OPTIMAL FOREST ROTATIONS WITH ENVIRONMENTAL VALUES AND ENDOGENOUS FIRE RISK

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Abstract

This paper develops a model that solves for the optimal economic harvest rotation problem to maximize revenue of an even-aged forest plantation when there is a risk of a catastrophic forest fire. The paper also investigates the feasibility of using fire prone stands for carbon sequestration and estimates the effects that it would have on the optimal management regime and rotation age empirically using a typical Douglas-fir stand in the Pacific Northwest. The model incorporates risk-reducing management practices that allow risk and growth to be endogenous, and the optimal rotation model is solved using numerical simulation techniques. Results show that higher carbon prices increase the rotation length regardless of the probability of fire and that the frequency of risk-reducing management practices increase as the stand approaches the optimal harvest age. Results also indicate that intermediate fuel treatments can provide economical and environmental benefits, even with a high probability of fire.

Keywords: Carbon sequestration; Stochastic risk; Forest management; Optimal rotation; Silviculture; Forest fires; Climate change

1. Introduction

There is widespread belief that forests can be used to sequester carbon from the atmosphere and consequently to help reduce the effects of climate change (see Sedjo and Solomon, 1989; Stavins, 1999; Richards and Stokes, 2004 for example). Concern has been raised, however, that if the area of forests is expanded and these forests are used to sequester carbon, much of the carbon gained through afforestation may be lost from fires. This concern has increased in recent times, as the fires burning in many regions of the world have grown in size and intensity, leading to large losses in timber reserves, habitat, and valuable carbon sinks (Westerling et al., 2006). Reports indicate that over 50 million hectares of forestland are burned globally, leading to upwards of 1 billion tC (1 tC = 1000 Kg C) of emissions annually (van der Werf et al., 2005). Although forests often grow back on land where fires occur, even short-term losses (e.g. 30 - 50 years of reduced carbon while forests are growing back) can have economic consequences for companies that have invested in timber reserves for carbon sequestration.

Historically, fire risk has been considered to be outside the control of landowners, but recent evidence indicates that land management can influence fire risk. For example, Peterson et al. (2005) show that large suppression efforts over the past 100 years have caused forests to accumulate fuels to levels well beyond the historical means, thus increasing the risk of loss once a stand ignites On the other hand, van Wagner (1977), Yoder (2004), and Curtis et al. (1998) show that management activities in existing forests can reduce the risks to landowners. Given the high value that forests may hold for sequestering carbon, and the potentially large risks associated with emissions from forest fires, it is useful to consider the link between forest management, and forest fire risk.

There are two critical issues to be addressed when considering forest management, fire risk, and carbon sequestration. The first issue relates to the optimal rotation age and whether it increases or decreases with fire risk. Early papers by Martell (1980), Routledge (1980), Reed (1984), and Reed and Errico (1985) evaluated the effect of risk of forest fires on the optimal rotation age of a single forest stand. These studies all concluded that in the presence of stochastic fire loss, optimal rotations would be *shorter* compared to the case when no risk was present. They also found that the presence of fire risk would reduce expected volume produced per unit time in the long run. None of these studies account for the possibility that forest managers may alter the management of their stands to reduce probability of fire. More recent work by Thorsen and Helles (1998) shows that thinning can reduce risks and that the change in the optimal rotation period is minimal. Amacher et al. (2005) suggest that when thinning and other management activities are undertaken, optimal rotation periods may or may not decrease. Unlike Amacher et al., this paper accounts for the potential increase in growth from intermediate treatments and investigates the role that a specific non-timber benefit (i.e. carbon sequestration) has on the optimal management regime.

The second issue relates to the effects that incentives to sequester carbon may have on landowners. Englin and Calloway (1993) and Van Kooten et al. (1995) suggest that carbon incentives should increase the optimal rotation period. Obviously, planting trees to avoid climate change and holding them for longer periods of time, exposes them to more risk than otherwise. In the face of fire risk, one must question if the results suggested by these authors still hold. Englin et al. (2000) suggest that amenity values would still increase the optimal rotation period, but Stainback and Alavalapati (2004) find that rotations would decrease as the price of carbon increases. The Stainback and Alavalapati (2004) result hinges on the inclusion of wood product pools for carbon, which implies that it is better to store carbon in wood products than accept the risks of emissions associated with fires. Neither of these studies account for risk reducing management strategies that forest landowners may have.

Substantial ecological research in recent years has been conducted to show that the effects of forest fires (i.e., the risk they pose to standing timber and carbon) may be reduced with management (Raymond and Peterson, 2005). Specifically, the research suggests that treatment programs aimed at reducing surface fuels, and dead and dying trees below the canopy, can reduce the probability of large crown fires that often destroy large amounts of merchantable timber (van Wagner, 1977; Yoder, 2004; and Curtis et al., 1998). Essentially, these treatment programs focus on eliminating small, non-merchantable materials that act as a "ladder," enabling the fire to shift from the forest floor (where it is often relatively benign) to the canopy (where it kills trees by destroying their ability to photosynthesize).

Although there is ample evidence that management can reduce fire risk, management is costly. Many of the existing management recommendations focus on removing non-commercial material, which does not yield economic returns, but is just a cost to the landowner. Given management costs, it is not clear that it is economical to invest in afforestatation and lengthening rotations for carbon sequestration in fire prone regions. Unfortunately, fire prone regions encompass a large proportion of the United

States. For example, current estimates indicate that approximately 35% of the forests of the U.S. are in regions that are considered to be at risk of a high-mortality stand-replacing forest fire in the next century (Schmidt et al., 2002). Thus, our existing stocks of forests appear to be particularly vulnerable to fire and related carbon emissions, and expanding and enhancing these stocks could be problematic. It is necessary to carefully assess whether there are any economic and carbon gains associated with investing in forest plantations and managing them optimally in order to minimize the risks of fires.

To model the optimal rotation problem in the presence of fire risk, this paper adopts a stochastic approach. The probability that fire occurs is assumed to be exogenous, however, land managers are assumed to have control over the likelihood that the stand will be destroyed by the fire. This means that even though forest fires are exogenous, the risk that stands die, or are unsalvageable, is endogenous in the optimal rotation problem. Within the context of the stochastic optimization model developed in the paper, it is not possible to present analytical solutions to the optimal rotation problem. Instead, we use numerical simulations to show how timberland management and optimal rotations adjust when fire risk is present. Douglas-fir stands in the Pacific Northwestern United States are used for our numerical example. This paper improves upon previous research by directly incorporating the endogenous growth and stand mortality rates in the case of a forest fire into the decision making process.

This paper is organized as follows. Because fire ecology is central to the notion that risk is endogenous in forest management, the next section discusses the current state of the fire ecology literature as it relates to management options available for reducing risk. The third section presents our stochastic dynamic model of forest management with endogenous risk, and incentives for carbon sequestration. The fourth section uses computational analysis to test these effects on the rotation length of a Douglas-fir stand in the Pacific Northwest, followed by the conclusion in the final section.

