The Impacts of Tradable Carbon Credits on Washington State Forestry Practices

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***Abstract**: Climate change is a challenge humanity is facing across the world. It is widely understood that human pollution, particularly the emissions of carbon are one of the driving factors of this trend. Currently many efforts to address this are focused on reducing the total amount of carbon emission. The Kyoto Protocols establish a system under which ability to pollute carbon is traded between firms, establishing an international market for carbon pollution. Many other efforts surrounding climate change are similar to this, with a focus on maintaining or reducing emission levels. The idea of carbon sequestration, where trees pull carbon out of the atmosphere and use it as a building block for growth, thus removing it from the environment, has growing support behind it as a method to actively reduce atmospheric carbon content. A program promoting this in Washington State is explored using a net present benefit model to create simulations of a carbon sequestration program, while including factors such as fire risk, the use of the wood after harvest, and various prices of carbon credits. This model showed that compensating foresters directly for the carbon sequestration was not the most efficient method of reducing atmospheric carbon, and a series of fees or safety requirements could achieve the desired result.*

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Introduction

Washington State Department of Natural Resources (DNR) holds over 5.6 million acres of land across the state. This land is used for a variety of endeavors, including mining, energy production, agriculture, and forestry. Of that land, 3 million acres are dedicated forest land used for recreation and business purposes alike. The working forests are often operated by a local branch of the National Forestry Service or private firms with DNR permits, both regularly harvesting the timber for market use. This land benefits Washington State in numerous other ways, including generating $94 million for Washington State' public education system and the environmental boon of a large and healthy forest (2016 Annual Report). Trees grow require three primary resources to grow; water, sunlight, and carbon. The process of trees extracting carbon from the atmosphere is called carbon sequestration, which, if the trees are not broken down through methods such as fire or decomposition, results in a permanent storage of the carbon. This paper will examine the possibilities of placing a value on carbon sequestration in Washington State and compensation of the foresters receive in doing so.

Literature Review

Forestry Management

Forestry Harvest Rotation Models

Forestry management was first examined through an economic lens in the late 19th century by Martin Faustmann, who wrote on the two inputs of logging: land and a stand of trees (Conrad, 2010). The stand of trees can vary in size, but are typically described as an area in which a group of trees grow, such as an acre or hectare. In this model, Faustmann derives the optimal harvest rotation of a stand of trees by comparing the marginal benefit of letting trees grow for one period more and the combined opportunity cost of harvesting and selling the wood now and the value of converting the land to another purpose. The Faustmann Rotation is based on the assumptions that prices of lumber are static, the rate of return on alternate assets, referred to as the discount rate, remains constant, and the stand to be harvested consists of trees that are the same age. The first of these assumptions has been expanded upon by many modern models, some having prices rise to match the rate of return, others letting risk of fire influence the price level (Gurtich and Howard, 2017; van Kooten, 1995; Daigneault et al., 2010; Spring et al., 2005; Insley and Lei, 2007). The discount rate is generally accepted to be a constant, with most models having a baseline set of parameters with a standard of 5% rate of return. The final assumption, that the trees are all of the same age, has been relaxed in more recent studies, with results discussed below.

Another model in forestry management is M. B. Usher's Matrix Approach to the Management of Renewable Resources (Usher, 1966). Usher's approach is tailored towards analyzing multiple stands of trees that are not of uniform age. While Usher's matrix approach can result in much more specific results regarding the percentage of trees harvested from each group in a given year, it does not provide insight of the economic benefits of harvesting at a given time, which is the scope of this endeavor.

Logging Practices

The assumption of a stand of trees all being the same age has also been challenged through changes to environmental views. There are two primary methods of harvesting timber in practice today (Kuuluvainen, 2012). The first is the most similar to harvesting of other crops; clearcutting, also called even-aged forest management. When clearcutting an area, such as the entire side of a hill, all trees are cut down and used in some way, be it fire wood, pulp for paper, or lumber. This process creates large stands of trees that are all of the same age, after the trees regrow from their initial harvest. Only a handful of trees are left as a security to keep the soil together with their root systems (Kuuluvainen, 2012). The second is a selective harvesting of trees based on width or diameter across a wide area. This method is called uneven-aged forest management due to its practice of leaving stands of trees that comprise a wide range of ages after each periodic harvest (Kuuluvainen, 2012). This practice can be done through a tree-by-tree selection, or by small groups of 5-10 trees at a time across a large area.

