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Department of Economics
University of Victoria

The Impact of Carbon on Optimal Forest Rotation Ages: An Application to Coastal Forests in British Columbia

G. Cornelis van Kooten

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REPA Research Group
Department of Economics
University of Victoria PO Box 1700 STN CSC Victoria, BC V8W 2Y2 CANADA
repa@uvic.ca

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by

G Cornelis van Kooten

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Abstract

Sequestration of carbon in forest ecosystems is considered important for mitigating climate change. Whether forests should be left unharvested to avoid CO_2 emissions and store carbon, or harvested to take advantage of potential carbon storage in post-harvest forest product sinks and removal of CO_2 from the atmosphere with new growth, remains a policy concern. The issue is addressed in this paper by examining carbon rotation ages that consider commercial timber as well as carbon values. Building upon earlier work by van Kooten et al. (1995), a discrete-time optimal rotation age model is developed that employs data on carbon fluxes stored in both living and dead biomass as opposed to carbon being a function of timber growth. Rather than relying on a 'pickling factor' (proportion of timber entering product pools) and permanent carbon storage, carbon is allocated to several ecosystem and post-harvest product pools that decay over time at different rates. In addition, the timing of carbon fluxes is taken into account by weighting future carbon fluxes as less important than current ones.

The application is to forests on Vancouver Island on Canada's west coast where a study by Morton et al. (2021) suggests that carbon concerns are significant enough to prevent harvest. Using data on timber growth and yield, and information on carbon uptake and storage, we find that there are few cases where forest sites should remain unharvested. Some surprising conclusions are as follows: (1) Reducing the price of timber while increasing the price of carbon will increase rotation age, perhaps to infinity (stand remains unharvested). (2) An increase in the rate used to discount physical carbon can raise or lower the rotation age. (3) As a corollary, an increase in the price of carbon increases or reduces rotation age depending on the chosen weight employed to discount future carbon fluxes. (4) Site characteristics and the mix of species on the site affect conclusions (2) and (3). (5) Finally, it is essentially impossible to determine how many carbon offsets any particular forest site might produce.

Key Highlights

- Forest policies affect carbon fluxes, which are important for mitigating climate change.
- An increase in the price of carbon can increase or decrease the optimal rotation age.
- Decay of biomass pools is an important factor affecting carbon uptake benefits.
- The timing of carbon fluxes affects the benefits to be realized from forestry activities.
- A forestry strategy to sequester carbon needs to be implemented immediately or not at all.
- Forestry activities should not be relied upon to produce tradeable carbon offset credits.

Keywords: optimal forest rotation age; carbon sequestration; life-cycle carbon; timing and decay of carbon pools

JEL categories: Q54, F64, Q57, Q2

1. INTRODUCTION

With the adoption of the Paris Agreement at COP21 of the UN's Framework Convention on Climate Change, the subsequent special report on the need to prevent the globe's mean surface temperature from exceeding 1.5ºC (IPCC 2018, 2022), and further commitments made at COP26 in 2021 at Glasgow, Scotland, countries have begun to implement policies that would eliminate carbon dioxide (CO_2) emissions by 2050[1]—a policy known as 'Net Zero'. Since it will be impossible to eliminate all emissions by 2050, it will be necessary to offset any remaining emissions from fossil-fuel use. Two means have been proposed for offsetting CO_2 emissions in a 'Net Zero' economy: (1) employ fossil-fuel related carbon capture and storage (CCS), and bioenergy (using forest and agricultural biomass) along with CCS—which together are referred to as BECCS. Although CCS facilities are under development, the technology requires some 20% to 30% of the energy produced by a power plant to implement—referred to as parasitic energy (International Energy Agency 2021). (2) In the forest sector, carbon dioxide removal (CDR) from the atmosphere occurs through reforestation, afforestation, reduced deforestation, silvicultural investments, and improved forest management (IPCC 2000, 2019; Smith et al. 2014; Griscom et al. 2020; Favero et al. 2020). This study focuses on forestry activities to mitigate climate change.

Carbon dioxide is sequestered in growing trees where it gets stored in the ecosystem's carbon pool, which consists of living biomass (growing trees including roots) and dead and decaying biomass (fallen leaves, dead branches, soil organic matter). When trees are harvested, carbon is released to the atmosphere, but some carbon will remain in the ecosystem while other carbon will enter post-harvest wood product pools. The latter include lumber, residuals used to produce various types of construction material (e.g., oriented strand board), wood pulp for paper making, and energy products (viz., burning sawdust and wood pellets to generate electricity). Because forests play an important role in the Earth's carbon cycle, the forest sector has come under increasing pressure to reduce emissions of CO_2 from deforestation, for example, while encouraging CDR.

