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Carbon Uptake and Forest Management under Uncertainty: Why Natural Disturbance Matters

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ABSTRACT

This study examines how natural disturbance can adversely affect the carbon sequestration potential of the forest, and the potential contribution that genomics might make towards offsetting these impacts when carbon is priced. A stochastic dynamic programming model of the BC interior, which includes a detailed carbon accounting module, shows that harvests are delayed as carbon prices rise, with less carbon stored in harvested wood products and more in the forest ecosystem, but an increase in the risk of natural disturbance causes the landowner to harvest sooner. As natural disturbance increases in prevalence and severity, this will somewhat offset the lengthening of rotation age that occurs when carbon is priced. With disturbance, the total amount of carbon sequestered falls significantly, but some of this can be recovered through proactive planting of genetically modified (GM) stems that are more productive and less susceptible to disturbance. To make such an investment worthwhile, however, the costs of planting GM stock should not exceed \$120–\$150/ha. Finally, this study suggests that a modest price of carbon (somewhat less than \$25/tCO_2) can be an effective incentive to encourage land owners to reduce the rotation age brought about by disturbance, and generate additional carbon offsets.

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1 Introduction

Through its Nationally Determined Contribution (NDC) to the Paris Agreement (December 2015) of the UN's Framework Convention on Climate Change (FCCC),[1] Canada agreed to reduce its carbon-dioxide-equivalent greenhouse gas (hereafter simply CO_2) emissions by 30% below 2005 levels by 2030. It will do so by, in the transportation sector, imposing CO_2 emission-intensity standards and requiring gasoline contain 5% ethanol and diesel fuel 2% canola-derived fuel.[2] In the electricity sector, the government will eventually eliminate coal-fired power and/or require carbon capture and storage, while incentivizing use of renewable sources, mainly wood biomass, solar and wind energy along with hydro and geothermal to a lesser extent, and improve the efficiency of natural gas-fired power plants. Canada's strategy will also involve reducing CO_2 emissions from the use of chemicals and nitrogen fertilizer, especially in agriculture, and reduce the use of HFCs; increase the role of terrestrial carbon sinks; and purchase carbon offset credits from other countries. While provincial governments have jurisdiction over natural resources, the federal government also intends to lean heavily on forests for sequestering carbon; indeed, under the earlier Kyoto Protocol (KP), Canada intended to rely on forestry activities for between one-fifth and one-quarter of its commitment (van Kooten, 2004, pp. 110–115; Stennes *et al.*, 2005, p. 274).

Canada's subsequent experience with carbon sequestration related to forestry activities was characterized by natural disturbance, particularly the mountain pine beetle invasion in British Columbia but also wildfire (Safranyik and Wilson, 2006). Indeed, Kurz *et al.* (2008) demonstrated that Canada's forests are a net carbon source if natural disturbances are taken into account. Further research by the Canadian Forest Service indicated that the greatest carbon benefits often came because carbon was stored in post-harvest wood products (Lemprière *et al.*, 2013; Smyth *et al.*, 2014; Xu *et al.*, 2017), which the KP did not recognize. As a result, when Canada developed its NDC for the Paris Accord, it specifically addressed the need to consider the role of wood product sinks in storing carbon and the threat of natural disturbance: "Canada intends to account for the land sector using a net-net approach, and to use a 'production approach' to account for harvested wood products. Canada will exclude emissions from natural disturbances."[3] This policy approach would

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[1] Available at http://unfccc.int/focus/ndc_registry/items/9433.php [Accessed February 21, 2018].

[2] Between September 2016 and August 2017, Canada imported 1256 million liters of ethanol from the U.S., with more likely to be imported in the future (USDA Foreign Agricultural Service, 2018).

[3] This statement appears near the end of Canada's NDC submission.

benefit Canada the most, regardless of what the actual forest carbon fluxes happen to be.

The management of forestlands in Canada, particularly public lands, has historically been characterized by one theme – natural disturbance, particularly wildfire. While the Fort McMurray fire of May 2016 burned nearly 600,000 ha and destroyed some 2,400 structures, it was not unusual from a historic perspective. The 1950 Chinchaga fire burned a swatch of 1.4 million ha between Fort St. John in BC and Keg River in north western Alberta, while the Miramichi fire of 1825 in New Brunswick burned more than 1.5 million ha (Pyne, 2007, pp. 61–63, 127–132); in the past, entire towns were destroyed by wildfire, often accompanied by significant loss of life (Van Wagner, 1990). Indeed, to this day, Canada remains "a country of fire, with a natural memory far deeper than that of any of its occupying societies" (Pyne, 2007, p. 249), and with policymakers continuing "to accept as a legitimate and necessary goal the abolition of fire" (p. 160).

In addition to the Canada-U.S. softwood lumber dispute (see Johnston and van Kooten, 2017), a current important forest management theme in Canada pertains to the role of forests in mitigating climate change (Malmsheimer *et al.*, 2011; Smyth *et al.*, 2014). Climate change mitigation and control of wildfire go hand-in-hand, because forest fires release large amounts of CO_2, so that the management of forests for their climate change mitigation benefits must address means of avoiding and suppressing wildfire, perhaps through pre-emptive harvesting, controlled burns or reducing slash from logging operations (which could be used to produce energy products such as wood pellets).

Countries with significant forestlands have included forestry activities as a major means for meeting their emission-reduction targets under the Paris Agreement, including Brazil, China, Russia, and Canada. Renewable energy is to account for 27% of the EU's total energy production, with 30% (or 8% of total energy) coming from wood biomass (European Commission, 2013, 2014; European Parliament, 2015). A recent report by the UK government examined how that country might meet its demand for electricity using biomass feed stocks from North America (Stephenson and MacKay, 2014). It considered scenarios that require the continuous removal of all coarse and fine woody materials from Canada's Pacific forests and faster rates of harvest in British Columbia (pp. 8–11, 130–132). While one cannot endorse a policy to 'vacuum up' all of the coarse and fine woody material from the forest floor, as suggested by the UK report, it does provide a strong signal that there will be pressure on the BC's forests to provide Europe with wood fiber to help in global climate change mitigation efforts.

Much of the forest-carbon sequestration literature aims to demonstrate that forest conservation, fire suppression, bioenergy production and/or some other forest activity will lead to the greatest reduction in atmospheric CO_2. Often there is little or no discussion of the role of incentives or opportunity costs. One exception is a study by Lubawski *et al.* (2006), who developed an econometric model of forest land use that is affected by forest-based carbon sequestration incentives in the U.S.; it was then used to estimate a supply function for carbon uptake. In another study, Latta *et al.* (2016) used an intertemporal model of land-use and forest management decisions to determine how incentives to sequester carbon on private forestlands in Oregon would affect future timber availability. Ning and Sun (2017) investigated how carbon policies affect the behaviour of private forestland owners in the context of the threat of wildfire. Forestland is more valuable if carbon is priced, but, if owners are penalized for CO_2 emissions associated with prescribed burns that reduce the threat of wildfire, they will delay controlled burns or reduce their intensity. Finally, van Kooten (2018) reviewed the effect of regulations and incentives on the life cycle of carbon, concluding that it is important to consider all carbon pools, especially post-harvest wood product pools, if forestland owners are appropriately to balance the commercial timber values and social concerns about climate change.

In this study, we provide a preliminary investigation into the impact of natural disturbance on carbon uptake and commercial harvests of timber in British Columbia, and optimal decision making given potential strategies for improving outcomes, including new technologies. Given the global demand on forest resources that climate change mitigation entails, and the constant threat of disturbance that undermines mitigation, new technologies need to be considered for enhancing the productivity of forests and preventing disturbance. One such technology is improved forest management that takes into account the life-cycle nature of carbon, but the other relates to the nature of the trees themselves. Carbon uptake can be greatly enhanced by planting genetically modified (GM) growing stock (Neale and Kremer, 2011). Genetic engineering greatly reduces the long-breeding cycle typical in forestry, leading to an increase in biomass yields, addressing yield-reducing factors, and enhancing drought, wildfire and cold tolerance (National Academies of Sciences, Engineering & Medicine, 2016). For example, since certain Mediterranean cypress trees were found to be resistant to wildfire (Rocca *et al.*, 2015), there exists an opportunity to develop GM growing stock for planting in BC that has the potential to deter wildfire in the future.