The two methods each have their own economic, ecological, biological and logistical issues. Uneven-aged harvest led to forests that were deteriorating over harvest cycles due to the strongest and largest trees being cherry-picked out, leaving the weaker trees behind to support the environment. This resulted in forests that had grown progressively less productive over generations as many of those that were left to reproduce were often slower growing (Kuuluvainen, 2012). The practice was banned in Finland in the late 1940s and in Sweden in 1950 (Kuuluvainen, 2012) due to the damage already done in years past after the forestry industry's products started declining in quality. Even-aged forest management, however, can be devastating to certain environments. When studying reptiles and amphibians in the Ozarks, Renken et al. (2004) found that even-aged and uneven-aged practices had little differences on the reptile population. The amphibian population, however, was found to have great losses in population and in biodiversity after even-aged harvests. They posit that this is due to the complete loss of canopy cover over water, which had a devastating effect on water quality (Renekin et al. ,2004). The forests in Washington face similar concerns due to the salmon spawning grounds in many of the rivers of the region. Conversely, it was found that watersheds suffered greatly under the regular use of machinery in uneven-aged forest management (Roberge et al., 2016). With annual harvests of timber, the heavy machinery would disrupt natural river paths, decreasing water purity as well. Even-aged forests had healthier waterways due to the infrequent presence of logging machinery, leaving plenty of time for recovery of the ecosystem (Roberge et al., 2016). A metastudy of comparisons between even-aged and uneven-aged practices and models do not determine one as being more economically efficient over the other. Even-aged management has an advantage by having an almost 15% lower marginal cost of timber volume harvested, but uneven-aged management has a higher revenue per year due to a being able to pick prime trees for harvesting, leaving smaller trees to grow and be harvested in subsequent years (Kuuluvainen, 2012).

Carbon Sequestration

Carbon sequestration in trees has great potential to mitigate the increasing carbon dioxide, which can then slow or optimistically reverse the changes in global mean temperature (IPCC, 2014). As trees grow, a vast majority of the matter they absorb and use for increasing their size comes from CO_2, which is then stripped of its carbon and released as Oxygen (Thompson et al., 2009). The carbon can then truly be sequestered and prevented from reentering the atmosphere by being used in some wood product, retaining the carbon in its current state for the foreseeable future (Daigneault et al, 2010). This way the wood is prevented from decomposing or being burned for energy, which will then release the carbon back into the air, defeating the purpose of sequestration. Turning wood into paper, however, has a questionable effect on the total carbon removed from the environment. This is due to most paper products finding a final resting place in a landfill, in which they will decompose over time, releasing any stored carbon. The rate at which the harvested lumber will remain in wood form is referred to as the pickling rate, which is approximately 50% across the industry, but can vary widely depending on the species of tree (Sedjo and Sohngen, 2000). The pickling rate accounts for such uses of wood as lumber or building supplies, carpentry, or any other durable wood product. This does not include disposable items such as pencils, chopsticks, or matches, as those products typically find their way to a landfill or the side of a road where they will deteriorate, or firewood and paper, as explained above. The practice of forest management as a way to offset a carbon footprint is used in a number of different regions, including Australia, New Zealand, Germany, and in the United States (Spring et al., 2005; Insley and Lei, 2007; Bosch et al., 2017; Hale et al., 2014; Gutrich). The United States National Forest Service has compiled data on carbon sequestration rates for all tree species found in the United States in the Carbon OnLine Estimator (Van Deusen, 2017).

Optimal Harvest Given Carbon Sequestration

Accounting for carbon sequestration as an addition to the Faustmann Rotation has extended the optimal harvest in nearly every case. In order to build upon the Faustmann Rotation, the value of the carbon credit was added to the price calculation of merchantable timber in many ways, such as an increase to the price of a given volume of lumber based on the carbon content at the time of harvesting, a series of payments based on carbon sequestration every year, or by reducing the costs faced by forestry firms such as taxes or fees (Gutrich and Howard, 2007; van Kooten et al., 1995; Price and Willis 2011; Hale et al., 2014). The compensation is dependent on the socially determined value of carbon through the trading of carbon emissions under the Kyoto Protocol. As more firms want to pollute, there will be an increase in the price of a carbon credit. The subsidy would then exist functionally as another source of revenue upon harvest.