Based on their Intended Nationally Determined Contributions (UNFCC 2015), many countries intend to rely on forestry activities to meet upwards of 25% of their self-determined emissions-reduction targets under the Paris Agreement (Grassi et al. 2017). With regard to forestry, two strands of thought have emerged. Some argue that forests should be left unharvested because harvesting would in a life-cycle sense release more carbon in the form of CO_2 (e.g., Harmon et al. 1990; Morton et al. 2021). In contrast, Kurz et al. (2013), Lemprière et al. (2013), Smyth et al. (2014) and Howard et al. (2021) emphasize the importance of including post-harvest carbon pools and biomass energy in decisions regarding whether a forest should be harvested. The two positions can be reconciled, in economic terms at least, by including carbon prices in the choice of an optimal rotation age (van Kooten et al. 1995; Ekholm 2015).

[1] For convenience, we use the term CO_2 to refer to any GHG, because policies have mainly focused on CO_2 emissions, and the IPCC converts the effects of GHGs into CO_2-equivalences using their global warming potentials.

If carbon fluxes are properly considered in the determination of a forest's rotation age, the optimal rotation age could turn out to be infinite if conservation leads to greater discounted net returns than harvesting. While van Kooten et al. (1995) found few cases where conservation was preferred, they did find that the inclusion of carbon values tended to lengthen rotation ages. However, the analysis neglected to include on-site ecosystem carbon and the potential decay of post-harvest biomass; it assumed carbon was solely a function of the commercial component of timber and that post-harvest wood-product pools stored carbon in perpetuity.

The purpose of the current research is to investigate how carbon prices and life-cycle carbon dynamics affect the optimal rotation age. In particular, the optimal forest rotation age that takes these considerations into account can be used to determine whether and under what conditions it might be worthwhile to conserve rather than harvest a mature forest. While Ekholm (2015) focused on the potential path of carbon prices, finding that the rotation age would increase with future increases in carbon prices, the focus in this study is on decay of carbon sinks and the weighting of carbon fluxes as to when they occur.

The current investigation proceeds as follows. In the next section, we provide background information that motivates the development in section 3 of a model for determining the carbon-financial rotation age. An application to the coastal forests of southern Vancouver Island is provided in section 4. Our conclusions follow in section 5.

2. BACKGROUND AND CHALLENGE

Background to Forest Offset Credits

Both a Convention on Climate Change and a Convention on Biodiversity were signed at the "Rio Earth Summit" in Brazil in 1992. Prior to the Third Conference of the Parties (COP3) to the former Convention, held in Kyoto, Japan in 1997, there was little focus on forestry. However, because many countries desired a mechanism that would enable them to avoid domestic emission reductions in order to meet carbon-reduction targets, complicated negotiations that followed COP3 led to the creation of carbon offset credits related to afforestation, reforestation and land use change (IPCC 2000). Negotiators also realized that climate change mitigation could be linked to biodiversity by crediting avoided deforestation—a main source of CO_2 emissions, particularly in tropical countries. Subsequently, offset accreditation expanded to encompass forest degradation, which resulted in efforts to Reduce Emissions from Deforestation and forest Degradation (REDD) (Angelsen 2014; Kaimowitz 2008). When sustainable forest management and reforestation were included as means of potentially earning offset credits, the result was REDD+ (Butler 2012).[2]

[2] For example, sustainable forest management led to reduced CO_2 emissions from wasteful logging practices. Meanwhile, reforestation was accepted as part of sustainable management whereas previously it only referred to the reforestation of sites that had earlier been forested but had been without tree cover for some time. For context, afforestation referred to tree planting on land that had never been forested.

The machinations required to certify forest-sector credits constituted a particular obstacle to their acceptance for use in mandatory markets, although they traded in voluntary markets (van Kooten 2017). A major obstacle was and remains their transitory nature. Carbon stored in forest ecosystems is quickly released when forests are harvested for their commercial timber benefits and/or cleared for agriculture. Even attempts to clarify how to deal with these issues resulted in a variety of confusing ways to measure the CO_2 that forestry activity removed from the atmosphere. In this study, we employ Ciriacy-Wantrup's (1968) insight and use a simple weighting method for counting carbon fluxes that occur in the future but are counted as an offset today.

Wood products can replace steel and concrete in construction, thereby reducing CO_2 emissions related to the production of steel and concrete, although the emissions reduction should appropriately be charged to the construction sector and not to forestry. The forest sector should only count the carbon stored in lumber and other long-lived wood products, but not the emissions saved by not producing steel and concrete. Of course, the same holds true when biomass replaces fossil fuels in power generation. The reduction in CO_2 emissions, if any, should be counted to the electricity sector, not to the forest sector.

Clearly, determining whether any given forest management strategy will result in more or less CO_2 emissions is not a straightforward task. It depends on the management scenario that is chosen, the biogeoclimatic characteristics of the forest, and the assumptions one makes. It is not surprising, therefore, that in the past few forestry activities had been certified to provide carbon credits for sale in mandatory carbon markets, because forest offsets are fraught with problems related to uncertainty and corruption (Helm 2010; van Kooten 2017, 2018).