2. Fire Ecology and Risk-Reducing Management

The intensity and severity of a fire is dependent on the weather, climate, wind, topography, ignition source, and the amount and types of fuels present when the stand ignites (Agee, 1993; Schoennagel et al., 2004). Fuels are traditionally separated by their structure and placement in the stand, and are characterized as crown fuels (live and dead material in the canopy of trees), surface fuels (grass, shrubs, litter, and wood in contact with the surface), and ground fuels (organic soil horizons and buried wood). Crown fires have been shown to be the most destructive, according to Agee (1993), and the severity of crown fires is dependent on fuel-moisture content, wind conditions, and the level of surface and ground fuels. Shrubs and small trees living under the forest canopy often act as a "ladder," helping fire move from the ground to the canopy. Activities that reduce the amount of fuel under the forest canopy can reduce the likelihood of catastrophic losses (Peterson et al, 2005). Forest managers, therefore, have long engaged in activities to mitigate the risk of a crown fire through fuel reduction techniques, such as prescribed fire or thinning. Quick suppression once a fire has begun has also been shown to be easier and less costly in stands that have been actively managed to remove fuel "ladders" (Oucalt and Wade, 1999; Agee, 2002).

Three techniques have been widely suggested to reduce the risks that timber stands will be destroyed by fire: prescribed burning, periodic thinning, and suppression. Prescribed fire (periodic burns of the under-story of a stand) is known as a cost-effective way to reduce fuel loads (Rummer et al., 2003; Yoder, 2004). It is not considered in this study because it leads to immediate carbon emissions from the material burned, there is the possibility that the fire will escape the managed area, and prescribed fires often have other negative externalities, such as particulate matter and nitrogen oxide emissions (Peterson et al., 2005). They also can only be performed during certain times of the year—usually in the autumn in the Pacific Northwest—and therefore provided limited flexibility to landowners.

Suppression efforts that take place after a forest fire has been detected are the most widely used fire management tool at the moment. Average expenditures fighting fires in the U.S. were $300 million per year between 1970 and 1998, and they have increased dramatically in some years (more than 200%) since 1998 because of the greater number of large fires (Calkin et al, 2005). However, large suppression efforts over the past century have raised fuel loads much higher than their historic levels, thereby increasing the risk of a catastrophic fire, especially in much of the Western United States (Covington and Moore, 1994). As with prescribed burning, this paper does not investigate fire suppression activities directly, however it is expected that the management techniques discussed in this paper will have a positive effect on the ability to suppress fires quickly because of the lower risk of crown fires and overall stand mortality (Agee, 2002).

The third fuel treatment option is the practice of thinning a stand to remove excess trees and fuels. Thinning can be used to mitigate fire risk by reducing high fuel loads and improving wind stability that can prevent large trees from being blown down (Curtis et al., 1998). It can also be used to salvage material from disturbances and to avoid insect outbreaks (Goyer et al., 1998). Thinning a stand also provides some income from small trees that can help offset the cost of management (Barbour et al. 2004), and the reduction in stand density increases the annual growth rate of the remaining trees and accelerates the amount of merchantable timber available at the time of harvest (Curtis et al., 1982). The key component of thinning that we investigate in this paper is the ability to reduce the risk of a crown fire as small trees, ladder fuels, and surface fuels are removed from the stand, and that it is the best silvicultural treatment for a fire-prone stand that is also seeking carbon credits. The improved yields associated with intensive silvicultural treatments is also a beneficial aspect of our model worth investigating, as it raises the level of carbon that can be sequestered in growing biomass and subsequently stored in long-lasting wood products after harvests (Sedjo et al., 1995).

3. Economic Model: Discrete Time, Mixed State Model with Endogenous Risk

Endogenous risk appears whenever there is the conjunction of (i) individuals reacting to their environment and (ii) where the individual actions affect their environment. In practice, landowners with valuable timberland will take risk into account when deciding how to manage their stands, so that if the stands are prone to wildfire they will undertake management decisions to minimize the chance that their investment will be destroyed before the optimal harvest age, subject to the costs of various management alternatives. In the case where landowners are also obtaining benefits from carbon sequestration, they must also account for the lost revenues (or penalties) that may occur if fire damages or destroys their stand.

In this paper, the optimal forest management problem is modeled as an infinite horizon, discrete time, mixed state model. The numerical optimization procedures used to solve the model (described below) allow us to simultaneously determine the optimal management regime and rotation age for a stand that faces catastrophic forest fire risk and benefits from carbon sequestration and timber sales. The two continuous states in the model are (i) the quantity of standing timber (m^3/ha), $q = [q_o, q_{max}]$; and (ii) the amount of combustible fuel in the stand (tons/ha), $m = [m_0, m_{max}]$. The state variable m is positively correlated with—but not included in—the quantity of standing timber (q). The discrete state captures whether or not a forest fire occurs during a given time period. It is a random variable, $\tilde{\theta} = \{0,1\}$. For the purposes of this model, the probability of a fire occurring, $P(\theta=1)$, is assumed to be an "act of God" (e.g. lightning), which cannot be prevented or controlled.[1] The probability of fire occurring in any period depends on the fire return interval (FRI), which is widely available for different types of forests in different regions. This probability is given as:

$$P(\theta=1) = \frac{1}{FRI}$$
$$P(\theta=0) = 1- \frac{1}{FRI} \qquad (1).$$

[1] Historical data show that fires in the Pacific Northwest Douglas-fir stands are caused by both humans and lightning, however in this paper we assume that none of these fires can be prevented and are therefore considered "natural."

The forest manager has a choice of three different actions during any given time period, X={1,2,3}. If X=1, the manager lets the forest continue to grow without active management; if X=2, the manager thins the stand to remove excess fuels, to increase the annual growth rate of merchantable sawtimber, and to increase the proportion of timber that can be salvaged if a fire occurs; or if X =3, the manager clearcuts the forest and replants the entire stand. It is assumed here that only one action can be taken each time period (years).

The forest manager is rewarded for actions undertaken during each time period. If a fire occurs in a given time period, θ=1, and the manager is rewarded the amount of merchantable timber available from salvage cutting. Salvage is imposed after all fires, although the value of salvage depends on the two continuous state variables q and m, which are in turn dependent upon the optimally chosen management regime. The reward function for timber (f_{timber}) is:

$$f_{timber}(q,m,\theta,x)=\begin{cases}(1-g(m))\varsigma p q_{merch}-c_{fire} & \text{if } \theta=1 \quad \text{(salvage clearcut)}\\ -c_{\text{maint}} & \text{if } \theta=0,\ \text{X}=1 \quad \text{(do nothing)}\\ (m-m_0)p_{bio}-c_{thin} & \text{if } \theta=0,\ \text{X}=2 \quad \text{(thin stand)}\\ pq_{merch}-c_{rep} & \text{if } \theta=0,\ \text{X}=3 \quad \text{(clearcut stand)}\end{cases} \tag{2}$$

In equation (2), p is the deterministic price of the timber, $0<\varsigma<1$ is the fraction of the market price of timber that salvaged logs can be sold for[2], p_{bio} is the deterministic price (\$/ton) for fuel removed from the stand, and g(m) is a function that represents the proportion of timber that is burned and dies if a fire occurs. Mortality is determined by the amount of fuel in the forest at the time of the fire. The specific path for g(m) is

[2] See Baumgartner (1987) and Prestemon and Holmes (2000) for empirical examples

discussed in section 3.1. The volume of merchantable sawtimber that can be salvaged after a fire is one minus the mortality rate.