Gurtich and Howard (2007) estimated that adding a carbon credit to the current model of forestry management would increase harvest rotations in New Hampshire by at least 16 years for quick-growing stock, and up to an additional 133 years of growth, depending on the forest type. In order to stabilize carbon dioxide levels, Guritch and Howard (2007) found that an optimal harvest cycle reaches up to 347 years. Interestingly, even though their model started with an even-age forest, after 45 years of growth, they found it to be almost as efficient to harvest 35% of the timber from the stand every 15 years as it would be to follow a fully even-aged rotation. Other concerns for extreme-duration growth cycles are given by Bosch et al. (2017) in that the lumber industry was not prepared to handle trees of such a diameter, cutting down on the ability to sell the timber and receive revenue. Further, while the growth models used could project trees living long past 120 years, Bosch stated that this is unreasonable considering that the expanding population may overtake forestland in that time period, rendering any growth null. These findings do assume that the timber being harvested will remain in that form and not deteriorate in any way; doing so would release the sequestered carbon back into the atmosphere. That means the lumber from the carbon sink trees would need to be preserved in some way, such as furniture, house frames, or even stored deep underground where they cannot decompose.

Fire Risk

Changes to the Harvest Rotation

Fires poses a great threat to a timber harvest rotation, even more so to one that is intended to act as a carbon sink. The threat of fire in a Faustmann rotation was first addressed by Reed (1984), who treated the occurrence as Poisson process, meaning they are random both in their appearance, but also in the time between them. Reed also assumed that a fire leaves no salvageable timber, and replanting will take place before the start of the next year. The Faustmann rotation model is altered to include the risk of fire by having it act similarly to the discount rate. As the probability of fire increases, the risk of losing all possible revenue is greater, leading the optimal harvest cycle to be shorter than without the presence of fire. Reed further extends this model by allowing for partial recovery of lost crop, given by a random percent as recoverable and the fixed costs to do so. He also allows for changes to the previously static risk of fire, setting it to increase as the age of the stand increases, simulating the accumulation of foliage and flammable groundcover.

Englin et al. (2000) support Reed's findings of forest fire risk, and expand on them further by loosening the prices of timber, allowing price to alter throughout the growth cycle. Building on Reed's adaptions and Englin's dynamic prices, the process of thinning to reduce wildfire risk, as well as the costs it incurs are added to the model of optimal harvest. Thinning is the process of going through and removing smaller trees in order to not crowd out larger, more profitable trees. It conversely removes more frail trees which may die and become fuel for a wildfire later. This resulted in an optimal rotation of greater duration than Reed's (Loisel, 2011).

Impact on Carbon Sequestration

Forest fires, such as those seen across the west all the way from Canada down to California in the summer of 2017, can undo a majority of the efforts to remove carbon from the atmosphere. This effect, however, does not happen instantaneously. Wildfires typically destroy entire stands of trees, and those left standing must be felled to not inhibit the regrowth of the forest (Spring et al., 2005). This process is expensive, not to mention the unanticipated replanting. Despite the relatively quick burning, much of the carbon still remains in the forest in the form of ash, mostly-burnt trees, and in underground stock of roots (McKinley et al.,2011). These remnants then take time to decompose, and the forest growing up around them sequesters the carbon they are releasing, and eventually the pre-fire stock level of carbon in the forest is achieved.