Challenge: To Conserve or Harvest Forests

In a study prepared for the Ancient Forest Alliance, Morton et al. (2021) find that carbon values dominate all scenarios. The preferred strategy is not to harvest any of the 200,700 hectares (ha) of forest around Port Renfrew on southwestern Vancouver Island. The 'no harvest' strategy leads to a discounted net benefit to society of \$176 million compared to \$44 million for a strategy that would allow for a four-year transition from protecting 50% of trees older than 140 years to 100% protection (p.45). Compared to scenarios that permit various levels of harvest, only the 'no harvest' scenario increases carbon storage (p.42)—by 1.67 million tonnes (Mt) of carbon, or 6.15 Mt CO_2. The carbon value to society of 'no harvest' is estimated at some \$200 million in present value terms compared with \$60 million for the next best scenario—one that includes some harvesting.

In the analysis, carbon fluxes are priced at the social cost of carbon (SCC), which is assumed to increase linearly from the BC government's carbon tax of \$40/tCO_2 in 2020 to over \$300/tCO_2 in 2050, with the annual value of carbon fluxes discounted to the present at a 3% discount rate. Information about future carbon prices are based on SCC and comes from Nordhaus' DICE model, which finds that, for an equilibrium climate sensitivity of 3°C, the SCC would lie between \$87/tCO_2 and \$313/tCO_2 in 2050, assuming a rate of social time preference equal to 1.5% and an elasticity of the marginal utility of consumption of 1.45.[3]

Interestingly, Morton et al. (2021) find that all non-carbon environmental plus recreation values do not exceed \$10 million in any scenario (p.46). However, in concluding that the forest should remain unharvested, the benefits of harvesting were taken to be quite low (p.46).

A special task force of the U.S. Society of Foresters concluded that conservation projects are highly variable, depending on numerous assumptions of which most are susceptible to bias, and virtually insurmountable measurement errors (Malmsheimer et al. 2011). One of the main problems with forest carbon offset credits is the misguided belief that an unmanaged forest will accumulate and retain an amount of carbon greater than what the offset buyer is emitting over time—a false sense that, upon purchasing offsets, a buyer's activity is carbon neutral. The task force also argued that the global benefits of forest offsets are overstated due to additionality and leakages that potentially nullify almost any carbon gains. Finally, protected forests are prone to release carbon to the atmosphere as a result of natural disturbance, a factor that often gets neglected in arguments favoring conservation (see Siebel-McKenna et al. 2020).

3. FOREST MANAGEMENT AND CARBON: METHODS

One means of determining the effectiveness of carbon dioxide removals in the forest sector is to examine the effect that the inclusion of a carbon price has on forest rotation ages. The Faustmann (1995/1849) rotation age deals only with the commercial value of timber, while the Hartman (1976) rotation age includes environmental benefits that are a direct function of the forest stand's age (i.e., stand volume). Carbon is ignored in the Faustmann and Hartman rotations because carbon benefits do not depend on the volume of standing timber (age of trees), but, rather, on changes in a stand's volume. Once the carbon has been sequestered it provides a one-time benefit—the benefit is only realized at the time CO_2 is removed from the atmosphere, with no further benefits attributable to the carbon once it is stored in biomass. There is a cost, however, when the stand is harvested and carbon is released in the form of CO_2. At the same time, account needs to be taken of carbon not released to the atmosphere at the time of harvest because the carbon is transferred (or transformed) into a wood product sink (e.g., lumber used in construction).

Rotation Age as a Function of Changes in Stand Volume

In their original article introducing the impact of carbon on forest rotation ages, van Kooten et al. (1995, p.368) provide equations describing the present value of financial earnings, including, as a cost of harvesting, any taxes for releasing carbon, and the present value of subsidies for CDR. At any stand age *t*, the equations for determining the present values of financial earnings, denoted

[3] The SCC represents the marginal damage of atmospheric CO_2. The SCC would need to be divided by the marginal cost of public funds in setting an appropriate carbon tax (Sandmo 1975, 1998; Dahlby 2008). A good rule of thumb might be to divide the SCC by 2.0, which implies that a tax should not exceed \$160/tCO_2.