The purpose of the current study is to demonstrate the role that economic incentives play in sequestering carbon, while establishing how sensitive forest strategies for mitigating climate change are to the social cost (price) of carbon and natural disturbance. In this regard, we develop a stochastic dynamic programming model that focuses on uncertainty related to natural disturbance and the potential to employ GM growing stock for mitigating disturbance. The effect of various incentives on the viability of GM investment is examined by changing model parameters related to carbon prices and the policy environment that determines how carbon offset credits are counted.

We begin in the next section with a discussion of forest management and the models economists have used to address carbon accounting under uncertainty. Then, in Section 3, we describe our dynamic optimization model and the forest in the BC interior to which we apply it. The model results and their implications are provided in Section 4. The conclusions ensue in Section 5.

2 Forest Management and Carbon Accounting

Since forests are capable of removing CO_2 from the atmosphere and storing it as carbon in living and even dead biomass, forest activities can contribute to climate change mitigation. When a forest reaches maturity, the public or private landowner must decide what to do with the trees. Clearly, if the costs of harvesting trees exceed the commercial benefits, the forest will be left as wilderness. In that case, the forest is not part of the working or managed forest because it is 'located' beyond the extensive margin. This is true of much of the boreal forest in both Canada and Russia, since trees are simply too far from markets; but it is also true of forests in mountainous regions, where it is too costly to harvest trees due to the combination of difficult terrain and distance to markets. For example, the Fort McMurray fire continued to burn boreal forest located outside the extensive margin for months after devastating the town. It was simply too difficult and not worthwhile to extinguish, which helps explain why Canada's policy is not to include natural disturbances in calculating its CO_2 emissions.

There are situations even in the working forest where it might be better not to harvest mature forests because harvesting activities and processing of timber results in the release of more CO_2 than is socially desirable, or unsustainable forest operations degrade the forest to such an extent that more CO_2 is released than is socially optimal. Subsequent regeneration in these cases may be unable to recover the CO_2 released as a result of harvesting activities (e.g., degraded soils result in a lower forest productivity). That is, the contribution to global warming caused by harvesting timber is less than the benefits from harvesting the trees plus the mitigation benefits of planting a new forest. Of course, if carbon can subsequently be stored in products or if wood biomass can substitute for the burning of fossil fuels, thereby lowering the overall release of CO_2, then it may yet be beneficial to harvest trees rather than preserve the forest (van Kooten, 2018). In regions characterized by natural disturbance, it may be beneficial to harvest timber despite its negative financial and/or carbon consequences. That is, the expected value of carbon fluxes from harvesting, processing and storing carbon in products might exceed the expected value of the carbon fluxes associated with leaving the forest uncut and subject to a natural disturbance such as wildfire that releases CO_2 to the atmosphere.

There is a rich literature on forest management but textbooks focus on operations research and include climate aspects only peripherally (Hof, 1993; Davis *et al.*, 2001; Buongiorno and Gilless, 2003; Kangas *et al.*, 2015). In contrast, climate change mitigation research in forestry is primarily concerned with carbon life-cycle analysis and the ability of forests to provide bioenergy (Malmsheimer *et al.*, 2011; Galik and Abt, 2012; Abt *et al.*, 2012, 2014). Research by Canadian Forest Service foresters has widely assessed the potential role of Canada's (and even BC's) forests in climate change mitigation (Lemprière *et al.*, 2013; Kurz *et al.*, 2013; Smyth *et al.*, 2014; Xu *et al.*, 2017). The problem is that forest management studies on this scale often ignores economics – the costs of harvesting, slash removal, wildfire suppression, etc., and principal-agent problems when large numbers of stakeholders are involved (see Pyne, 2007; Bogle and Kooten, 2015; Boyland, 2006). It also fails to take into account natural disturbance and how to manage for it in the context of carbon sequestration.

Economic incentives can influence the potential carbon offsets that could be generated by forest activities if forestlands are managed for commercial plus carbon benefits. This is done by identifying all ecosystem and post-harvest carbon flows and sinks (Skog and Nicholson, 1998; van Kooten, 2018), and integrating them into the decision calculus. Further, uncertainty due to natural disturbances such as catastrophic wild fire and the effects of using enhanced GM growing stock to regenerate sites post-harvest need to be considered. This can be done within the Faustmann-Hartman rotation-age framework that takes account carbon fluxes and catastrophic risk (van Kooten *et al.*, 1995; Amacher *et al.*, 2009). However, rotation-age models are not up to the task of providing guidance at a practical level – they cannot determine the number of carbon offset credits that various on-the-ground management activities might generate. In essence, a numerical approach to the economics of forest management is required (Van Wagner, 1990, p. 136; Van Deusen, 2010; van Kooten *et al.*, 1992).

2.1 Discrete-time, Stochastic Dynamic Programming Model

Economists have predominantly approached the subject of natural disturbance in the context of the Faustmann rotation age literature. The research on wildfires and prescribed burns has tended to employ stochastic processes and Ito calculus to determine optimal rotation ages. This is the approach used by Yin and Newman (1996), Thorsen and Helles (1998), Amacher *et al.* (2005; 2009 pp. 267–292), Amacher and Brazee (2014), and others, and first pioneered by Reed (1984).

An alternative approach is to use simulation, relying on heuristics and not on analytically-derived Faustmann formulae for finding optimal rotation ages under different parameterizations. Simulation allows for more complex and realistic analyses. Early papers employing this approach include Routledge

(1980), van Kooten *et al.* (1992), Asante *et al.* (2011), and Johnston and Withey (2017), and Buongiorno *et al.* (2017). Routledge argues that the optimal rotation age can increase under uncertainty, but finds a tendency for uncertainty to reduce rotation age, which corresponds to the finding by van Kooten *et al.* using stochastic dynamic programming (SDP).

Johnston and Withey (2017) use Markov chain programming to solve for optimal adaptive decisions under uncertainty. They found that such decisions are sensitive to the magnitude of carbon prices, and, consequently, so too are ecological outcomes. Buongiorno and Gilless (2003) investigate the consequences of risk preferences among forestry decision makers, concluding that financial risk aversion induced shorter cutting cycles, while also lowering expected financial returns and the level of stored CO_2 in standing biomass.

Asante *et al.* (2011) are the only ones to take into account the effect of carbon accounting on the rotation age using dynamic programming, but they are only concerned with ecosystem carbon in the form of dead organic matter (DOM). Not surprisingly, economic returns are sensitive to the initial level of DOM – the level of the initial carbon stock – and the price of carbon. Their results indicate that, when carbon is taken into account, the optimal harvest age is lengthened and the level of carbon in DOM is lower. However, the authors do not address uncertainty.

In the current study, we employ stochastic dynamic programming using a Markov stochastic process, which is why SDP is also known as Markov-chain programming. Our approach to SDP is similar to that used in a different context by Sells (1993), Eiswerth and van Kooten (2002), and others. In the current implementation, it is necessary to construct probability transition matrices for each management strategy. The transition matrices provide the probabilities that a certain strategy (e.g., reforest with GM seedlings) reduces ignition/pest invasion and the spread of a natural disturbance. The objective function is optimized subject to the transition matrices, which enables one to identify a set of strategies over time that is optimal. Indeed, if the transition matrices do not change over time, we can obtain a closed-loop solution to the SDP problem, which results in the determination of an optimal rotation age; if the transition matrices change over time (e.g., climate change might increase risk of wildfire), one can only derive an open-loop solution that is time dependent so an optimal rotation age cannot be found. The objective function in this application includes all CO_2 emissions related to forestry activities (e.g., logging, processing), carbon stored in sinks and lost due to decay, and emissions avoided when wood biomass is used to generate electricity or when cement and steel are not produced because wood products substitute for non-wood in construction.[4]

[4]One might also include emissions avoided because wood buildings require less energy to heat.