The model assumes that thinning only produces merchantable pulp and/or biomass energy material, but not merchantable sawtimber. Typically, pre-commercial thinning activities for forest fire management do not produce enough merchantable material to offset the costs of undertaking the thinning activity (Rummer et al., 2003 and Barbour et al., 2004). For simplicity, the costs of thinning (c_{thin}) are assumed to be fixed for each intermediate treatment, with the total cost (or profit) determined by the amount of fuel removed from the stand. Other costs include the costs of maintaining a stand on an annual basis (c_{maint}), costs of replanting the stand after a clearcut (c_{rep}), and the costs of clearing the site and replanting the stand after a fire (c_{fire}). Empirically, these costs are assumed to differ relatively as $c_{maint} \leq c_{thin} \leq c_{rep} \leq c_{fire}$. (Reed, 1984; Bair and Alig, 2006). There are no variable costs in this model.

The yield of growing stock (q) has a typical logistic shape such that the stand experiences faster growth in the early periods and slower growth as it matures. The amount of standing volume that can be converted to merchantable sawtimber is defined as q_{merch}, such that $\frac{dq_{merch}}{dq} \geq 0$, or the fraction of standing volume that can be converted to merchantable sawtimber increases as the stand grows over time (Figure 1). The remainder of the growing stock is used as pulpwood. The proportion used for sawtimber is also influenced by the management regime. Empirical studies suggest that thinning from below can increase merchantable sawtimber by 15% or more at harvest time (Miller et al., 1987; B.C. Ministry of Forests, 1997). Figure 2 shows the merchantable sawtimber volume for a hypothetical Douglas-fir stand with annual thinning and no thinning for the lifetime of the stand. Empirically, thinning is not performed every year, so the actual yield of merchantable sawtimber will fall between the two yields shown in Figure 2.

At the end of a year, all of the state variables face a transition function based upon the management decisions (or forest fire) that occur at the beginning of the period. The transition function for the growing stock volume ($q' = q_{t+1}$) is:

$$q' = \begin{cases} q_0 & \text{if } \theta = 1 \quad \text{(salvage clearcut)} \\ f(q)h(m) & \text{if } \theta = 0, \mathrm{X} = 1 \quad \text{(do nothing)} \\ f(q)h(m_0) & \text{if } \theta = 0, \mathrm{X} = 2 \quad \text{(thin stand)} \\ q_0 & \text{if } \theta = 0, \mathrm{X} = 3 \quad \text{(clearcut stand)} \end{cases} \qquad (3).$$

In equation (3), q_0 is the initial growing stock volume planted after a fire or clearcut, and *f(q)* is the change in the standing volume during the year (annual growth). The change in quantity of growing stock volume (timber) during the year is also influenced by the growth of fire-fuel, h(m). In this model, *f(q)* and *h(m)* are assumed to be separable, such that the fuel levels influence the rate of growth but not the total yield once the stand reaches biological maturity. This follows from the notion that a thinned stand, i.e. one with minimal surface and ladder fuels to hinder dominant tree growth, will increase merchantable sawtimber yields at a faster rate than an un-thinned stand.

3.1 Fuel accumulation and stand mortality

The stock of fuel, and consequently the change in the stock of fuel in the stand, is determined by management decisions. It is assumed that every time the stand is thinned, clearcut, or salvaged, the amount of fuel is reset to an optimal level[3] (m_0). The transition function ($m' = m_{t+1}$) for the state of fuel on the stand is:

$$m' = \begin{cases} k(m) & \text{if X = 1 (do nothing)} \\ m_0 & \text{otherwise (thin, clearcut, salvage harvest)} \end{cases} \quad (4).$$

In equation (4), m_0 is the initial fuel level, and $k(m)$ is the path of fuel accumulation in the stand over time. The proportion of timber that can be destroyed by a fire is formulated as a function of current fuels, $0<g(m)<1$, such that $\frac{dg(m)}{dm} > 0$ (Omi and Martinson, 2002; van Wagner, 1977). As a result, the fuel volume and fire hazard (mortality rate) are positively correlated, and fire intensity can be reduced through fuel treatments (Fig. 3). As fuel volume increases, the level of mortality when a fire occurs increases as well. When the stand is managed, by thinning, final management, or salvage harvest after fire, the fuel level and mortality rate are reset to the initial state, such that the proportion of trees destroyed in the event of fire is reduced.

3.2 Carbon benefits

Thus far, the model captures only timber market benefits. In order to take into account carbon benefits associated with holding mature trees and storing carbon in marketed products, the returns for carbon sequestration must be described. The value of carbon sequestration is assumed to a direct function of the stock of standing timber, and the quantity of timber harvested. The reward function for carbon sequestration is f_{carbon}, which is given as:

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[3] In this example, we consider "optimal" to be the amount of fuel that minimizes the risk of fire without compromising the growth of the stand. Different management objectives (e.g. increase biodiversity or riparian benefits) might require other levels of fuel.

$$f_{carbon}(q,m,\theta,x)=\begin{cases}(1-g(m))\alpha\beta p_c q_{merch} & \text{if } \theta=1 \quad \text{(salvage clearcut)}\\ \alpha r p_c q & \text{if } \theta=0,\ X=1,2 \quad \text{(do nothing, thin)}\\ \alpha\beta p_c q_{merch} & \text{if } \theta=0,\ X=3 \quad \text{(clearcut stand)}\end{cases} \qquad (5).$$

In equation (5), p_c is the price of carbon in \$/ton C (assumed to be constant in this analysis), α is amount of carbon in tons per cubic meter of growing stock, r is the interest rate, and β is the proportion of carbon that is permanently stored in finished wood products after the stand is harvested (i.e. the "pickling rate"). Using a rental price of carbon approach allows landowners to receive annual payments when the stand remains intact, thereby improving the incentives to reduce fuel levels. It is uncertain whether incorporating payments for converting timber into long-lasting wood products will increase or decrease the number of intermediate treatments or the rotation age. Also we assume that if the stand is thinned, landowners do not receive a carbon payment for removing the surface and ladder fuels, as there is no guarantee that it will be used as biomass energy. Material left on-site or converted into pulpwood is assumed to decay immediately.

3.3 Numerical analysis

The optimal management path can be solved by combining the state variables, the action variables, and the reward and transition functions for both the timber and carbon sequestration markets into a single Bellman equation:

$$V\{q,m,\theta\}=\max_{x=\{1,2,3\}}\begin{cases}(1-g(m))q_{merch}[p\varsigma+\alpha\beta p_c]-c_{fire}\cdots \\ \qquad +\delta E_{\tilde{\theta}}V(q_0,m_0) & \text{if } \theta\text{=1}\\ -c_{maint}+\alpha p_c r q_t+\delta E_{\tilde{\theta}}V(q',m') & \text{if } \theta\text{=0, X=1}\\ mp_{bio}-c_{thin}+\alpha p_c r q_t+\delta E_{\tilde{\theta}}V(q',m_0) & \text{if } \theta\text{=0, X=2}\\ q_{merch}[p+\alpha\beta p_c]-c_{rep}+\delta E_{\tilde{\theta}}V(q_0,m_0) & \text{if } \theta\text{=0, X=3}\end{cases} \qquad (6)$$

$V\{q,m,\theta\}$ is the expected present value of stage returns from applying the derived optimal policy X* across an infinite amount of stages, starting with a freshly planted stand. The maximand is the expected return of the current period from applying the optimal policy decisions plus the expected present value of continuing to apply the optimal policy starting at the next period, which is discounted by $\delta = 1/(1+r)$. This problem accounts for the stochastic effect of forest fires by incorporating the probability that a random shock, $\tilde{\theta} = \{0,1\}$, will occur equally in the next period or the subsequent periods that follow.