Minimizing Fire Risk

Yoder (2004) discusses many ways to reduce the possibility of fire, such as prescribed burns in which humans start fires that can be controlled, consuming groundcover that could serve as fuel for a larger fire. Yoder works in a framework of strict liability, a situation in which the person who starts the controlled burn is liable for all damages it may cause. From his work, it is found that short intervals of prescribed burns, once every 6.4 years, minimize the potential for a wildfire given an average risk of wildfire, determined from records of such events (Yoder, 2004). Periodic thinning of the timber can also mitigate losses due to wildfire. When there is a carbon credit present, the timber will be thinned less often in order to harvest greater lumber in the process, as well as maximizing the carbon sequestration (Daigneault et al., 2010; Guritch and Howard 2007). Instead of the controlled burn of Yoder, Daigneault et al. studies the effects of thinning as a means of reducing forest fire risk. He found that the time at which thinning should occur was at 30 and 39 years after planting, resulting in a reduced risk of fire, and a higher revenue per hectare than a Faustmann rotation without fire prevention as well as greater rate of carbon sequestration. This follows Guritch and Howard's findings for optimal output given a concern for carbon sequestration. It is, however, at odds with the "burn early, burn often" findings of Yoder. This may be due to the opposing interests of the two; Yoder aimed to minimize losses, where Daigneault et al. aimed to maximize profit through a Faustmann rotation.

Model Selection

The basis of the model used will be the Faustmann rotation model, using adaptions of Reed (1964) to include a growing risk of fire, as well as adding the value of carbon sequestration rates and their prices. A description of all used variables is summarized in Table 1, at the bottom of this section. The species chosen for this study is the Douglas Fir conifer tree due to forests in the pacific northwest having high proportions of Douglas (Daigneault et al., 2010). The cubic growth function for the Douglas Firs is as follows below as *Q(T),* the volume of wood in board feet harvestable on a given acre of land where *T* is the number of years since the trees were planted.

$$Q(T) = aT + bT^2 - dT^3$$

The value of merchantable timber, *V(T),* which will be maximized under the Faustmann Rotation model, is given below.

$$V(T) = Q(T) * [P_L + (P_C * SC * CbV)]$$

The value of merchantable timber which is a function of the volume of merchantable timber, *Q(T)*, the price of lumber, P_L, and the effective price of the carbon content in the harvested wood, $P_C * SC * CbV$). This effective carbon price is a product of the price of carbon, P_c, the pickling rate, *SC*, and the carbon by volume, *CbV*. This results in a price of carbon that takes into account the amount of carbon in a given volume of wood and what portion of that volume of wood that will be used in a durable good, keeping the sequestered carbon out of the atmosphere for the foreseeable future. The Faustmann optimal rotation model begins with the statement that the present value of net benefits of the forest harvest rotation, π, is the value of the merchantable volume of wood*, V(T)*, minus the costs of harvesting and replanting, *c*, discounted to the future for an infinite number of periods.

$$\pi = [V(T) - c]e^{-\delta T}(1 + e^{-\delta T} + e^{-2\delta T} + e^{-3\delta T} + \cdots)$$

This simplifies to the following equation with the infinite series $(1 + e^{-\delta T} + e^{-2\delta T} + e^{-3\delta T} + \cdots)$ converging to $\frac{1}{1-e^{-\delta T}}$, so long as 1 > $e^{-\delta T}$ > 0.

$$\pi = \frac{[V(T) - c]e^{-\delta T}}{1 - e^{-\delta T}}$$

$$\pi = \frac{[V(T) - c]}{e^{\delta T} - 1}$$

This equation gives the present value of net benefits for a single rotation of duration *T*. To find the optimal rotation, the net present value must be maximized. This can be done by taking the partial derivative *dπ/dT* and setting it equal to 0, thus finding the maximum.

$$\frac{\partial \pi}{\partial T} = [V(T) - c](-1)\left(e^{\delta T} - 1\right)^{-2} e^{\delta T}\delta + \left(e^{\delta T} - 1\right)^{-1} V'(T) = 0$$

Solving for *V'(T)* leaves the classic Faustmann equation for finding optimal growth.

$$V'(T) = \frac{\delta[V(T) - c]e^{\delta T}}{e^{\delta T} - 1}$$

$$V'(T) = \frac{\delta[V(T) - c]}{1 - e^{-\delta T}}$$

This equation states that the optimal harvest period to maximize π will occur when the marginal benefit of letting the forest grow for one more period, *V'(T)*, is equal to the interest earned on the profit from harvesting the forest now. Simply put, this demonstrates that if an alternative asset will provide a better rate of return than the forest, the optimal course of action to take is to liquidate the trees and invest in that other asset. Otherwise, it is best to let the forest continue to grow for another period and harvest in a later period. From this point, a few observations can be made.