Our specific dynamic optimization problem deals with uncertainty related to the effectiveness of controls (decisions about what to do) and how the state variable (volume of timber on a site) evolves over time. In the current application, forest managers seek to maximize net revenues from commercial timber operations and sale of carbon offsets, while faced with potential but uncertain natural disturbance that destroys such values and even imposes costs. They must decide when to harvest a stand on the basis of the rate at which timber volume is growing, discount rates for carbon and monetary values, prices of carbon and wood products, and the probability that the stand is destroyed by natural disturbance.

The producer's objective is to maximize the present value of a future stream of net returns from forestry activities:

$$NPV = \sum_{t=1}^{T-1} \beta^t \left[\left(\sum_{j=1}^{N} p_j \varepsilon_j \right) H_t - K_t - p_C \left(E_t - C_t - F_t \right) \right] + \beta^T S \left(V_T \right), \tag{1}$$

where p_c refers to the price of carbon ($\$/tCO_2$), p_j to the price of forest product $j \in \{$lumber, engineered products, pulp chips, and residues/waste$\}$), ε_j is the proportion of the harvest processed into product j, and $\beta = 1/(1+r)$ is the discount factor, with r the discount rate on monetary values. For simplicity, we assume given and fixed product prices p_j and proportions ε_{i} of these products originating with harvested timber H_t at time t. In addition, K_t refers to harvest costs at time t; E_t refers to the CO_2 emissions related to logging, trucking and processing harvested timber H_t into its various products; C_t is the carbon stored in various sinks, which, in the case of products, equals discounted physical carbon (see below); and F_t refers to the CO_2 emissions avoided because of the reduced production of cement and steel if wood substitutes for these materials in construction, or if wood biomass substitutes for fossil fuels in the generation of electricity. Finally, T is the length of the planning horizon with $S(V_T)$ the 'salvage' value of the stand as a function of remaining timber V_T at T. The producer is assumed to receive carbon offset credits for carbon stored and must purchase carbon offsets to cover emissions.

We calculate the discounted physical amount of carbon that is stored in various products at the time that timber is harvested and processed into products. When carbon enters a product pool, and the product decays slowly over time at rate d, we weight (or effectively discount) the carbon released in future periods at rate r_c. The discount rate reflects the urgency of removing CO_2 from the atmosphere: The more urgent is the need to address climate change, the more important are current CO_2 releases to or removals from the atmosphere relative to future ones. Thus, the less important that future fluxes of CO_2 are relative to current ones, the lower the weighting of the future, or the higher the rate used to discount future carbon flux. The weighted carbon stored in a particular post-harvest wood product pool at time t is given by (see van Kooten, 2018):

$$V_{Cstored} = \left(\frac{r_c}{r_c + d}\right) \varepsilon C, \tag{2}$$

where d is the rate at which the wood decays, C is the amount of carbon in harvested timber and ε is the proportion of timber entering the product pool. If $d = 0$ (no decay) then the amount of carbon released from products is also zero and all the carbon is retained regardless of the rate used to weight carbon. If $r_c = 0$, no carbon is stored because it is all released, which would normally be the case for biomass burning.

The general form of the equation of motion for the natural disturbance shows up in what we refer to as the timber volume (V_t) transition equation:

$$V_{t+1} = g(V_t, k_t) + \delta_t, \tag{3}$$

where $g(\cdot)$ is a growth function, k_t the decision (harvest, conserve) taken at time t, and δ is a random variable with zero mean and variance σ^2. Equation (3) is the Markov condition: the current volume of timber on the stand is a function only of last period's standing volume and the control k applied. The evolution of the timber stock over time thus depends on the previous level, the choice to harvest or not, and stochasticity given by δ – the natural disturbance.

Then the Bellman equation for the SDP problem is:

$$\begin{aligned} Z_t\left(V_t, k_t\right) = \max_{k0,k1,\ldots,kT-1} \Bigg\{ E\left[\left(\sum_{j=1}^{J} p_j \varepsilon_j\right) H_t - K_t - p_C\left(E_t - C_t - F_t\right)\right] \\ + \beta \sum_{n=1}^{N} P(m, n, k_t) Z_{t+1}\left[V_{t+1}(n)\right] \Bigg\} \end{aligned} \tag{4}$$

where E is the expectations operator, $P(m, n, k_t)$ represents the probability that a forest site with timber volume in state $m (m = 1, \ldots, N)$ in period t will transition to state n $(n = 1, \ldots, N)$ by period $t + 1$, given that control option k is chosen in period t. Z_t denotes the expected discounted value of the future stream of net revenues in period t, given the timber stock in period t and assuming that the optimal path is taken in every future period. To implement the SDP approach, a routine was written in R (R Core Team, 2017) to solve the Bellman Equation (4). Further details of the modelling approach and the data used are provided in Section 3.

3 Application and Data

Our application is to the Quesnel Timber Supply Area (TSA) in the interior of British Columbia. The Quesnel TSA is a major timber producing region of Canada that has experienced disturbances related to pests, with the mountain pine beetle, Douglas-fir bark beetle, spruce bark beetle and balsam bark beetle presently at endemic levels within the TSA, and frequent forest wildfires. The forest inventory for the Quesnel TSA is available from the BC Ministry of Forests, Lands and Natural Resource Operations (hereafter MFLNRO) as part of the provincial government's TIPSY model that it uses to forecast timber supply based on the topographical and environmental conditions of the forest (BC MFLNRO, 2015).[5] We use TIPSY to generate the forest stand yield for a representative stand within the Quesnel TSA (see Table A1). Inputs contain species, density, regeneration method, site index, and silvicultural treatments

TIPSY also tracks carbon in living and dead biomass using the Canadian Forest Service's Carbon Budget Model CBM-CFS3 (Kull *et al.*, 2011). Since carbon in living and dead biomass pools is essentially a function of the volume of timber on the site, carbon removed from the site constitutes a loss of ecosystem carbon that is subsequently emitted to the atmosphere or transferred to wood product pools as discussed above. Any carbon entering a pool at the time of harvest is assumed to be released slowly over time, and is therefore accounted for using Equation (2). This carbon pool constitutes the carbon offset credit that can be claimed at the time of harvest (term C_t in Equation 4). If emissions avoided when wood biomass substitutes for fossil fuels in energy production or when wood products substitute for non-wood in construction, these offset credits are counted at the time of harvest as well (term F_t in Equation 4). The parameters associated with these activities are found in Table A2 in the Appendix. Likewise, logging, hauling and processing costs and associated CO_2 emissions are provided in Table A2.

The TIPSY growth and yield model does not take into account natural disturbance or stochasticity of any form. That is, even growth in commercial timber volume is deterministic. However, growth and yield do vary from one site to another. For this application, we have growth and yield data for 364 sites in the Quesnel TSA; commercial volume available to a logging company differs from one site to another within the TSA according to the biogeoclimatic zone or sub-zone, slope characteristics, species composition and other factors. Growth and yield data start with planting in period 1 and end with old-growth forest in period 21 – the model employs a decadal time step.

[5] TIPSY (Table Interpolation Program for Stand Yields) was developed to provide yield tables for stands under different management regimes using TASS (Tree and Stand Simulator) and economic data using SYLVER (Silviculture on Yield, Lumber Value, and Economic Return) (BC MFLNRO, 2015).

The timber volume transition matrix for the base case is then determined as follows: All of the possible 7280 (V_t, V_{t+1}) pairs are arranged into 28 volume categories of 20 m^3 increments, with mid-points beginning at 10 m^3 (increasing by 20 m^3), with the final category given by a mid-point of 550 m^3 and including all volume $<$540 m^3. This is done using a program written in R, which then creates a probability transition matrix such that the entries in each row sum to 1.0.[6] This is the 'no disturbance' probability transition matrix. The 'harvest' probability matrix consists of a column of ones.