The endogenous specification and functional equations in this optimal rotation problem do not allow a closed form solution. Therefore, we approximate a solution to the Bellman equation using computational methods, specifically the method of collocation. This is achieved by writing the value function approximant as a linear combination of *n* known basis functions whose coefficients are to be determined, and then fixing the basis function coefficients by requiring that the value function approximant satisfy the Bellman equation, not at all possible states, but rather at the *n* collocation nodes (Miranda and Fackler, 2002). Once the collocation equation has been solved, residuals from the chosen collocation method are calculated to verify that the approximation errors are minimal across the entire domain of the value function. For our analysis, cubic spline basis functions were chosen to solve equation (6) in MATLAB 6.1 using the `dpsolve` routine included in the Miranda and Fackler (2002) COMPECON library.

4. Empirical data and application to Pacific Northwestern Douglas-fir stand

The model described above is implemented for a representative Douglas-fir (*Pseudotsuga menziesii*) stand in the Pacific Northwestern United States. Douglas-fir is important as a timber species and, potentially, as a warehouse for carbon sequestration. An average old-growth Douglas-Fir stand in the Pacific Northwest can hold over 200 metric tons of above-ground carbon per hectare (Birdsey, 1992). Stands in the Pacific Northwest are already susceptible to various levels of forest fire risk depending on the slope, elevation and weather and climate conditions of the stand. We test for alternative management regimes depending on the different fire return intervals using sensitivity analysis, and specifics are discussed below.

The specific functions and parameters used in the base case model are listed in Table 1. Alternative values used in the sensitivity analysis are also listed. The growth and yield functions are for an average Site III Douglas-fir with a site-index of 140 (average tree height at 100 years) were based upon stand tables compiled by McArdle (1949, 1961). The effects of thinning on stand growth were estimated based on USDA Forest Service technical reports on silviculture in Douglas-fir plantations (Miller et al., 1988; Curtis et al., 1998)

The price for timber is given as the average annual real stumpage sale prices (deflated to 1997 dollars using general producer price index) of Douglas-fir from national forests in Washington and Oregon from 1965 to 2002 (Howard, 2003). Carbon prices are varied across several different levels, consistent with other literature on the economics of climate change (van Kooten et al., 1995; Murray, 2000). Both the timber and carbon prices are assumed to be constant over time. Stand maintenance (c_{maint}) and replanting costs (c_{rep}) are assumed to be \$10/ha/yr and \$800/ha respectively. Thinning costs (c_{thin}) are varied across \$200/ha, \$400/ha, and \$800/ha in the analysis to test the sensitivity of the results to different levels of marketable outputs from thinning (Rummer et al., 2003). Post-fire replanting costs are assumed to be 25% greater than replanting costs after a regular clearcut because of the extra work necessary to prepare a site for regeneration (Reed, 1984).

The discount factor, δ, is set equal to 0.95 for most scenarios, implying a real rate of interest of approximately 5%. This is consistent with the commonly used discount factors that range from 0.93 to 0.97 in other forest investment research, which are also tested in two alternative scenarios. On average, fire return intervals for many Pacific Northwestern Douglas-fir stands are 50 years (Morrison et al., 1994), however, the actual fire return interval for a site will depend on slope, elevation and climate. To assess differences in fire return intervals caused by stand location, the fire return interval in the analysis is varied across three values, 25, 50, and 100 years.

The fuel accumulation and mortality rate functions are developed based on research by Brown et al. (2003), Omi and Martinson (2002), and Smith et al. (2003) (see Fig. 3). The salvage function is based on the potential for a stand-destroying crown fire based upon the current state of the fuel loads. This function was generated by multiple runs of the USDA Forest Service's Forest Vegetation Stand (FVS) growth simulator (Dixon, 2002) and the FVS-Fire and Fuels Extension Model (Reinhardt and Crookston, 2003). The FVS model projects stand conditions under a range of thinning alternatives (timber quantity and quality, fuel loads, likely fire severity, and stand mortality under fires with different levels of severity). The model was used with site conditions similar to those for our representative Douglas-fir stand to develop a representative fuel accumulation function, and to develop the stand mortality and salvage function shown in Figure 3.

5. Results

A number of different scenarios are developed in order to test the effects of different assumptions about fire frequency, thinning costs, carbon prices, the pickling of carbon in long-lasting wood products, and the discount factor on management intensity and the final rotation age. In the results, both stochastic and deterministic results are presented for each scenario. The stochastic results show what happens when simulations are conducted assuming a positive probability of fire. The deterministic results assume that this probability is 0.00.

5.1 Baseline

The baseline scenario in this example assumes that there is no value for carbon sequestration, and the fire return interval is 50 years (P(fire)=0.02). Under these conditions, the optimal rotation length in the stochastic model for Douglas-fir is 48 years. One thinning is found to occur optimally at 31 years after planting (Table 2). A deterministic version of the same model assumes no fire risk, and finds an optimal rotation age of 53 years, with one thinning, at 35 years. Thinnings are projected to occur earlier when there is a positive probability of fire, and the rotation age is five years younger for the baseline case when there is a probability of fire versus no risk. Thus, landowners invest in management and reduce their rotations to limit the potential losses from fires. Findings for the baseline are consistent with the other fire and optimal rotation literature. Bare land value (BLV)[4], a common method of measuring stand value in forest rotation problems, is only slightly higher in the deterministic case ($194/ha) than in the stochastic case ($189/ha).

5.2 Scenario analysis

Scenarios 2 and 3 examine the effect of a change in the fire return interval, holding all other parameters constant. As expected, an increase in the fire return interval, or probability of a fire, reduces the final harvest, while a decrease in the probability of a fire results in a longer rotation. The increase in fire return interval also results in one thinning that will occur earlier in the rotation, thus limiting the economic loss associated with the higher fire probability. The shorter rotation period relative to the deterministic model is consistent with results from others that modeled the stochastic risk of forest fires (Reed, 1984; Yoder, 2004), however the expected net present value of the stand does not decline all that much in the stochastic model. Where P=0.04, BLV is $187/ha suggesting that a doubling of the fire probability from 0.02 to 0.04 only reduces BLV by 4%, assuming that the stand reaches the optimal rotation age. Where P=0.01, the result is similar to the baseline case with no risk of fire, as the rotation age is 51 years, with one thinning at 33 years. The BLV is $190/ha, a decline of 2% relative to the deterministic baseline scenario.

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[4] In this analysis, the bare land value is equivalent to the maximum net present value of a stand that is harvested over an infinite horizon. Calculations are based upon modified Faustmann equations that are prevalent in the literature (see Reed (1984), and van Kooten et al. (1995) for examples).