$PV(t)_F$, and carbon earnings, $PV(t)_c$, over a single rotation are as follows:

$$(1)\ PV(t)_F = P_F v(t)e^{-rt} - P_c\alpha(1-\beta)v(t)e^{-rt} = \big(P_F - P_c\alpha(1-\beta)\big)v(t)e^{-rt}.$$

$$(2)\ PV(t)_c = P_c\alpha \int_0^t v'(s)e^{-rs}ds = P_c\alpha\left(v(t)e^{-rt} + r\int_0^t v(s)e^{-rs}ds\right).$$

In these equations, P_F and P_c denote the prices of commercial timber and carbon, respectively; $v(t)$ denotes the volume of commercial timber on the stand at age t and $v'(t)$ denotes the first derivative of the growth function with respect to time; α represents the carbon in a unit volume of timber; β is the proportion of carbon in timber that is transferred to wood product sinks—referred to as the 'pickling factor'; r is the social discount rate; and s is an integration variable. The first term in equation (1) represents the return to commercial harvests at age t, and the second term represents the penalty for releasing CO_2 into the atmosphere upon harvest (a cost of harvesting trees), with an adjustment made for carbon stored in wood product sinks. Equation (2) provides the discounted monetary payment provided the forestland owner in each period for sequestering carbon in the biomass that grows during that period.

Following van Kooten et al. (1995), upon summing the two present value functions, we obtain:

$$(3)\ PV(t)_F + PV(t)_c = (P_F + \alpha\beta P_c)v(t)e^{-rt} + \alpha P_c\, r\int_0^t v(s)e^{-rs}ds.$$

To determine the present value of the financial plus carbon sequestration benefits over all rotation ages, we divide $PV(t)_F + PV(t)_c$ by $1-e^{-rt}$ to get:

$$(4)\ V(t) = \frac{(P_F+\alpha\beta P_c)v(t)e^{-rt} + \alpha P_c\, r\int_0^t v(s)e^{-rs}ds}{1-e^{-rt}}.$$

Setting $V'(t) = 0$, and rearranging the resulting expression, gives the following equation for finding the optimal rotation age:

$$(5)\ \frac{(P_F+\alpha\beta P_c)\frac{v'(t)}{v(t)} + r\alpha P_c}{(P_F+\alpha\beta P_c) + \frac{r\alpha P_c}{v(t)}\int_0^t v(s)e^{-rs}ds} = \frac{r}{1-e^{-rt}}.$$

If $P_c = 0$, one gets the usual condition for finding the financial or Faustmann rotation age:[4]

$$(6)\ \frac{v'(t)}{v(t)} = \frac{r}{1-e^{-rt}}.$$

One can numerically solve equation (5) to find the optimal rotation age for various growth functions, $v(t)$, discount rates, and values of parameters α and β. Upon doing so, van Kooten et al.

[4] Setting P_F=0 in equation (5) gives result (8), and setting P_F=β =0 gives result (9), in van Kooten et al. (1995, p.368).

found that, in coastal British Columbia, carbon considerations increased the length of the optimal rotation age compared to the financial rotation age. Only when the price of carbon exceeded about \$175/tCO_2 and the commercial value of timber was low would it be uneconomic to harvest trees. What is missing in the van Kooten et al. analysis are the carbon associated with non-commercial elements of the forest ecosystem (carbon not a direct function of the volume of standing timber), a mechanism for counting decay of post-harvest wood-product pools that store carbon, and a method for addressing the fact that future removals of CO_2 from the atmosphere are less important than current removals.

A Model of the Carbon Rotation Age

The determination of an optimal rotation age needs to take into account forest ecosystem and post-harvest, wood-product carbon sinks, as well as the potential for wood biomass to replace fossil fuels in space heating and the generation of electricity. In practice, it also needs to consider stands with a mix of species growing at different rates and with various carbon dynamics. This means that the second term in equation (1) is replaced by an appropriate carbon account—no longer is carbon directly linked to the volume of commercial timber on a stand, $v(t)$, but, rather, to the various forest-related carbon pools. This then requires a numerical rather than an analytic analysis.

In this study, the focus is on the commercial and carbon benefits of forests while ignoring other environmental benefits. When climate change benefits of forestry are taken into account, there are four components in the present value function that a forest landowner needs to take into account. This can be done by incentivizing landowners to take carbon fluxes into account using either a tax/subsidy scheme or a carbon market.[5] The four components are (1) the commercial value of logs at the time of harvest; (2) the annual payment the landowner receives for CO_2 removed from the atmosphere by growing trees during that period; (3) the penalty the landowner pays at the time of harvest when all the carbon on the site is released; and (4) the payment received for any carbon entering post-harvest product pools after timber has been harvested and processed. The CO_2 emissions related to harvesting trees, transporting logs, and processing logs into final products are ignored because these would be accounted for and charged to the logging, transportation and processing firms through their use of energy (e.g., a carbon tax on gasoline).

In discrete form, we can write the present value function over a single rotation as:

$$(7)\quad PV = \frac{P_F v_t}{(1+r)^t} + P_c \sum_{s=1}^{t} \frac{\Delta C_s}{(1+r)^s (1+r_c)^s} - \frac{P_C C_t}{(1+r)^t}\left(1 - \sum_{k=1}^{K} \frac{r_c}{r_c+\delta_k}\gamma_k\right).$$

[5] A tax/subsidy is the simplest mechanism to employ; to keep monitoring and enforcement costs to a minimum, payments and penalties could be based on a computer model so only land use needs to be monitored. Otherwise, the forestland owner must purchase carbon offsets for any CO_2 emitted to the atmosphere at harvest, say, while selling CDRs when carbon is removed from the atmosphere.