Next, natural disturbance is introduced through fire probability information for this region and an assumed variance distribution across the age structure of the forest – filtering the 'no disturbance' probability transition matrix through a probability vector, where the probability of disturbance increases with the volume density of the stand. This is the 'disturbance' probability transition matrix that reflects the situation in the interior of British Columbia. Finally, a 'proactive disturbance' probability transition is constructed that reflects the possible benefits of planting faster growing and fire-resistant, genetically modified tree varieties.

The SDP problem is solved for each of the three situations to determine the optimal decision vector of 'harvest' and 'no harvest' for each state of the system. First, the solution vector, along with the expected long-run returns and variance of returns, are determined for the 'no disturbance' case. This is followed by an examination of the SDP solution for the 'disturbance' and 'proactive disturbance' situations. By comparing the expected long-run returns and their variance, it is possible to ascertain whether it is optimal to be proactive in addressing natural disturbance. To determine the importance of carbon accounting, we employ different prices of carbon (whether a carbon tax/subsidy or price determined in a carbon market) and different rules concerning the creation of carbon offsets from various forestry activities. For example, in addition to carbon entering post-harvest product pools, we count forgone CO_2 emissions from fossil fuels when wood replaces non-wood in construction or in the production of electricity.

The Bellman Equation (4) is solved using a recursive backward algorithm written in R. As noted above, the parameters used in the model are found in the Appendix. Because we assume the transition probability matrices to remain constant over time, we employ 'policy iteration', which leads to a repeated solution after some six to ten iterations, rather than 'value iteration' where the solution depends on time. In the case of policy iteration, one can determine the long-run probability that the system is in a particular state if the optimal policy is followed. Denote this long-run probability vector by π. Multiplying π by the vector of returns associated with the mid-point of each volume category gives the long-run expected net return.

[6] The probability matrices are available from the authors upon request.

To determine π, however, it is necessary to determine the probability transition matrix associated with the optimal decision strategy, denoted $\mathbf{P}$. This matrix is constructed by taking, for every state, the row from the probability transition matrix associated with the optimal decision for that state. Then, π is found by solving $\pi = \pi\mathbf{P}$ (e.g., Buongiorno and Gilless, 2003). This is done by finding vector π as any one of the identical row vectors of Π, where Π is found as $\Pi = \lim_{n\to\infty} \mathbf{P}^n$. The problem is that, since all elements of $\mathbf{P}$ are less than one (but greater than zero), making n arbitrarily large often causes $\mathbf{P}^{\mathrm{n}}$ to collapse to a null matrix since elements of $\mathbf{P}$ are less than 1.0. Π can be found, instead, by solving $\Pi = \mathbf{D}(\mathbf{I} + \mathbf{D} - \mathbf{P})^{-1}$ (Hastings, 1973, pp. 114–115). In this expression, $\mathbf{I}$ is an identity matrix, $\mathbf{D}$ is a matrix of zeros except that the last column consists of a vector of ones, and $\mathbf{P}$ is the probability transition matrix with each row of $\mathbf{P}$ corresponding to the transition probabilities for the optimal decision associated with that state. The dimensions of $\mathbf{I}$ and $\mathbf{D}$ are identical to $\mathbf{P}$.

Finally, we calibrated the model to the approximate rotation age for the region, which is about 70 years.[7] This was done by specifying a non-market value for leaving the stand unharvested. This value was simply added to the conservation value of the stand – the value in any given period of leaving the stand unharvested. A non-market value of \$5/ha calibrated the rotation age to 70 years; by doubling the non-market value, the rotation age was delayed to 90 years.

4 Results

We begin by examining three scenarios and, in each case, finding the optimal harvest age, net expected returns and standard deviation of returns, and the carbon offsets that are created in each of the three carbon pools and in total. The three scenarios are:

1. No disturbance: We employ growth and yield data from TIPSY and develop a probability transition matrix by allocating all of the (V_t, V_{t+1}) pairs to $(20 \times 20\ \mathrm{m}^3)$ cells using the 'table' function in R and then calculating probabilities so that each row sums to 1.0. The resulting matrix gives the probabilities that, if a site has a particular volume of commercial timber, it moves to another volume category in the next period. TIPSY growth and yield data do not account for natural disturbances; thus, the

[7] Given the financial rotation age for this region is often shorter than the observed 70 years indicates the province does not cut according to the Faustmann formula. According to economic theory, this suggests that there has to be an age-related, non-market value (unrelated to carbon uptake and release as that consideration is more recent) that lengthens the rotation age. That is, we assume the province cuts according to the Hartman rotation age. To address this issue in the simplest fashion, we iterated over an age-related, non-market value to calibrate the model to the observed rotation age.

only source of uncertainty relates to growth, and includes site-specific factors that are necessarily 'aggregated' in establishing a representative site.[8]

2. Disturbance: The probability transition matrix obtained using the TIPSY data (as just described) is filtered using a vector of disturbance probabilities that vary by the maturity of the stand (i.e., volume of the stand). Unlike the previous case where the transition from any volume category is never to a lesser one, with the possibility of natural disturbance, there are non-zero probabilities that there is a transition from any volume category to a lower one, including the lowest volume category, and that this is not the result of harvest.

3. Proactive disturbance: In this case, the 'no disturbance' transition matrix is filtered through a probability vector that ensures faster growth than in the previous two scenarios and lower probabilities of landing in a lower volume category. The first condition represents a genetic modification that leads to faster growth, while the second a GM that results in greater resistance to wildfire and/or pests.

The results are compared to a business-as-usual (BAU) scenario defined as 'disturbance with carbon unpriced.' The results for the 'no disturbance', 'disturbance' and 'proactive disturbance' scenarios are provided relative to the BAU case in Tables 1 through 3, respectively, for various carbon prices ranging from \$0/tCO_2 through \$250/tCO_2.

Consider first the effect of carbon prices on net returns and optimal harvest choice.[9] The two main results are obvious: (1) As the carbon prices increases, harvests are delayed somewhat so that more carbon can enter dead and living biomass pools. (2) Expected net revenues rise as the price of carbon offsets increases because the forest landowner/manager receives payments for creating carbon offsets, but the variability of returns also increases. With greater risk of loss due to natural disturbance, the forest manager will harvest somewhat earlier (a standard result). However, it does not take a very high price of carbon (somewhat less than \$25/tCO_2) to offset the reduction in rotation age brought about by disturbance.

Tables 1 through 3 also provide information on the amounts of carbon that get sequestered (and stored) in various carbon pools at different incentive levels. Carbon offsets/emissions are calculated in reference to the BAU scenario with $p_c = \$0/\text{tCO}_2$. While total carbon sequestered increases as the price of carbon rises, the carbon stored in harvested wood products (HWP) falls as carbon prices increase, and this is exacerbated with disturbance. One reason

[8]Probability transition matrices are available upon request.

[9]These results are provided visually for the 'no disturbance', 'disturbance' and 'proactive disturbance' scenarios in Appendix Figures A1 through A3, respectively, for carbon prices of \$0, \$25, \$50, and \$100 per tCO_2.