The implications of carbon prices are introduced in scenarios 4, 5, and 6, with a price of $50/t C. The optimal rotation age increases relative to the baseline in each of the scenarios to 65, 62, and 58 years, respectively. Management becomes more intensive as well, with three thinnings in each case. Valuing carbon has a substantial effect on the value of land, as BLV rises substantially, to $1044/ha under scenario 4. Setting the probability of fire to zero reveals that the optimal harvest age is 69 years, with three thinnings, both similar to the stochastic case. BLV in the deterministic scenario is $1050/ha. All of the thinnings for the deterministic case are projected to occur later than the scenarios with a positive carbon price and risk of destruction. As before, BLV calculations for the stochastic and deterministic cases are similar, indicating that active management in a fire prone stand can yield similar payoffs if the risk of destruction is kept to a minimum.

Scenarios 7 and 8 examine the influence of changing the carbon price, but holding the fire return interval constant (50 years). Lower carbon prices reduce the rotation period, reduce the number of thinnings, and reduce BLV compared to higher carbon prices. In all cases, however, rotation ages are longer and management is more intensive than in the baseline case without carbon prices. Tests of carbon prices higher than those shown in Table 2 indicate that the rotation age continues to expand, management becomes more intensive (i.e., more thinnings), and BLV rises. In the presence of fire risk, landowners enrolled in a carbon sequestration program will continue to increase rotation lengths, and they will invest more in risk-reducing thinnings throughout the rotation period.

Altering the net financial effects of thinning does influence the rotation period and management (see scenarios 8 & 9). Lower net costs of fuel treatments (e.g., there are many opportunities to convert material to markets nearby) result in more frequent thinnings, and higher BLV. Not only are expected losses from fires minimized by frequent fuel removals, but growth is also enhanced. Interestingly, with lower fixed fuel costs and many thinnings, as the stand approaches the optimal harvest age, it is managed more intensely (i.e. less time between each thinning). Thus, in regions where there are many opportunities for harvesting pulpwood, or biomass material, nearby stands are likely to end up being highly managed, with many thinnings before final harvest. Of course, if net costs of fuel treatments are higher, fewer thinnings would occur, and stands are under more risk over their lifecycle. If society wishes to reduce the risk of fires, it may need to subsidize landowners or have large carbon payments to engage in more intensive management.

Scenarios 11 and 12 assess the effect of changing the pickling rate for carbon that is permanently stored in wood products. In scenario 11, the pickling rate is set to zero, such that the carbon is assumed to be immediately turned over in wood products and emitted into the atmosphere. When compared to scenario 5 (P(fire)=0.02, P_c=\$50), with all other parameters the same except that the pickling rate is 40%, the rotation age increases only 1 year, to 63. In scenario 12, where the pickling rate is 1 (i.e.,wood is permanently stored "forever"), the rotation age decreases relative to scenario 5, but only by 1 year. BLV differs only modestly across scenarios 5, 11, and 12. There is little influence on thinnings because the material thinned is not assumed to enter market storage. While pickling of carbon does have a slight impact on the rotation age, it does not have large effects on thinning rates, final rotation ages, or BLV when active forest management is taken into account.

Scenarios 13 and 14 test how rotations differ if we alter the discount factor relative to scenario 5. A lower discount factor (higher interest rate) reduces the rotation age, the number of thinnings and the BLV. A higher discount factor increases the all three indicators significantly. These findings are consistent for both the stochastic model and the deterministic case with no probability of fire. The changes in rotation age, thinnings and BLV are greater for the case where there is a lower interest rate, as investors are assume to discount the future less and are therefore willing to hold on to their investment for longer periods of time. Additionally, the frequent thinnings for the longer rotation insures against large losses in timber and carbon in the event of a fire.

Comparisons over the fourteen scenarios show that the deterministic model had at least as long of a rotation as the stochastic model for all twelve scenarios. A comparison of the number of thinnings performed for each rotation reveals that most of the scenarios had the same number of thinnings for the stochastic and deterministic case. The key difference between the stochastic and deterministic solutions is the age at which the thinnings occur. For every scenario, thinnings are performed earlier when the stand faces a positive risk of fire.

5.3 Comparison with previous research

It is perhaps useful to compare the results of the stochastic model developed in this paper with the earlier models of Reed (1984), van Kooten et al. (1995) and Stainback and Alavalapati (2004). These earlier models assume that the sole adjustment landowners can make in the face of forest fire, or other risks, is to adjust the rotation age. This is one important adaptation, but landowners can also work to "fire-proof" their forests by thinning. This section compares the results in this study with those in the earlier papers across several of the scenarios.

The four models compared are (1) The traditional Faustmann (1849) approach, which ignores fire risk entirely and which does not accommodate thinning; (2) The deterministic version of the model developed above, which sets P=0.00; (3) Reed's model; and (4) the stochastic model developed in this paper. For the implementation of Reed's (1984) model, the fire probability is simply added to the interest rate and the optimal rotation period and BLV are calculated. The exact methods and equations used to calculate models (1) and (3) are highly cited in the literature. The solutions[5] for stands with and without carbon pricing are calculated in a similar manner as models (2) and (4), with the exception that there is no option for intermediate management to influence both the growth and fire risk (see van Kooten et al., 1995, for example). The results for optimal rotations and BLV are shown for the baseline and scenarios 2, 3, 4, 5, and 6 in Table 3.

The Faustmann and deterministic models, as expected, show no differences across the different fire probabilities. Both show an increase in rotation age and an increase in BLV when carbon prices are incorporated. In the Reed and stochastic models, increasing fire probability reduces the rotation age. Adding carbon prices increases the rotation age in all cases. Of particular interest, however, is the notion that the Reed model suggests that land values are negative when fire probabilities are incorporated and there is no market for carbon sequestration. As fire probability increases, BLV becomes more

[5] Functional forms and calculations are available upon request.

negative. Under the stochastic model with endogenous fire risk, land values are positive in all cases. In fact, the Reed model would indicate that it is not economically efficient at all to invest in timber in the presence of fire risk, unless there is a positive price for carbon.

The results from our stochastic model found that in the presence of fire risk, landowners will continue to increase rotation lengths, although they will invest in risk-reducing thinnings throughout the rotation period. This result contrasts the findings of Stainback and Alavalapati (2004), who suggest that rotations in stands that were at risk of total destruction should *decrease* as the price of carbon increases because carbon storage is more effective as permanent storage in durable wood products. The model presented here allows for permanent storage of wood in products as well, but finds that rotations are still extended. Results from our study are more consistent with van Kooten et al., (1995), and Murray (2000), who both had deterministic models with no risk of fire.

5.4 Carbon storage

The results show that it is feasible to sequester carbon in forests that have fire risk. While it is true that higher fire risk reduces the carbon sequestered, with carbon prices, regions that face fire risk can still sequester carbon by intensifying management and increasing the rotation age. To show this, the following formula is used to calculate the present value of the carbon stock (S_0) over 200 years:

$$S_0 = \int_0^{200} c'(t) e^{-rt} dt \qquad (7)$$

where *c'(t)* is the annual change in carbon stock (tons C) in both growing stock, and the wood product stock (accounting for turnover). To account for the carbon turnover in durable wood products, we assume that merchantable sawtimber faces a decay rate of 1% per year (Winjum et al., 1998). Longer rotations extend the period for which carbon is accumulating as biomass and also delay the time when it is reintroduced to the atmosphere through harvesting and product emissions. Therefore, S_0 is representative of the present value of the carbon stock benefits of bare land allocated to rotational forestry.