In addition to the explanations of the variables and parameters provided earlier, here C_t refers to the carbon stored in living and dead biomass at stand age t and ΔC_s refers to the carbon sequestered in the living plus dead biomass carbon sinks between stand ages s–1 and s, and t is the age when the stand is harvested. There are K post-harvest carbon pools; we use γ_k and δ_k to denote the proportion of carbon entering pool k and the rate of decay of the k^{th} pool, respectively. Finally, r_c refers to the weight used to discount carbon fluxes as discussed below.

The first three terms are almost self-explanatory, while the fourth requires further discussion. The first term in equation (4) is the net return to commercial harvests or, perhaps more appropriately, the stumpage value.[6] The second term in equation (4) refers to the carbon that gets stored in the forest ecosystem as a stand develops. In each growth period s, it tracks the changes in the carbon found in living biomass, including the commercial component of the trees, plus carbon in dead biomass resulting from falling leaves/needles, broken branches, organic matter in the soil, and so on. As a result of biomass growth, an amount ΔC_s carbon is stored and valued at the price of carbon and then discounted to the present at the financial rate. Carbon (in the form of CO_2) is further weighted by the rate used to discount the physical carbon flux. The third term constitutes the value of the CO_2 that is potentially released to the atmosphere—it is a cost of harvesting trees; however, some of the carbon is subsequently shifted to other carbon pools. In essence, offsetting the tax that results from the release of all carbon in the forest ecosystem at the time of harvest is the subsidy received for carbon that enters post-harvest carbon pools.

The final term has the following interpretation: at the time of harvest, wood biomass is processed into various product pools that store carbon, where γ_k is the proportion of carbon C_t that goes into product pool k. Since these product pools slowly release their carbon over time as a result of decay, this is accounted for by the term $\frac{r_c}{r_c+\delta_k}$,[7] where δ_k denotes the decay rate of products in carbon pool k. The stream of future carbon that is lost over time is discounted at rate r_c to the time the stand is harvested and subtracted from the original carbon entering the product pool at that time. We assume that, at the time of harvest, all of the carbon is stored in four post-harvest product pools: (i) lumber; (ii) long-lived engineered wood products (plywood, various fiber boards, etc.); (iii) residues and waste used to produce pulp, wood pellets for exports, heat or electricity;[8] and (iv) carbon left and stored in the forest ecosystem. In equation (4), it is assumed that decay of wood products begins in period t+1 following harvest in period t. Although the rates of decay vary depending on the particular carbon pool, for convenience we employ average decay rates for the different carbon pools.

[6] This is not to be confused with a stumpage fee that the forest company might pay to a landowner. From a societal perspective, the stumpage value is what the log is worth at the mill minus the stumpage fee and felling, yarding, bucking, loading and transporting costs.
[7] See van Kooten (2018) for a derivation of this formula.
[8] Residuals and waste are often burned on site at sawmills to reduce energy costs. Emissions avoided when wood substitutes for fossil fuels in generating electricity are ignored, partly because some 90% of electricity consumed in BC constitutes emissions-free hydropower but also because such emissions reductions are credited to the power sector.

Suppose that 100 kg of carbon is released at time of harvest, with one-quarter (25 kg) entering a lumber product pool (γ_{lumber}=0.25). If lumber decays at an annual rate of 2% (δ_{lumber}=0.02) and the weight used to discount physical carbon is chosen to be 1% (see van Kooten et al. 2021), then 8.33 kg (=25 kg × 0.01/0.03) of carbon is assumed to enter permanently into the lumber product pool. If the carbon discount rate were 1.5% instead of 1%, then 12.5 kg would remain permanently in the lumber product pool. There is an increase in the carbon stored as r_c declines because more distant CO_2 emissions due to decay are weighted less. Consequently, when the discount rate on carbon is zero (r_c=0%), it is assumed all carbon is (eventually) released to the atmosphere even if it takes hundreds of years—no carbon is effectively retained in carbon products.

To find the age at which to cut trees for a one-time benefit—known as the Fisher or single rotation age—we set the first derivative of (4) to zero and solve for *t*. To account for regeneration and future harvests, we calculate the value of the forest at any future time and divide by $(1+r)^t - 1$ (van Kooten and Folmer 2004, p.370). The value function over all rotations is thus given by:

$$(8)\ V = \frac{\frac{P_F v_t}{(1+r)^t} + P_c \sum_{s=1}^{t} \frac{\Delta C_s}{(1+r)^s (1+r_c)^s} - \frac{P_C C_t}{(1+r)^t}\left(1 - \sum_{k=1}^{K} \frac{r_c}{r_c + \delta_k} \gamma_k\right)}{(1+r)^t - 1},$$

where *t* refers to the optimal rotation age. Notice that the second term is multiplied by $(1+r)^t$ so that the current value of the annual stream of carbon benefits is compounded to the time of harvest and subsequently discounted to the present. The optimal rotation age is found numerically since we do not have explicit expressions for changes in carbon found in living and dead biomass.