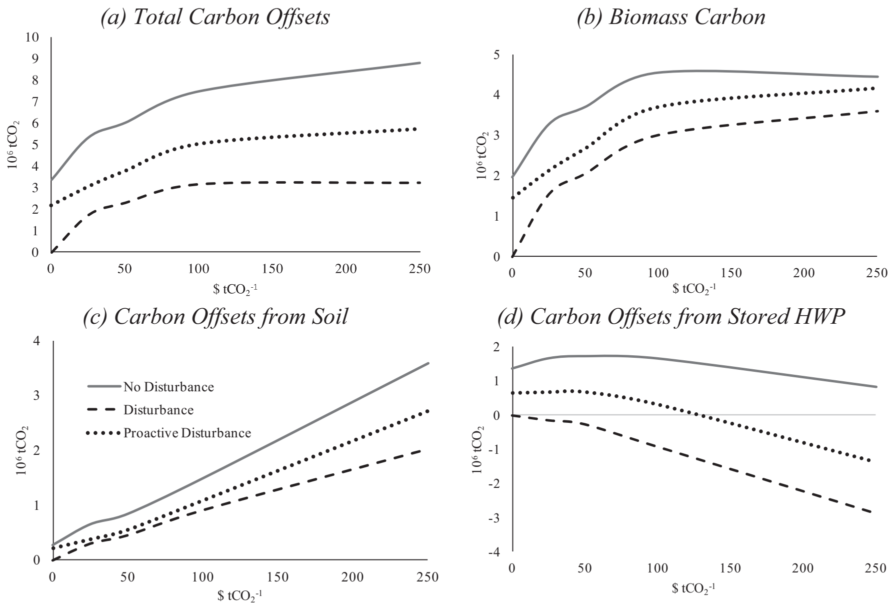

Figure 1: Carbon Offsets Created by One Hectare of Forest, Various Component Pools, Quesnel TSA, British Columbia.

for this is that, as the price of carbon increases, it is costlier to harvest and process trees as emissions are penalized. While some have also noted this (e.g. Lubowskia *et al.*, 2016; Latta *et al.*, 2016) others have found that this does not always appear to hold true (e.g., see van Kooten, 2018; Xu *et al.*, 2017; Smyth *et al.*, 2014). But it does caution against using carbon price incentives to increase carbon sequestered in HWPs. Uptake of carbon in various pools is demonstrated quite starkly in Figure 1. The carbon stored in biomass seems to plateau at a certain carbon price, and converges across disturbance scenarios, but the opposite happens with soil carbon and HWP.

From Figure 1, notice that there comes a certain point beyond which increases in carbon prices have little impact on the amount of carbon that gets sequestered. While behaviour changes slightly (increasing the rotation age), the higher prices simply redistribute rents from those purchasing carbon offset credits to forestland owners. Although not shown, if we consider a scenario where only the carbon stored in on-site biomass counts – only ecosystem carbon is important – then carbon prices cause a delay in harvesting. Alternatively, if we value the carbon stored in all pools (including HWPs), harvests occur sooner; then, when risk is present, harvests occur even sooner. In the future, as climate change causes disturbance to increase in prevalence and severity, forests would be harvested sooner contrary to the lengthening of rotation

Table 1: Rotation Age, Net Returns and Carbon Offset Credits Created per ha in Various Pools, No Disturbance.

Item	Price of carbon (per tCO_2)				
	$0	$25	$50	$100	$250
Rotation age (yrs)	70	90	100	130	220
Expected Long Run (compared to BAU):					
Return ($'000s)	5.55	6.16	6.74	8.03	12.09
Standard deviation of returns	1.55	1.98	2.11	2.53	3.20
Carbon offsets from biomass (10^6 tCO_2)	1.97	3.28	3.71	4.56	4.45
Carbon offsets from soil (10^6 tCO_2)	0.26	0.64	0.83	1.48	3.58
Carbon offsets from HWP (10^6 tCO_2)	1.37	1.67	1.73	1.67	0.83
CO_2 emissions from harvest/processing (10^6 tCO_2)	0.22	0.26	0.27	0.25	0.09

Table 2: Rotation Age, Net Returns and Carbon Offset Credits Created per ha in Various Pools, with Disturbance.

Item	Price of carbon (per tCO_2)				
	\$0	\$25	\$50	\$100	\$250
Rotation age (yrs)	60	80	90	120	200
Expected Long Run (compared to BAU):					
Return (\$'000s)	5.38	5.93	6.45	7.60	11.24
Standard deviation of returns	1.13	1.55	1.73	2.18	3.32
Carbon offsets from biomass (10^6 tCO_2)	0.00	1.54	2.05	3.00	3.58
Carbon offsets from soil (10^6 tCO_2)	0.00	0.30	0.46	0.91	2.03
Carbon offsets from HWP (10^6 tCO_2)	0.00	−0.14	−0.26	−0.92	−2.88
CO_2 emissions from harvest/processing (10^6 tCO_2)	0.00	−0.03	−0.05	−0.16	−0.49

Table 3: Rotation Age, Net Returns and Carbon Offset Credits Created per ha in Various Pools, with Proactive Disturbance.

Item	Price of carbon (per tCO_2)				
	\$0	\$25	\$50	\$100	\$250
Rotation age (yrs)	70	80	90	120	210
Expected Long Run (compared to BAU):					
Return (\$'000s)	5.50	6.00	6.55	7.77	11.65
Standard deviation of returns	1.48	1.63	1.82	2.28	3.23
Carbon offsets from biomass (10^6 tCO_2)	1.44	2.12	2.67	3.69	4.16
Carbon offsets from soil (10^6 tCO_2)	0.21	0.37	0.55	1.08	2.71
Carbon offsets from HWP (10^6 tCO_2)	0.64	0.66	0.66	0.30	−1.39
CO_2 emissions from harvest/processing (10^6 tCO_2)	0.10	0.10	0.10	0.03	−0.25

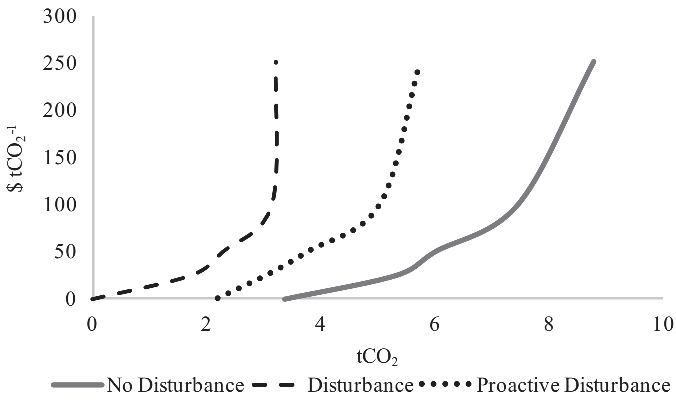

Figure 2: Carbon Supply Curves: Steady State Changes in Total Net Discounted Carbon per Hectare of Forest (Relative to BAU) at Various Carbon Prices.

age that an increase in carbon prices brings about; this would cause forest managers to manage forests more actively for commercial and carbon benefits.

The original data underlying Tables 1 through 3 are used to develop carbon supply curves for each of our scenarios, as found in Figure 2. These indicate that timber supply analyses based on growth and yield models that do not account for natural disturbance overestimate the carbon offset credits that could be forthcoming from forests in the BC interior. With disturbance, the total carbon offsets generated falls by a substantial amount (Figure 1), but that some of this can be recovered through proactive planting of GM stems. Upon comparing results in Tables 2 and 3, the costs of planting GM stock should not exceed some \$120–\$150/ha to make such an investment worth undertaking. However, the marginal costs of generating extra carbon offsets by reducing the impact of natural disturbance might be worthwhile, ranging from \$38.50/tCO_2 when no incentives are provided to create carbon offsets ($p_c = 0$) to \$120.70/tCO_2 when the price of carbon is set at \$100 per tCO_2.

5 Concluding Discussion

In this study, stochastic dynamic programming was used to examine the effect of carbon pricing incentives and the potential of technological advances in genomic research to make trees more productive and less susceptible to natural disturbance. Results indicate that both policies lead to greater sequestration of carbon through forest activities. Surprisingly, at least for the interior BC forest and data employed in this study, higher carbon values resulted in less carbon stored in harvested wood products and more in the forest ecosystem. It turns out that, given the product pools identified here and at a reasonable carbon price of \$50/tCO_2, about half of the net income from forest activities come from sale of carbon offset credits with the remainder coming from commercial forest operations (which are reduced for carbon prices above \$50/tCO_2). If managers harvest less timber on a large scale because of carbon incentives, this could have repercussions throughout the larger economy, resulting is reduced employment, exports and so on. These factors are not considered here, but should be examined because the carbon price incentive is paid for out of the types of activities that are slowed as a result.