Fig. 4 presents the path of the NPV of carbon stock per hectare for the four forest fire probabilities analyzed in this paper, assuming that all other base case parameters are held constant. In the baseline ($0/ton C) around 20.4 t C/ha is stored over the life of the stand, assuming no fire risk. With fire risk, sequestration decreases. This makes sense given that stands are likely to undergo a fire if they are not managed. Harvesting also reduces carbon stock by removing the carbon stored on the site. With carbon prices, however, rotations are extended, growth rates for merchantable wood are increased, and carbon storage increases. This is apparent in the graph, as the NPV of carbon stock goes increase with the price of carbon before reaching an asymptote of approximately 28 tons C/ha for all probabilities of fire.

6. Conclusion

This paper develops an optimal rotation model with endogenous risk for a stand with both timber and carbon sequestration benefits in a fire prone region. Silvicultural practices (specifically thinning) that allow risk and growth to be endogenous are introduced in the model. Because of the context of the stochastic optimization model developed in the paper, it is not possible to present analytical solutions to the optimal rotation problem. Instead, we use numerical simulations to show how timberland management and optimal rotations adjust when fire risk is present. Douglas-fir stands in the Pacific Northwestern United States are used for our numerical example, as they are important as a timber species and, potentially, as a warehouse for carbon sequestration.

Previous research on the effect of non-timber values on optimal rotation have shown mixed results. Englin et al. (2000) suggest that amenity values would still increase the optimal rotation period, but Stainback and Alavalapati (2004) find that rotations would decrease as the price of carbon increases. Their result hinges on the inclusion of wood product pools for carbon, which implies that it is better to store carbon in wood products than accept the risks of emissions associated with fires. Neither of these studies account for risk reducing management strategies that forest landowners may have. Amacher et al, (2005) developed a model with intermediate fuel treatments and a general non-timber amenity, but did not acknowledge its effect on timber yields. This paper improves upon previous research by directly incorporating the endogenous growth and stand mortality rates in the case of a forest fire into the decision making process. It also investigates the impacts that carbon prices could have on the optimal management regime.

A number of different scenarios are developed in order to test the effects of different assumptions about fire frequency, thinning costs, carbon prices, the pickling of carbon in long-lasting wood products, and the discount factor on management intensity and the final rotation age. Both stochastic (P(fire)>0) and deterministic results (P(fire)=0) are presented for each of the fourteen scenarios. Results indicate that a probability of fire *always* results in a lower rotation age relative to the deterministic case when there is no risk of fire. Higher carbon prices have a counter-effect, as the length of rotations increase regardless of the probability of a fire. This finding contradicts Stainback and Alavalapati (2004), who find that rotations would decrease as the price of carbon increases if there is a risk of total stand destruction.

Results also determine that thinnings used to reduce the risk of a stand-destroying crown fire increase in frequency as the stand approaches the optimal harvest age, especially when carbon prices are high. The amount of thinnings also increase when fixed costs for the fuel treatment is low. Thus, in regions where there are many opportunities for harvesting pulpwood, or biomass material, nearby stands are likely to be highly managed, with many thinnings before the final harvest. On the contrary, if net costs of fuel treatments are higher, fewer thinnings occur, and stands are under more risk over their lifecycle.

The Faustmann (1849) and Reed (1984) models are used to check the effect that endogenous risk and growth have on the optimal rotation problem. The Faustmann and deterministic models both show an increase in rotation age and an increase in BLV when carbon prices are incorporated. In the Reed and stochastic models, increasing fire probability reduces the rotation age. The Reed solution always indicates a shorter rotation relative to the stochastic model with thinnings, as there was no option to reduce fire risk with intermediate fuel treatments. Adding carbon prices increases the rotation age in all cases. Of particular interest, however, is the notion that the Reed model suggests that land values are negative when fire probabilities are incorporated, unless carbon prices are high. Under the stochastic model with endogenous fire risk, land values are positive in all cases, and shows that it can be economical to invest in fire prone areas if landowners exhibit active forest management.

According to our findings, enrolling a typical Douglas-fir plantation in a carbon sequestration program can provide significant benefits even when carbon prices are low. Carbon payments of $50/ton C can increase rotation ages by more than twenty percent and the present value stock of carbon by 10 to 25 percent compared to when there is no carbon market. This result was consistent regardless of the probability of fire, as landowners account for the risk of timber loss by increasing fuel treatments. Reduced thinning costs for a stand enrolled in a carbon sequestration program can increase carbon stocks by more than 25 percent relative to the baseline case as both the expected rotation age and sawtimber yields are increased with frequent stand management.

As the desire to curb global warming continues to rise, the benefits for investing in afforestation efforts in the Pacific Northwest and starting new plantations that can be used for long-term sequestration are expected to increase (USEPA, 2005). Having the knowledge and ability to mitigate the chance that a valuable stand will be destroyed in the fire prone areas of the Western U.S. further enhances the benefits of investing in timber plantations and enrolling in carbon sequestration programs. The overall reduction in emissions from forest fires coupled with the increase in carbon sequestration from optimal forest management provide benefits to landowners and society as a whole. Further research is needed to determine the effects of thinning and carbon prices on the optimal management of other stands that might vary in species composition, growth rates, or risk of mortality. This model could also be extended to research the optimal rotation problem with other non-timber amenities (riparian benefits, water quality, etc.), other risks (hurricanes, invasive species, etc.), and the role of biomass energy markets on large fuel removal programs.

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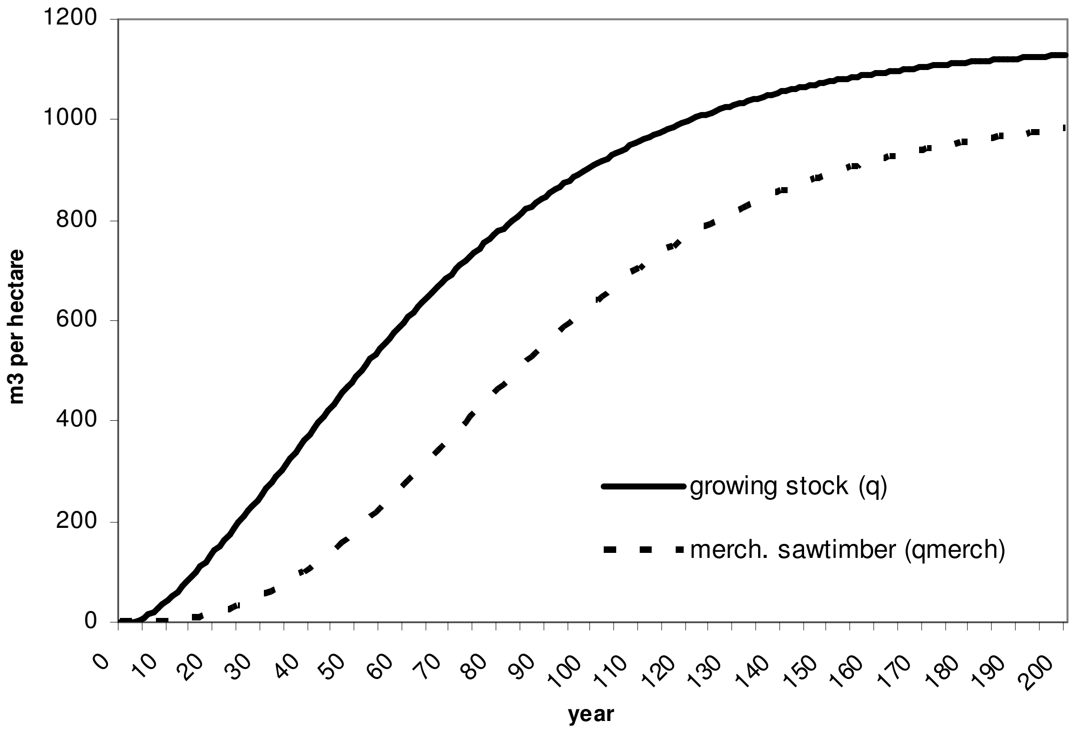