To calculate the carbon sequestered over multiple rotations, we employ the carbon dioxide removals associated with the optimal rotation age and employ the following equation to derive the total carbon at the current time:

$$(9)\ CRD = \frac{(1+r_c)^n}{(1+r_c)^n - 1} C^n,$$

where *n* refers to the (optimal) rotation age and C^n is the carbon removed at age *n* but brought to the present by discounting future carbon fluxes at rate r_c. Note that, in the numerator of equation (9), the current-period carbon needs to be brought to the future to invoke the standard bond formula.

4. FOREST MANAGEMENT AND CARBON: RESULTS

For any given forest stand, if the required information is available, the easiest means of solving the rotation age problem is to calculate the present value given in equation (8) for each year over a sufficiently long time horizon. The year in which PV attains a maximum represents the optimal rotation age. If PV<0 then the site should be left unharvested as the carbon benefits of leaving the trees standing exceeds the commercial benefits of harvesting the trees. The remaining issue concerns data availability.

Data

We employ data from BC Ministry of Forests (2021) growth and yield model, known as TIPSY. Information on the carbon sinks found in forest ecosystems is available from the Canadian Forest Service's Carbon Budget Model (Government of Canada 2021), which has been integrated into TIPSY. The modeling software includes the growth and yield of commercial timber (Nigh and Mitchell 2003) and all of its biomass components. For forest stands consisting of various tree species, mix of species, site indexes, slopes and biogeoclimatic zones, TIPSY provides growth and yield data on commercial timber volume, carbon in living and dead biomass, utilization data, costs and a lot of other information that is used by the Province in its timber (and wood product) supply analyses. TIPSY also provides information on expected logging, yarding, bucking, loading and transportation costs, the various products that are likely available from the stand, employment and so on. The user only needs to provide information on the forest stand itself, including the proportion of the site that is occupied by various species, whether the site was planted or left to grow naturally, options concerning selected silvicultural practices (e.g., fertilization and thinning of trees to cause them to grow larger, although volume might be less), a site index (quality of site for growing trees), slope of the site, and the biogeoclimatic zone in which the stand is located.

Determining the value of standing timber is difficult. We examined data from the Vancouver log market, the provincial government's billing system, and Morton et al. (2021). The latter used information from TIPSY to calculate average stumpage value, grade-weighted over one year, for species found on southern Vancouver Island, which encompasses the current study region. Morton et al. then subtracted an average cost of bringing timber to market of \$79.26/m^3 to obtain stumpage values.[9] The stumpage values of various species for each of these methods is found in Table 1.

We identified 20 alternative stands of trees to represent potential sites in the study region. The majority of stands are assumed to have site indexes of 30 or 40, which are the most common in the study region. Half of the sites are natural while the remainder are planted. Information on the sites employed in this study is found in Table 2.[10] Upon harvesting a forest stand, the biomass is allocated to three post-harvest product pools and an ecosystem pool that represents dead biomass left on the site after harvest. The approximate allocations of biomass to these pools are based on TIPSY data and are provided in Table 3. In addition, decay rates for the various pools are provided in Table 3; these rates are determined from various studies that examined decay of biomass on-site and post-harvest (Harmon et al. 1986; Krankina and Harmon 1995; Dymond 2012).

[9] By subtracting \$79.26/m^3 and due to the preponderance of hemlock harvests early in their timeframe, Morton et al. find that firms should not log forests on southern Vancouver Island since discounted net returns would be negative. We focus on the data from the Vancouver log market as it includes harvesting and marketing costs.
[10] Greater detail about the individual sites is available upon request.

Table 1: Log Values, by Source of Data, $/m^3

Species	Vancouver Log Market[a]	BC Billing System[b]	ESSA[c]
Alder	89.68	0.99	41.68
Birch	57.25	40.98	—
Cedar	257.15	74.14	212.49
Cypress	117.83	33.6	98.81
Fir	219.66	46.91	111.89
Hemlock	71.62	38.28	68.21
Maple	59.44	0.99	29.41
Pine	46.90	63.51	62.79
Spruce	102.31	102.69	102.23

[a] Vancouver Log Market values based on the average of October through December, 2018.
[b] Source: BC MFLNRO (2021) Prices for January through November, 2021.
[c] Source: Morton et al. (2021, pp18-19, Table 5). The authors subtract a marketing cost of $79.26/m^3 to obtain the true value.

