science. 26:389-399.

Stainback, G.A. and J.R.R. Alavalapati. 2002. Economic analysis of slash pine forest carbon sequestration in the southern U.S. Journal of Forest Economics. (In Press)

Timber Mart-South. 2001. The Norris Foundation. Athens, GA: University of Georgia.

van Kooten, G. C., C.S. Binkley and G. Delcourt. 1995. Effect of carbon taxes and subsidies on optimal forest rotation Age and supply of carbon services. American Journal of Agricultural Economics 77:365-374.

Yin, R., L.V. Pienaar, and M.E. Aronow. 1998. The productivity and profitability of fiber farming. Journal of Forestry 96:13-18.