The analysis has looked only at carbon fluxes in the ecosystem (live and dead biomass) and subsequent carbon stored in post-harvest products. Even so, it is clear that the costs of sequestering carbon might be extremely high. For the three scenarios, additional carbon offsets generated range from 7.46 tCO_2/ha (additional CO_2 sequestered when p_c =\$100/tCO_2 minus carbon sequestered when carbon is unpriced) for the unrealistic case of no disturbance down to only 3.15 tCO_2/ha with disturbance. Given that forest operations take place on only 25 million ha of forestland in BC (coast and interior), the carbon that is sequestered might amount to about 78.8 million tCO_2 (78.8 Mt CO_2). Although this is a considerable carbon saving, and amounts to about one-tenth of Canada's total annual CO_2 emissions (771 Mt CO_2 in 2015), it is important to recognize that this is realizable only over an infinite time horizon. If we annualize this amount of carbon, we find it amounts to an insignificant 0.8 Mt CO_2, or less than 0.1% of Canada's annual emissions.[10] While forestry activities can be effective strategies to mitigate climate change, our research suggests that policymakers need to be careful not to incentivize forestry activities that could harm the forest industry while contributing little if anything to climate change mitigation.

The results of this study depend on a number of assumptions related to modelling structure and input data. The growth and yield data for the Quesnel TSA of British Columbia, including ecosystem carbon data, are derived from TIPSY, which is used by the province in their timber supply analyses to make real decisions, including decisions about carbon uptake and how much Canada might claim towards meeting its Paris targets. TIPSY does not make any assumption about likely disturbance regimes, and therefore, we have offered our own related to average fire probability observed in the region. The realized carbon offsets will depend on the accounting method employed, the various carbon pools considered, and whether emissions from disturbance are acknowledged. Additionally, the results are sensitive to input data including timber prices, monetary and biophysical decay rates, and basic modelling parameters as they related to local markets and life cycle assumptions.

[10]The net discounted total carbon saved is annualized by multiplying by 0.01, which is the rate (1%) used to discount future carbon. See Johnston and van Kooten (2015) for a discussion of discounting and the use of a low rate for carbon.

A Appendix

Table A1: Quesnel TSA Inventory.

	Area		Volume	
Species	hectares	%	$\times 10^3$ m^3	%
Lodgepole pine	1,118,208	74.3	154,475	66.1
Spruce, Engelman & White	207,689	13.8	49,059	21.0
Douglas-fir	73,745	4.9	12,303	5.3
Trembling aspen	57,190	3.8	6,396	2.7
Sub-alpine fir	30,100	2.0	7,978	3.4
Other	18,060	1.2	3,386	1.5

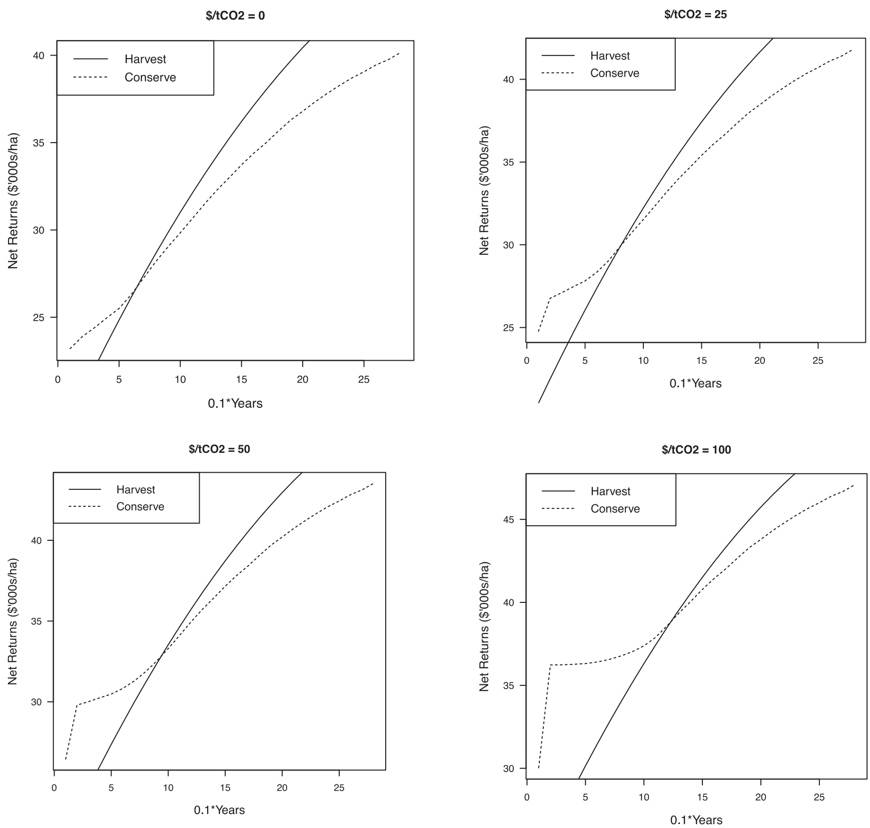

Figure A1: Net Returns from Harvesting versus Conservation, Selected Carbon Prices, No Disturbance.

Table A2: Basic Model Parameters.

General:		**Decay rates:**	
Price of carbon (\$/tCO_2)	0	Dead organic matter	0.0718
Forest conservation value (\$/ha)	5	Softwood lumber	0.0082
Discount rate on monetary values	0.025	Pulpwood	0.0234
Rate of discount on physical carbon	0.01	Biomass for fuel	0.7000
Carbon to CO_2 conversion parameter	3.6667	Engineered wood products	0.0080
Prices (\$/m^3):		**Proportion of residuals going to:**	
Lumber	160	Engineered wood products	0.151
Engineered products	200	Pulp	0.697
Chips in pulp	145	Biomass fuel	0.152
Residues for fuel	155		
Costs:		**Carbon in input material to (tCO_2/m^3):**	
Logging (\$/m^3)	22.2	Sawnwood	0.0293
Hauling (\$/m^3 per cycle hour)	6.77	Engineered product	0.0660
Round trip hauling distance (km)	150	Chemical & mechanical pulp	0.1000
Speed of trucks incl. loading (km/hr)	50		
Milling lumber & eng. wood (\$/m^3)	72	**Emissions (tCO_2/m^3):**	
Extra milling cost if product from		Residuals (= 0 if CO_2 neutral)	1.82
chips (\$/m^3)	50	Harvesting	0.01173
		Trucking per km	0.000078

Source: van Kooten (2018)

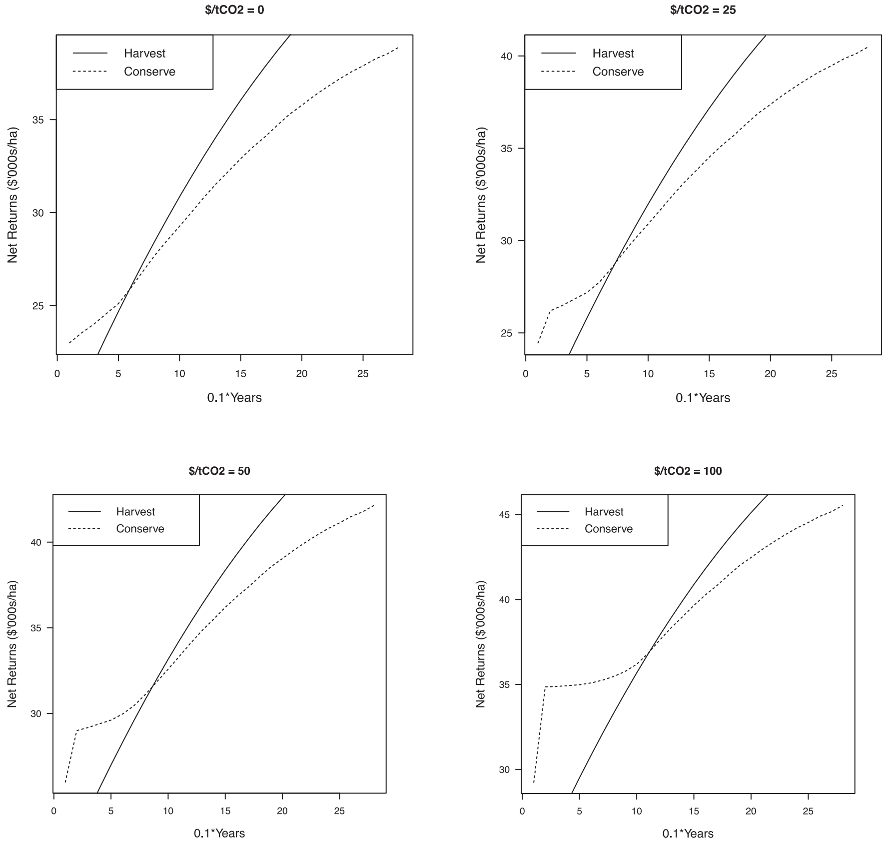

Figure A2: Net Returns from Harvesting versus Conservation, Selected Carbon Prices, with Disturbance.