Table 2: Description of Stands Used in the Model

Species[a]	Stand Abbreviation	Site Index	Natural or planted	Years of data[b]
Douglas fir	fir30N	30	natural	250
Douglas fir	fir40N	40	natural	117
Douglas fir	fir30P	30	planted	250
Douglas fir	fir40P	40	planted	112
Western hemlock	hem30N	30	natural	250
Western hemlock	hem40N	40	natural	141
Western hemlock	hem30P	30	planted	250
Western hemlock	hem40P	40	planted	137
Western red cedar	ced30N	30	natural	250
Western red cedar	ced40N	40	natural	149
Western red cedar	ced30P	30	planted	250
Western red cedar	ced40P	40	planted	144
Mix 40/32/16/6/6	mix30N	30	natural	176
Mix 40/32/16/6/6	mix40N	40	natural	151
Mix 40/32/16/6/6	mix30P	30	planted	171
Mix 40/32/16/6/6	mix40P	40	planted	147
Mix 20/25/30/15/10	smix30P	20	planted	200
Mix 40/20/20/20/0	smix40P	Various[c]	planted	200
Mix 40/22/13/15/10	smixQN	Various[c]	natural	200
Mix 25/15/15/20/25	smix20N	40	natural	132

[a] For mix of species, the proportions are for: fir/hemlock/cedar/spruce/other. Fir refers primarily to coastal Douglas fir, but may include some anabilis fir; hemlock refers to Western coastal hemlock, but may include some mountain hemlock; cedar is Western red cedar; spruce refers to Sitka spruce; and other includes red alder, sub-alpine fir, and/or lodgepole pine.
[b] The years of data are set to 200 or 250, although TIPSY may provide an earlier age beyond which no further data are provided.
[c] Site index depends on species included in the mix.
Source: Author's calculations based on data from TIPSY and determination of the optimal rotation age.

Table 3: Post-harvest Allocation of Biomass to Four Pools and Associated Decay Rates

Post-harvest carbon pool	Allocation of stand biomass to carbon pools post-harvest	Decay rates of carbon pools
1. Lumber	0.2903	0.0082
2. Long-lived engineered wood products	0.1185	0.0080
3.Residues & waste (pulp, wood pellets, energy)	0.3412	0.0234
4. Biomass left in forest ecosystem.	0.2500	0.0718

Source: Author's estimates based on data from Dymond (2012), Krankina and Harmon (1995), and Harmon et al. (1986).

Optimal Harvest Decisions

Much debate centers about the issue of whether mature or old-growth forests should be left unharvested because harvesting would lead to the release of huge stores of carbon to the atmosphere. As noted earlier, non-carbon environmental benefits of forests in the study region tend to be small at the margin compared to their commercial benefits (e.g., Morton et al. 2021). This is not to suggest that they are unimportant and could even lead to a lengthening of the rotation age. Rather, the largess of forest on BC's Coast offers many alternative opportunities to recreationists, while still not threatening loss of biodiversity (van Kooten and Bulte 1999).

For each of the sites identified in Table 2, we solved equation (8) to find the optimal rotation age and the expected discounted net returns using discount rates on monetary values of 3% and 4%. Then, equation (9) was used to determine the CO_2 that could be credited as carbon offset credits (i.e., CDRs). In Table 4, for each of the 20 sites we provide the Faustmann (financial) rotation age and rotation ages for selected assumptions about in the price of carbon—\$0/tCO_2, \$50/tCO_2, \$100/tCO_2, and \$200/tCO_2—and three carbon weighting schemes—0%, 1% and 5%. If physical carbon is not weighted, it does not matter when a growing forest removes CO_2 from the atmosphere. If carbon is discounted at 5%, 100 kg of CO_2 removed 50 years from today is counted as if 8.7 kg are removed today. Indeed, CO_2 removals from the atmosphere after 2050 might be considered superfluous as they are considered too late to prevent expected damages from climate change.

It is assumed that the BC billing data represent actual stumpage values and that financial data are discounted at a rate of 3%. Then, in Table 5, we present the net present value of the forestry operations for these assumed parameters, while the associated carbon dioxide removals are provided in Table 6. Additional scenarios that employ a higher financial discount rate and lower and higher timber prices are provided in the Appendix.[11]

[11] We provide information on rotation ages, the soil expectation (net present value), and potential carbon offsets for higher (VLM prices) and lower (ESSA estimated prices) stumpage values, and a 5% financial discount rate.