Reed's expansions of the Faustmann equation allow for the risk of fire, λ, to be included into the calculation of net present value as such:

$$V'(T) = \frac{(\lambda + \delta)[V(T) - c]}{1 - e^{(\lambda + \delta)T}}$$

Doing so “effectively adds a premium to the risk-free time-preference rate [that is] determined exogenously” (Reed, 1984). Adding a risk of fire in this way will decrease the optimal harvest cycle in the same way as if δ increased, as outlined above. Reed’s (1984) expansions on this model included a risk of forest fire that increased as the number of years elapsed since the last harvest, represented as $\lambda(T)$.

$$\lambda(T) = \lambda_0 + .001\mathrm{T} - \theta$$

The probability of fire is a function of the total wood volume, a probability of fire given that there are no trees present, λ_0, and preventative measures, such as thinning, θ. The preventative measures also incur costs, represented by c_θ for thinning. Combining these additional factors results in the specific simulation model that will be used in the examination of the effects of foresters being able to use their production to claim the benefits of carbon sequestration and the related carbon credits.

$$V'(T) = \frac{(\lambda(T) + \delta)[V(T) - c - c_\theta]}{1 - e^{(\lambda(T)+\delta)T}}$$

Excel’s Solver analysis toolkit will then be used to solve a number of simulations with a range of each variable, as well as with and without the added revenue of carbon credits. Using these comparative dynamic models, an effect on the optimal harvest rotation time can be gained, as well as information about the short-term and long-term impacts on the supply for lumber.

Table 1: Summary Table of Variables

Name	Symbol	Base Simulation Values	Alternative Values
Harvest cycle duration in years	T	*n/a*	
Factors of tree growth, based on the site class-index of land	*a, b, d*	$a=-293.524$ $b=9.428$ $d=-0.034$	
Present Value of Net Benefits of forest	π	n/a	
Discount rate	δ	0.05	0.00, 0.1
Risk of fire in year 0	λ_0	0.02	Increasing by .01 per 10 years
Chance of Fire as a function of *T*	$\lambda(T)$	*n/a*	
Price of Lumber	P_L	\$0.579 board foot	OTHER VALUES
Price of Carbon	P_C	\$0 per ton	\$25, \$50, \$75, and \$100 per ton
Pickling rate	*SC*	0.2	0.5, 0.8, 1.0
Carbon by Volume that is sequestered in harvested tree	*CbV*	0.5	
Reduction of fire risk through thinning	θ	0.01 per thinning	0.02 per thinning
Costs of harvesting and replanting	c	\$161.87 harvest per acre	200, \$400
Costs of thinning	c_θ	\$161.87 per thinning, per acre	\$323.74 per thinning, per acre

Parameter Selection

This set of simulations will examine the Olympic Experimental State Forest (OESF), located on the western side of the Olympic Peninsula in Washington State. This site was chosen due to the historic rate of low fire risks, as well as the possibility for a carbon-sensitive forest management to be partially or fully adopted. The OESF contains approximately 270,000 acres of state trust lands and an area of active research into timber revenue production and the resulting ecological impacts. The parameters for the growth rate of the forest will be attained using McArdle et al (1961)'s study of Douglas Fir timber production per acre. This data was chosen due to accessibility in terms of regression and that it has been used repeatedly in this field and remains a standard of the industry (Daigneault et al., 2010). A map of Washington State's soil quality categorized a majority of the OESF to be that of site class 3, the average of which is at site class index 110 ("ArcGIS Site Class," 2017). The corresponding site class's timber production data was then regressed using the OLS method to produce the following growth function, where T is the number of years since the trees were planted and Q is the board feet of wood at a given year in an acre.

$$Q(T) = -293.524\,T + 9.428\,T^2 - 0.034T^3$$

$$R^2 = .999 \quad (28.472)^{***} \quad (0.531)^{***} \quad (0.002)^{***}$$ [1]

Many of the values of the simulations will be closely tied to those found by Daigneault et al. (2010) because of the similarity of the regions studied. Table 1 displays these initial values, as well as the values tested in other scenarios. The price of timber is initially set at \$579/ thousand board feet, or \$.579 per board foot ("Mill Log Prices," 2017). Further values tested include \$0.876 per board foot and \$0.198 per board foot, the regional high and low bids for the coastal region of Washington. The price of carbon is initially set to \$0 per ton to show the lack of accounting for carbon sequestration, then expanded upon using Daigneault et al.'s array of prices at \$25, \$50, \$75, and \$100 per ton (Daigneault et al, 2010). Many simulations will use a price of carbon at \$50, indicating a high social value of carbon.