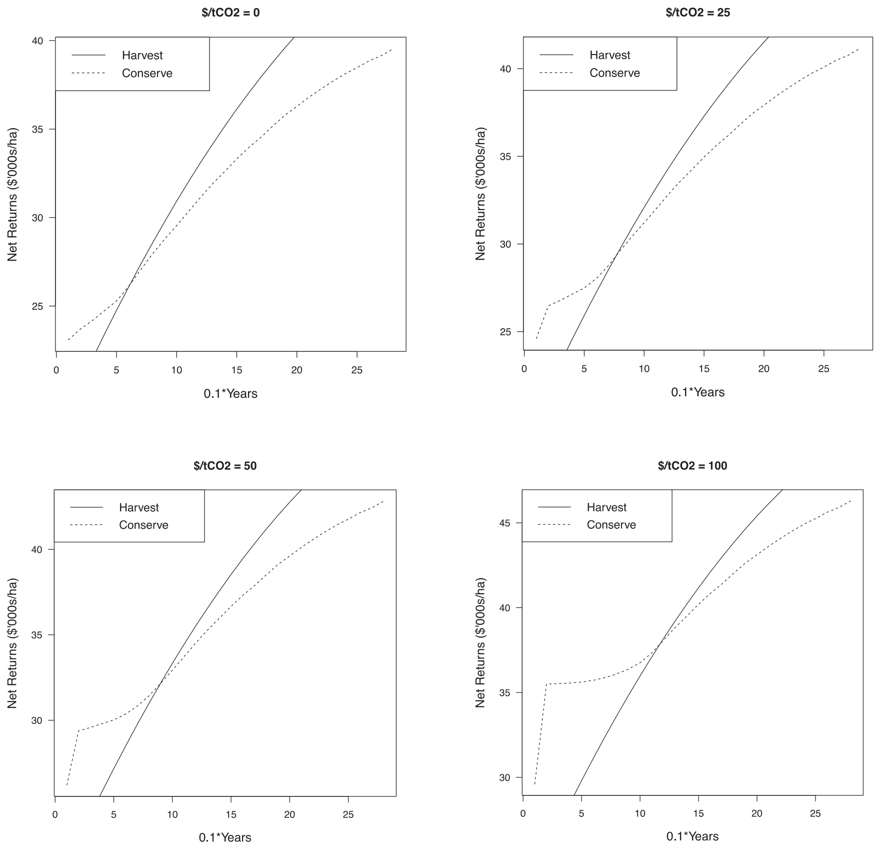

Figure A3: Net Returns from Harvesting versus Conservation, Selected Carbon Prices, with Proactive Disturbance.

References

Abt, K. L., R. C. Abt, and C. S. a. Galik. 2012. "Effect of Bioenergy Demands and Supply Response on Markets, Carbon, and Land Use". *Forest Science*. 58: 523–539.

Abt, K. L., R. C. Abt, C. S. Galik, and K. E. Skog. 2014. "Effect of Policies on Pellet Production and Forests in the U.S. South: A Technical Document Supporting the Forest Service Update of the 2010 RPA Assessment". Gen. Tech. Rep. SRS-202. 33pp. Asheville, NC: USDA Forest Service, Southern Research Station.

Amacher, G. S. and R. J. Brazee. 2014. "Risk and Uncertainty in Forest Resources Decision Making". In: *Handbook of Forest Resource Economics*. Ed. by S. Kant and J. R. R. Alavalapati. Oxon, UK: Routledge. Chap. 20. 309–321.

Amacher, G. S., A. S. Malik, and R. G. Haight. 2005. "Not Getting Burned: The Importance of Fire Prevention in Forest Management". *Land Economics*. 81(2): 284–302.

Amacher, G. S., M. Ollikainen, and E. Koskela. 2009. *Economics of Forest Resources*. Cambridge, MA: MIT Press.

Asante, P., G. W. Armstrong, and W. L. Adamowicz. 2011. "Carbon Sequestration and the Optimal Forest Harvest Decision: A Dynamic Programming Approach Considering Biomass and Dead Organic Matter". *Journal of Forest Economics*. 17: 3–17.

BC Ministry of Forests, Lands and Natural Resource Operations (MFLNRO). 2015. *Major Primary Timber Processing Facilities in British Columbia, 2014*. Victoria: Competitiveness and Innovation Branch.

Bogle, T. and G. C. van Kooten. 2015. "Protecting Timber Supply on Public Land in Response to Catastrophic Natural Disturbance: A Principal-Agent Problem". *Forest Science*. 61(1): 83–92.

Boyland, M. 2006. "The Economics of using Forests to Increase Carbon Storage". *Canadian Journal of Forest Research*. 36(9): 2223–2234.

Buongiorno, J. and J. K. Gilless. 2003. *Decision Methods for Forest Resource Management*. San Diego, CA: Academic Press.

Buongiorno, J., M. Zhou, and C. M. T. Johnston. 2017. "Risk Aversion and Risk Seeking in Multi-Criteria Forest Management: A Markov Decision Process Approach". *Canadian Journal of Forest Research*. 47: 800–807.

Davis, L. S., K. N. Johnson, P. Bettinger, and T. E. Howard. 2001. *Forest Management to Sustain Ecological, Economic, and Social Values*. 4th ed. Edition, Long Grove, IL: Waveland Press.

Eiswerth, M. E. and G. C. van Kooten. 2002. "Uncertainty, Economics and the Spread of an Invasive Plant Species". *American Journal of Agricultural Economics*. 84: 1317–1322.

European Commission. 2013. “A New EU Forest Strategy: Forests and the Forest-Based Sector”. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Brussels: 20.9.2013. Com(2013) 659 Final.

European Commission. 2014. “A Policy Framework for Climate and Energy: The Period from 2020 to 2030”. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Brussels: 22.1.2014. Com(2014) 015 Final.

European Parliament. 2015. “Briefing: Biomass for Electricity and Heating”. Opportunities and Challenges. (Author: D. Bourguignon) PE 568.329. September. 8 pp. European Parliamentary Research Service, European Union.

Galik, C. S. and R. C. Abt. 2012. “The Effect of Assessment Scale and Metric Selection on the Greenhouse Gas Benefits of Woody Biomass”. *Biomass and Bioenergy*. 44: 1–7.

Hastings, N. A. J. 1973. *Dynamic Programming with Management Applications*. London: Butterworths.

Hof, J. 1993. *Coactive Forest Management*. San Diego, CA: Academic Press.

Johnston, C. M. T. and G. C. van Kooten. 2015. “Back to the Past: Burning Wood to Save the Globe”. *Ecological Economics*. 120(December): 185–193.

Johnston, C. M. T. and G. C. van Kooten. 2017. “Impact of Inefficient Quota Allocation under the Canada-U.S. Softwood Lumber Dispute: A Calibrated Mixed Complementarity Approach”. *Forest Policy and Economics*. 74: 71–80.