Fig. 1. Yield functions for Pacific Northwest Douglas-fir growing stock and sawtimber.

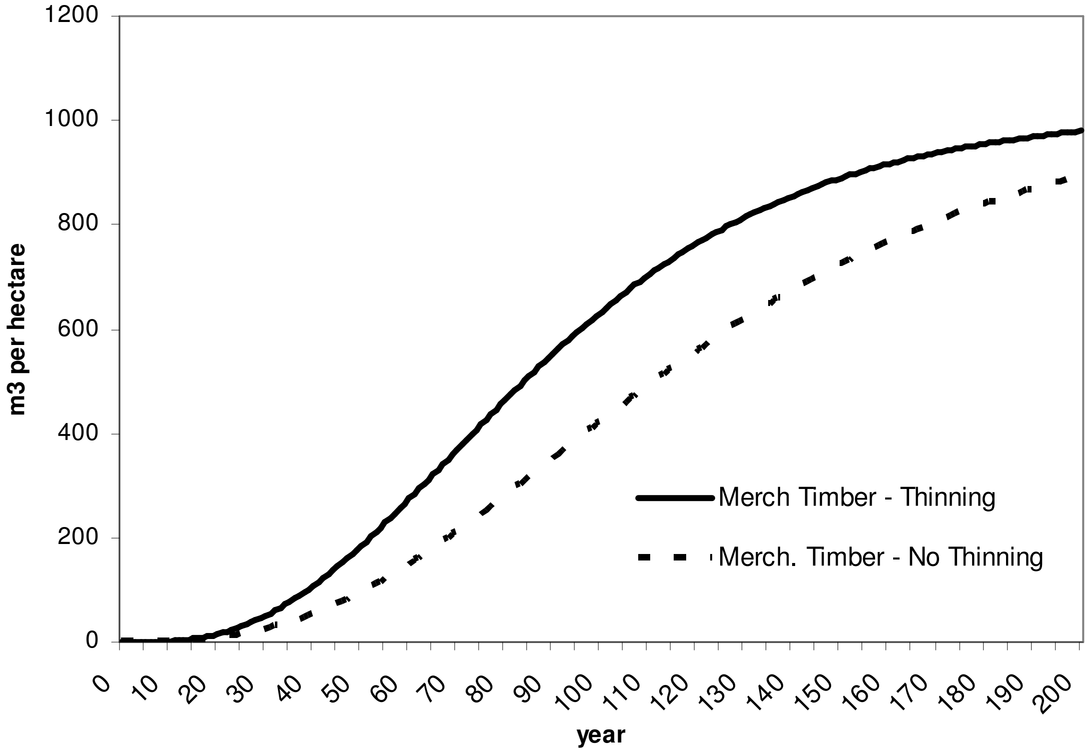

Fig. 2. Yield functions for Pacific Northwest Douglas-fir sawtimber with and without thinning.

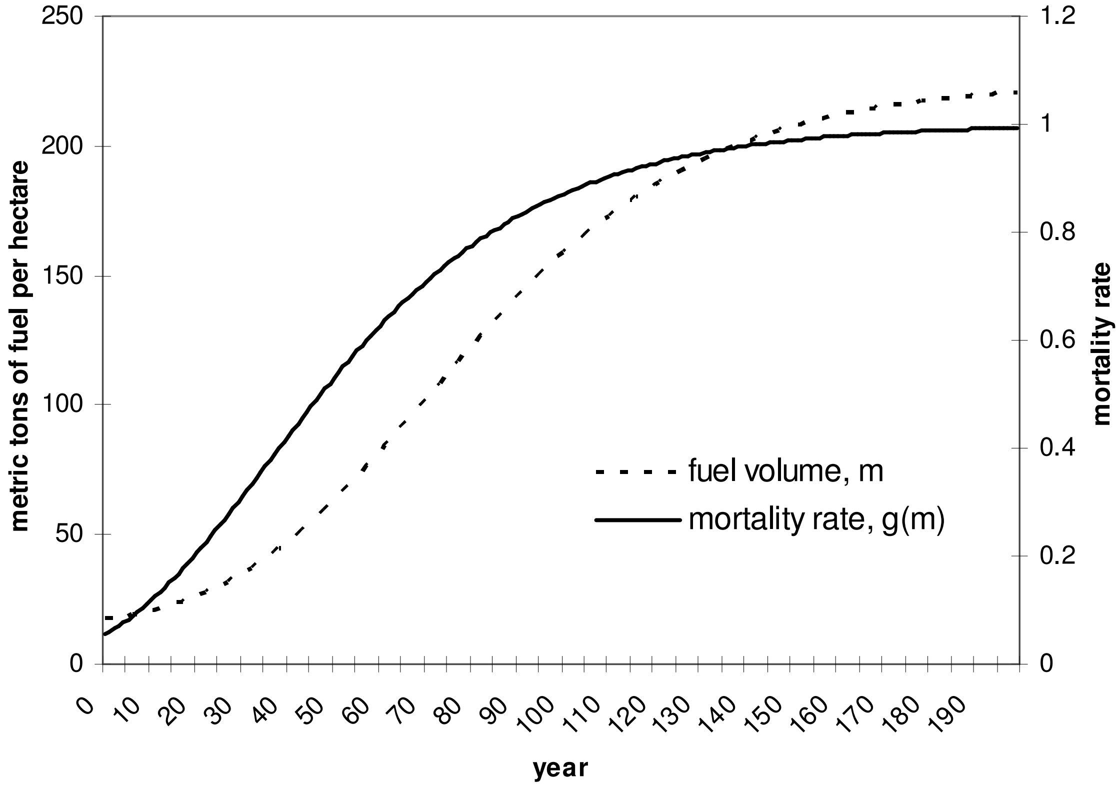

Fig. 3. Surface and ladder fuel volume and corresponding mortality rate, no thinning.