The discount rate is set to 5% and the risk of fire when no trees are present is 2% (Daigneault et al, 2010). Much higher and lower values of the discount rates are also examined to find a trend effect on the optimal harvest cycle. The fire rate will also increase at 1% per 10 years, so in the 60th year of the harvest cycle, the total risk of fire is 8%, representing the accumulation of foliage, fallen branches, and the like. Preventative actions, such as thinning, will take place in the 30th and 39th year, as found by

[1] *** indicates significance at 1% level

Daigneault, reducing the risk of fire by 1% and incurring a cost of $161.87 per acre, per thinning. More rigorous thinning will be simulated with a fire reduction of 2% at $323.74 per acre, per thinning. The cost of harvesting and replanting will also be $161.87 per acre (Daigneault et al, 2010). The cost of harvesting and replanting will also be examined at $200 per acre and $400 per acre.

The carbon by volume, is set to 50% because half of the mass in dry wood is carbon (Dovetail Partners, 2013). To find the carbon content in a given board foot, the following set of conversions were implemented. Douglas Fir wood has a density of 33 pounds per square foot, translating to 2.75 pounds per board foot, converting to 0.001375 tons per board foot ("Density of Wood Species"). The pickling rate, the rate at which harvested timber will be used in such a way as to not release the carbon back into the environment, will be initially set using Daigneault et al. value of 20%, but will be increased to values of 50%, 80%, and 100% (Daigneault et al, 2010). With a value of 20% for pickling and 50% for sequestration, only 10% of the value of carbon sequestration impacts the harvest cycle. Further, Douglas Fir is a porous conifer, meaning it is a poor fuels source when burned for energy due to the lower density of the wood, and the high sap content of the wood produces large quantities of smoke when burned (Keeler, 2016). Further simulations will use a secondary baseline value of 50% to demonstrate active efforts to use the timber in such a way that would store the sequestered carbon for the foreseeable future.

Results

Simulations were run by maximizing the net present value of the harvest by changing the harvest period, T, using Excel's Solver program to compute the calculations. The detailed results of the simulations can be seen in Table 2, Table 3, Table 4a and 4b, Table 5 and Table 6. The total carbon sequestered per acre, the secondary output of these simulations, was obtained by multiplying the carbon content per board foot with the pickling rate, finding the weight of carbon that would be sequestered per acre at the end of the harvest cycle.

The first set of scenarios, 1-4, demonstrate the impact on the harvest cycle duration as various prices of carbon are included to the calculation. The highest price for carbon, $100 per ton, results in a miniscule change from the initial scenario; that of .112 years, or just under 41 days. The shortening of harvest duration comes from the method of including the price of carbon and its related rates as an aspect of determining the value of the merchantable timber. As an increase in P_L would reduce the harvest duration, so does an increase in price increase in P_C, although P_C is filtered through the density conversions and, pickling rate. Each dollar increase in the price of carbon results in a total price increase of under 7 thousandths of a cent per board foot. The maximum carbon price simulated, $100 per ton, only resulted in a total price increase of just $0.06875 per board foot. At the $100 price point, carbon accounts for $87.28 of the total acre's value of $1,994.24. As can be expected, a small decrease in harvest duration reduces the total yield from the acre, decreasing the total carbon sequestered per acre. The impacts of these simulations can also demonstrate the effect of a government program, such as tax cuts or subsidies, to incentivize foresters to cut a socially optimal manner time when including carbon. The effects of such a program are not to the effect desired, reducing the harvest duration and reducing carbon uptake overall.