Johnston, C. M. T. and P. Withey. 2017. “Managing Forests for Carbon and Timber: A Markov Decision Model of Uneven-aged Forest Management with Risk”. *Ecological Economics*. 138: 31–39.

Kangas, A., M. Kurttila, T. Hujala, K. Eyvindson, and J. Kangas. 2015. *Decision Support for Forest Management*. Dordrecht, NL: Springer.

Kull, S. J., G. J. Rampley, S. Morken, J. Metsaranta, E. T. Neilson, and W. A. Kurz. 2011. “Operational-scale Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) Version 1.2: User’s Guide”. CFS Technical Bulletin. 344pp. Edmonton, AB: Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre.

Kurz, W. A., C. Shaw, C. Boisvenue, G. Stinson, J. Metsaranta, D. Leckie, A. Dyk, C. Smyth, and E. T. Neilson. 2013. “Carbon in Canada’s Boreal Forest — A Synthesis”. *Environmental Reviews*. 21: 260–292.

Kurz, W. A., G. Stinson, G. J. Rampley, C. C. Dymond, and E. T. Neilson. 2008. “Risk of Natural Disturbances makes Future Contribution of Canada’s Forests to the Global Carbon Cycle Highly Uncertain”. *PNAS*. 105(5): 1551–1555.

Latta, G. S., D. M. Adams, K. P. Bell, and J. D. Kline. 2016. "Evaluating Land-use and Private Forest Management Responses to a Potential Forest Carbon Offset Sales Program in Western Oregon (USA)". *Forest Policy and Economics*. 65: 1–8.

Lemprière, T. C., W. A. Kurz, E. H. Hogg, C. Schmoll, G. J. Rampley, D. Yemshanov, D. W. McKenney, R. Gilsenan, A. Beatch, D. Blain, J. S. Bhatti, and E. Krcmar. 2013. "Canadian Boreal Forests and Climate Change Mitigation". *Environmental Reviews*. 21: 293–321.

Lubowskia, R. N., A. J. Plantinga, and R. N. Stavins. 2016. "Land-use Change and Carbon Sinks: Econometric Estimation of the Carbon Sequestration Supply Function". *Journal of Environmental Economics and Management*. 51: 135–152.

Malmsheimer, R. W., J. L. Bowyer, J. S. Fried, E. Gee, R. L. Izlar, R. A. Miner, I. A. Munn, O. E., and W. C. & Stewart. 2011. "Managing Forests because Carbon Matters: Integrating Energy, Products, and Land Management Policy". *Journal of Forestry*. 109(7S): 7–50.

NAS, Engineering & Medicine. 2016. *Genetically Engineered Crops: Experiences and Prospects*. Washington, DC: The National Academies Press.

Neale, D. B. and A. Kremer. 2011. "Forest Tree Genomics: Growing Resources and Applications". *Nature Reviews Genetics*. 12(February): 111–122.

Ning, Z. and C. Sun. 2017. "Forest Management with Wildfire Risk, Prescribed Burning and Diverse Carbon Policies". *Forest Policy and Economics*. 75: 95–102.

Pyne, S. J. 2007. *Awful Splendour. A Fire History of Canada*. Vancouver, BC: UBC Press.

R Core Team. 2017. *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing. URL: https://www.R-project.org/.

Reed, W. J. 1984. "The Effects of the Risk of Fire on the Optimal Rotation of a Forest". *Journal of Environmental Economics and Management*. 11: 180–190.

Rocca, G. D., C. Hernando, J. R. Madrigal, J. Danti, M. Moya, A. Guijarro, B. Pecchioli, and Moya. 2015. "Possible Land Management Uses of Common Cypress to Reduce Wildfire Initiation Risk: A Laboratory Study". *Journal of Environmental Management*. 159: 68–77.

Routledge, R. D. 1980. "The Effect of Potential Catastrophic Mortality and Other Unpredictable Events on Optimal Forest Rotation Policy". *Forest Science*. 26(3): 389–399.

Safranyik, L. and B. Wilson. 2006. *The Mountain Pine Beetle. A Synthesis of Biology, Management, and Impacts on Lodgepole Pine*. Victoria, BC: Her Majesty the Queen in Right of Canada.

Sells, J. E. 1993. "Calculating Transition Probabilities for Modelling Weed Management Options using Stochastic Dynamic Programming". *Agricultural Systems*. 41: 41–52.

Skog, K. and G. Nicholson. 1998. "Carbon Cycling Through Wood Products: The Role of Wood and Paper Products in Carbon Sequestration". *Forest Products Journal*. 48(7/8): 75–83.

Smyth, C. E., G. Stinson, E. Neilson, T. C. Lemprière, M. Hafer, G. J. Rampley, and W. A. Kurz. 2014. "Quantifying the Biophysical Climate Change Mitigation Potential of Canada's Forest Sector". *Biogeosciences*. 11: 3515–3529.

Stennes, B., S. Wang, C. Luján, C. McDermott, B. Wilson, B. Cashore, S. J. Alexander, D. N. Bengston, A. Carroll, J. M. Olivas, H. González, S. Kant, D. Mills, D. Mtichell, B. Peter, S. Tedder, and G. van Kooten. 2005. "Forests in North America: Responding to Social, Economic and Ecological Pressures". In: *Forests in the Global Balance – Changing Paradigms*. Ed. by G. Mery, R. Alfaro, M. Kannien, and M. Lobovikov. *IURFRO World Series Volume 17*. Helsinki: International Union of Forest Research Organizations. Chap. 16. 265–279.

Stephenson, A. L. and D. J. C. MacKay. 2014. "Life Cycle Impacts of Biomass Electricity in 2020". Scenarios for Assessing the Greenhouse Gas Impacts and Energy Input Requirements of Using North American Woody Biomass for Electricity Generation in the UK. Report #URN 14D/243. July. 154pp. London, UK: Department of Energy and Climate Change, Crown Copyright. URL: https://www.gov.uk/government/publications/life-cycle-impacts-of-biomass-electricity-in-2020.

Thorsen, B. J. and F. Helles. 1998. "Optimal Stand Management with Endogenous Risk of Sudden Destruction". *Forest Ecology and Management*. 108: 287–299.

USDA Foreign Agricultural Service. 2018. "Feed Grains Database; Yearbook". URL: https://www.ers.usda.gov/data-products/.

Van Deusen, P. C. 2010. "A Method to Evaluate the Option of Storing Carbon in Your Forest". *Canadian Journal of Forest Research*. 40: 2243–2247.

van Kooten, G. C. 2004. *Climate Change Economics. Why International Accords Fail*. Cheltenham, UK: Edward Elgar.

van Kooten, G. C. 2018. "The Challenge of Mitigating Climate Change through Forestry Activities: What Are the Rules of the Game". *Ecological Economics*. 146: 35–43.

van Kooten, G. C., C. S. Binkley, and G. Delcourt. 1995. "Effect of Carbon Taxes and Subsidies on Optimal Forest Rotation Age and Supply of Carbon Services". *American Journal of Agricultural Economics*. 77(2): 365–374.

van Kooten, G. C., R. E. van Kooten, and G. Brown. 1992. "Modeling the Effect of Uncertainty on Timber Harvest: A Suggested Approach and Empirical Example". *Journal of Agricultural and Resource Economics*. 17: 162–172.

Van Wagner, C. E. 1990. "Six Decades of Forest Fire Science in Canada". *Forestry Chronicle*. 66: 133–137.

Xu, Z., C. E. Smyth, T. C. Lemprière, G. J. Rampley, and W. A. Kurz. 2017. "Climate Change Mitigation Strategies in the Forest Sector: Biophysical Impacts and Economic Implications in British Columbia, Canada". Mitigation and Adaptation Strategies for Global Change Published online February 17. URL: https://doi.org/10.1007/s11027-016-9735-7.

Yin and Newman. 1996. "The Effect of Catastrophic Risk on Forest Investment Decisions". *Journal of Environmental Economics and Management*. 31(2): 186–197.