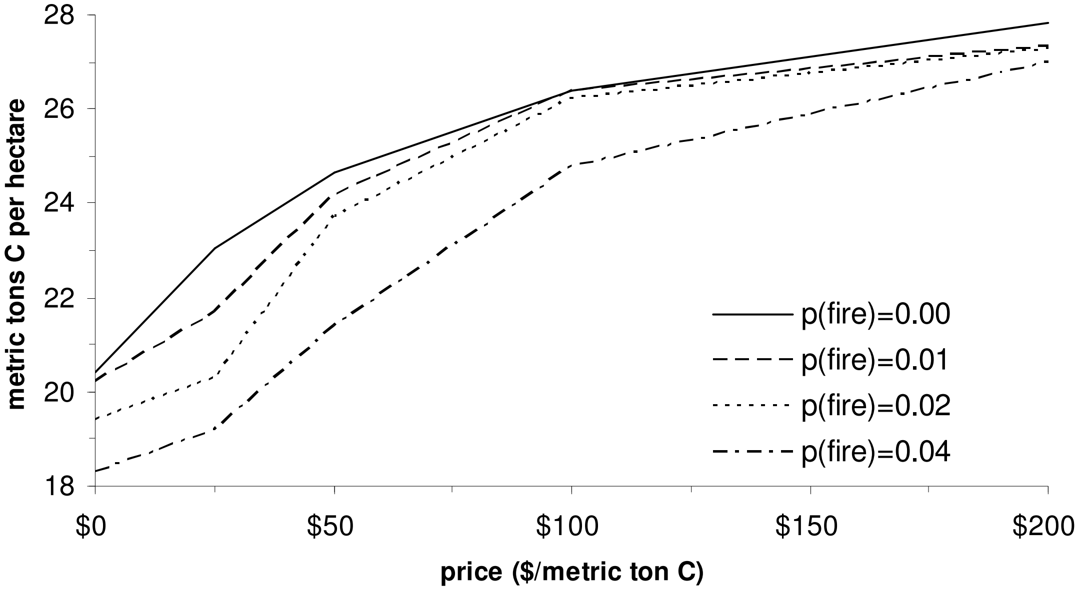

Fig. 4. Net present value of carbon stock (metric tons/ha) over 200 years for varying carbon prices and forest fire probabilities.

Table 1
Parameters and values used for Douglas-fir optimal rotation model

Parameter name	Symbol	Functional form / value	Alternative value(s)
Maintenance cost	c_{maint}	10	n/a
Thinning cost	c_{thin}	400	200, 800
Replanting cost	c_{rep}	800	n/a
Salvage cost	c_{fire}	1000	n/a
Discount factor	δ	0.95	0.93, 0.97
Rental rate of carbon	r	(1-delta)/delta	n/a
Stumpage price	p	60	n/a
Fraction of stumpage price for salvage sales	ς	0.75	n/a
Pulp price	p_{bio}	30	n/a
Min. forest stock	q_0	$q_0=1*10^{-23}$	n/a
Max. forest stock	q_{max}	1150	n/a
Optimal fuel level	m_0	0.05	n/a
Standing volume	q	q + h(m)f(q)	n/a
Annual growth function	h(m)f(q)	$\left[\frac{m_0}{m}\right]\left[q^{0.28}(3+\frac{q}{q_{\max}})(1-\frac{q}{q_{\max}})\right]$	n/a
Merchantable timber yield	q_{merch}	$q^2/1300$	n/a
Mortality function	g(m)	m^{γ}	$\gamma = 0.93$
Carbon price	p_c	50	0, 25, 100, 200
Carbon conversion	α	0.2	n/a
Permanent storage (pickling rate)	β	0.4	0.00, 1.00
Probability of natural fire	$P(\theta)$	$P(\theta=1) = 0.02$ $P(\theta=0) = 0.98$	0.01, 0.04
Fire return interval	FRI	50	25, 100
Fuel accumulation function	k(m)	$15^{(1+m\wedge\gamma)}$	$\gamma = 0.93$

Table 2
Results for stochastic and deterministic optimal harvest and management model

Parameters	**Baseline**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**	**Scenario 7**
stumpage price	$60	$60	$60	$60	$60	$60	$60
discount factor	0.95	0.95	0.95	0.95	0.95	0.95	0.95
fixed thinning cost	$400	$400	$400	$400	$400	$400	$400
price of carbon $/ton	$0	$0	$0	**$50**	**$50**	**$50**	**$25**
fraction perm. storage	0	0	0	**0.4**	**0.4**	**0.4**	**0.4**
probability of fire	0.02	**0.01**	**0.04**	**0.01**	0.02	**0.04**	0.02
Solutions (years)							
Stochastic Rotation	48	51	44	65	62	58	54
Deterministic Rotation	53	53	53	69	69	69	60
Stochastic Thinnings	31	33	29	26, 41, 54	26, 41, 51	26, 39,49	26, 41
Deterministic Thinnings	35	35	35	27, 43, 57	27, 43, 57	27, 43, 57	28, 46
Stochastic BLV	$189	$190	$187	$1,044	$1,040	$933	$382
Deterministic BLV	$194	$194	$194	$1,050	$1,050	$1,050	$504

Parameters	**Scenario 8**	**Scenario 9**	**Scenario 10**	**Scenario 11**	**Scenario 12**	**Scenario 13**	**Scenario 14**
stumpage price	$60	$60	$60	$60	$60	$60	$60
discount factor	0.95	0.95	0.95	0.95	0.95	**0.93**	**0.97**
fixed thinning cost	$400	**$200**	**$800**	$400	$400	$400	$400
price of carbon $/ton	**$100**	**$50**	**$50**	**$50**	**$50**	**$50**	**$50**
fraction perm. storage	**0.4**	**0.4**	**0.4**	0	**1**	**0.4**	**0.4**
probability of fire	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Solutions (years)							
Stochastic Rotation	73	61	66	63	61	59	74
Deterministic Rotation	73	65	73	69	67	61	84
Stochastic Thinnings	19, 33, 45, 56, 65	18, 30, 40, 47, 54	38, 55	26, 40, 52	26, 39, 51	28, 44	25, 38, 50, 59, 67
Deterministic Thinnings	19, 35, 48, 61	18, 30, 41, 50, 58	48	26, 44, 58	26, 42, 55	30, 49	26, 40, 53, 66, 75
Stochastic BLV	$2,302	$1,210	$907	$1,020	$1,141	$410	$2,984
Deterministic BLV	$2,310	$1,214	$918	$1,030	$1,149	$415	$3,005

Table 3
Comparison of endogenous risk models with Faustmann (1849) and Reed (1984) models without thinning option

Scenario	Faust.	Deter.	Reed	Stoch.	Faust.	Deter.	Reed	Stoch.
	Rotation length (years)				Bare land value ($/ha)			
Baseline								
Pc=0	51	53	42	48	$180	$194	-$189	$189
P(fire)=0.02								
Scenario 2								
Pc=0	51	53	45	53	$180	$194	-$50	$190
P(fire)=0.01								
Scenario 3								
Pc=0	51	53	40	44	$180	$194	-$339	$187
P(fire)=0.04								
Scenario 4								
Pc=$50	64	69	59	65	$1,050	$1,050	$590	$1,044
P(fire)=0.01								
Scenario 5								
Pc=$50	64	69	55	62	$1,050	$1,050	$352	$1,040
P(fire)=0.02								
Scenario 6								
Pc=$50	64	69	51	58	$1,050	$1,050	$69	$933
P(fire)=0.04								