Table 2. Introduction of Price of Carbon

	Initial Scenario	Simulation 1	Simulation 2	Simulation 3	Simulation 4
Discount Rate	0.05	0.05	0.05	0.05	0.05
Risk of Fire in Year 0	0.02	0.02	0.02	0.02	0.02
Price of Lumber, $/FBM	$0.58	$0.58	$0.58	$0.58	$0.58
Price of Carbon, tons	$0	$25	$50	$75	$100
SC	0.2	0.2	0.2	0.2	0.2
CbV	0.5	0.5	0.5	0.5	0.5
Reduction of Fire by thinning	0.01	0.01	0.01	0.01	0.01
Costs of harvesting	$161.87	$161.87	$161.87	$161.87	$161.87
Costs of thinning	$161.87	$161.87	$161.87	$161.87	$161.87
Optimal Harvest Cycle	46.655	46.625	46.597	46.570	46.543
Carbon Sequestered, tons	0.458	0.456	0.455	0.454	0.453

Table 3 shows the second set of simulations, showing the middle price point of $50 and the subsequent effect increasing the pickling rate has upon the optimal harvest cycle. This results in a similar decrease in harvest cycle as the increase in P_C due to it functionally increasing the V(T) at any given year. The main demonstration of this set of scenarios is in how the total carbon sequestered increases dramatically as more of the harvest is used in such a way that the carbon is not released back into the environment. An extremely high effort to sequester carbon after harvest, SC=1.00 is indicative of a situation in which all wood that is harvested is then used in extremely strict ways, such as storing all the harvested wood deep underground in some way to stop all deterioration, such as being treated in tar. A value of SC=0.50 is understandably more possible, and will be used in further simulations to display a moderate effort to sequester carbon.

Table 3. Increasing Carbon Sequestration Efforts

	Simulation 1	Simulation 5	Simulation 6	Simulation 7
Discount Rate	0.05	0.05	0.05	0.05
Risk of Fire in Year 0	0.02	0.02	0.02	0.02
Price of Lumber, $/FBM	$0.58	$0.58	$0.58	$0.58
Price of Carbon, tons	$50	$50	$50	$50
SC	0.2	0.50	0.80	1.00
CbV	0.5	0.5	0.5	0.5
Reduction of Fire by thinning	0.01	0.01	0.01	0.01
Costs of harvesting	$161.87	$161.87	$161.87	$161.87
Costs of thinning	$161.87	$161.87	$161.87	$161.87
Optimal Harvest Cycle	46.640	46.516	46.440	46.391
Carbon Sequestered, tons	0.458	1.129	1.791	2.227

An increase in the costs of harvesting and replanting, shown in Table 4a and 4b yeild an overall increase in the harvest duration. Simulations 8 shows a small increase in *c*, just $28.13, with all else equal, but results in an increase in optimal harvest cycle of 73 days, a change of greater magnitude than P_C=$100 of simulation 4. Further increases in *c* results in extended harvest durations in all scenarios, and the inclusion *PC*=$50 with low and middle values of *SC* did little to alter this. Simulation 14 demonstrates a massive change to price, more than quadrupling it from simulation 10. This results in over a 2.8-year increase in the optimal harvest cycle, and consequently sequestering more carbon. This set of simulations is included to demonstrate the possible effects of a government program aimed to increase total uptake of carbon in the logging industry, though methods such as taxation. When compared to positive values of P_C in simulations 1-4, this set of cost increases is much more effective at changing the optimal harvest rate than an increase in benefits in terms of increasing total carbon sequestration. If there were to be a push in government to take considerations of climate change into effect, this model demonstrates the most effective way to do so.

Table 4a. Increasing Costs of Harvesting and Replanting

	Initial Scenario	Simulation 8	Simulation 9	Simulation 10
Discount Rate	0.05	0.05	0.05	0.05
Risk of Fire in Year 0	0.02	0.02	0.02	0.02
Price of Lumber, $/FBM	$0.58	$0.58	$0.58	$0.58
Price of Carbon, tons	$0	$0	$50	$50
SC	0.2	0.2	0.20	0.50
CbV	0.5	0.5	0.50	0.50
Reduction of Fire by thinning	0.01	0.01	0.01	0.01
Costs of harvesting	$161.87	$200.00	$200.00	$200.00
Costs of thinning	$161.87	$161.87	$161.87	$161.87
Optimal Harvest Cycle	46.654	46.854	46.793	46.706
Carbon Sequestered, tons	0.458	0.468	0.465	1.152

Table 4b. Increasing Cost of Harvesting and Replanting

	Simulation 11	Simulation 12	Simulation 13	Simulation 14
Discount Rate	0.05	0.05	0.05	0.05
Risk of Fire in Year 0	0.02	0.02	0.02	0.02
Price of Lumber, $/FBM	$0.58	$0.58	$0.58	$0.58
Price of Carbon, tons	$0	$50	$50	$50
SC	0.2	0.20	0.50	0.50
CbV	0.5	0.50	0.50	0.50
Reduction of Fire by thinning	0.01	0.01	0.01	0.01
Costs of harvesting	$400.00	$400.00	$400.00	$800.00
Costs of thinning	$161.87	$161.87	$161.87	$161.87
Optimal Harvest Cycle	47.879	47.797	47.681	49.541
Carbon Sequestered, tons	0.520	0.516	1.275	1.518

Changing the time sensitivity of the foresters is also simulated in the presence of no inclusion of carbon, as well as medium prices of carbon and sequestration efforts, seen in simulations 15-18. The result is an inverse relationship between discount rate and harvest cycle; as discount rates decrease, the effect of costs on the evaluation of net present benefits become less impactful, so the harvest cycle increases in duration. As shown in Reed’s adaption of the Faustmann rotation, a risk of fire operates in the same way as the discount rate. Combining the effects in simulations 8-15 and 15-18, simulations 19-21 demonstrate the effects of increasing the effort of fire prevention and their associated costs. In these simulations, the risk of fire per thinning is reduced by 2%, but the total cost of each thinning is doubled. As could be inferred from above simulations, the end result is to increase the harvest cycle under these conditions.

Table 5. Alternate Discount Rates

	Simulation 15	Simulation 16	Simulation 17	Simulation 18
Discount Rate	0.1	0.1	0.00	0.02
Risk of Fire in Year 0	0.02	0.02	0.02	0.02
Price of Lumber, $/FBM	$0.58	$0.58	$0.58	$0.58
Price of Carbon, tons	$0	$50	$0	$50
SC	0.2	0.5	0.2	0.5
CbV	0.5	0.5	0.5	0.5
Reduction of Fire by thinning	0.01	0.01	0.01	0.01
Costs of harvesting	$161.87	$161.87	$161.87	$161.87
Costs of thinning	$161.87	$161.87	$161.87	$161.87
Optimal Harvest Cycle	44.708	44.562	49.532	49.401
Carbon Sequestered, tons	0.364	0.893	0.607	1.499

Table 6. Increasing Fire Prevention Efforts

	Initial Scenario	Simulation 19	Simulation 20	Simulation 21
Discount Rate	0.05	0.05	0.05	0.05
Risk of Fire in Year 0	0.02	0.02	0.02	0.02
Price of Lumber, $/FBM	$0.58	$0.58	$0.58	$0.58
Price of Carbon, tons	$0	$0	$50	$50
SC	0.2	0.2	0.2	0.5
CbV	0.5	0.50	0.50	0.50
Reduction of Fire by thinning	0.01	0.02	0.02	0.02
Costs of harvesting	$161.87	161.87	161.87	161.87
Costs of thinning	$161.87	323.74	323.74	323.74
Optimal Harvest Cycle	46.654	49.332	49.245	49.120
Carbon Sequestered, tons	0.458	0.596	0.591	1.462

Conclusions

This paper expands upon Reed's adaption of Faustmann's optimal harvest rotation by including the socially determined value of carbon sequestration and efforts to reduce fire risk. The model presented includes the primary aspects of forestry management, such as growth of lumber, price of lumber, costs of harvest, discount rate, risks and associated costs of fire, and carbon sequestration. Each of these aspects can be expanded upon further, such as including independently and identically distributed fire risk, changing prices through multiple periods, or carbon payments over time instead of as a large sum upon harvest. This model's findings also reinforce the idea of socially optimal results and the necessary steps to do so. Providing a positive incentive, such as a payment for socially beneficial action, may not always be as effective as creating a penalty for undesired behavior. In a case where the goal is to extend the harvest duration for timber, a tax could be put in place that incentivizes foresters only to harvest only after a certain time period from planting. Further examination of tree growth patterns that reflect recent changes to the environment, as well as more in-depth study of how certain efforts of fire risk reduction actually impact the probability of fire can expand on the accuracy of this model and the applications of its results.

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