Table 4: Rotation Ages for Various Carbon Prices (P_c) and Weights on Physical Carbon Fluxes (r_c), Stumpage Values (P_F) based on BC Billing Data, and a Financial Discount Rate (r) of 3%, Number of Years

Stand Type[a]	Faustmann or financial[b]	$50/tCO$_2$		$100/tCO$_2$		$200/tCO$_2$	
		r_c=1%	r_c=5%	r_c=1%	r_c=5%	r_c=1%	r_c=5%
fir30N	49	42	40	40	35	38	28
fir40N	44	41	39	39	31	36	27
fir30P	37	34	30	32	29	30	23
fir40P	37	34	27	31	24	27	22
hem30N	49	22	18	28	19	30	20
hem40N	40	18	15	23	17	26	19
hem30P	42	20	16	24	18	26	20
hem40P	32	15	14	20	16	22	17
ced30N	56	53	53	51	51	50	44
ced40N	42	42	42	42	42	42	40
ced30P	37	37	37	37	37	37	36
ced40P	36	36	35	35	33	33	26
mix30N	50	43	41	41	37	39	29
mix40N	47	42	40	40	34	37	29
mix30P	38	36	32	33	29	32	26
mix40P	40	34	31	32	28	30	24
smix30P	52	48	48	44	43	43	33
smix40P	52	48	48	48	48	46	43
smixQN	61	57	58	51	43	47	19
smix20N	58	52	48	43	19	37	17

[a] Stand types are described in the footnotes to Table 2.
[b] Faustmann or financial rotation age occurs when price of carbon is $0/tCO$_2$ and carbon fluxes are not weighted (r_c=0%).
Source: Author's calculations.

An increase in the price of timber does not affect the rotation age, ceteris paribus,[12] while rotation ages would shorten with an increase in the financial discount rate (see Appendix Tables A1–A6). Likewise, if the price of carbon increases, the rotation age is extended as long as carbon fluxes are not weighted (Table 4). These are standard results that can be found in the literature. It is hardly necessary to point out that the net discounted value received by the forest landowner increases with a rise in timber prices and prices received for CO_2 offsets, but only as long as carbon fluxes remain unweighted (Table 5). As a corollary, the number of CDRs that can be attributed to any forest stand rises with the price of CO_2, ceteris paribus. Although not explicitly examined here, an increase in decay rates of various post-harvest carbon pools, or an allocation of biomass towards pools with higher decay rates, will reduce the rotation age, net present value and CDRs.

[12] An exception occurs for hemlock sites because, for the (low) prices, denoted ESSA and determined by Morton et al. (2021), forest companies would face negative returns and, therefore, would not harvest hemlock. At higher prices, hemlock stands would be harvested with the rotation age remaining the same as prices continued to rise.

Table 5: Discounted Net Value of Timber Stand for Selected Carbon Prices (P_c) and Rates for Discounting Physical Carbon (r_c), Stumpage Values (P_F) based on BC Billing Data, and a Financial Discount Rate (r) of 3%, $C per ha[a]

Stand	$0/t$CO_2$	$100/t$CO_2$			$200/t$CO_2$		
Type	Faustmann	r_c=0%	r_c=1%	r_c=5%	r_c=0%	r_c=1%	r_c=5%
fir30N	4,466	4,471	5,618	3,142	4,475	6,938	2,423
fir40N	8,745	8,755	11,434	7,012	8,765	14,341	6,932
fir30P	6,820	6,830	10,153	7,505	6,840	13,667	8,826
fir40P	12,381	12,398	18,474	14,847	12,415	25,025	19,133
hem30N	5,337	5,343	6,557	3,714	5,348	8,095	2,974
hem40N	10,864	10,878	15,100	10,364	10,891	19,633	11,228
hem30P	7,283	7,293	10,515	7,516	7,302	14,110	8,781
hem40P	14,316	14,337	22,165	18,360	14,358	30,290	24,416
ced30N	10,085	10,088	10,624	8,196	10,092	11,401	6,813
ced40N	20,277	20,287	22,799	18,371	20,297	25,387	16,985
ced30P	14,295	14,303	16,818	14,032	14,311	19,353	13,931
ced40P	27,018	27,034	32,567	28,852	27,049	38,415	32,492
mix30N	6,202	6,207	7,402	4,727	6,212	8,854	3,893
mix40N	7,286	7,293	8,828	5,786	7,299	10,655	5,081
mix30P	8,056	8,065	11,033	8,322	8,074	14,219	9,399
mix40P	10,150	10,161	14,129	11,079	10,172	18,352	13,030
smix30P	4,503	4,506	5,227	3,591	4,509	6,085	3,002
smix40P	4,341	4,344	5,018	3,375	4,347	5,825	2,747
smixQN	2,621	2,622	2,682	1,513	2,624	2,875	713
smix20N	2,929	2,931	3,257	1,987	2,933	3,730	2,418

[a] See Table 4 for footnotes.
Source: Author's calculations.

Although rather obvious, rotation ages, net present values and the number of CDRs that could be claimed vary significantly among sites. This is important to remember if, as proposed, some 900 million ha of land globally, much of which is marginal, can be planted to tress thereby enabling society to make a sizable dent in its CO_2 mitigation targets (e.g., see Grassi et al. 2017). Site quality and choice of species matter a great deal, although this issue is often neglected.

More importantly, the timing of carbon removals from the atmosphere is a concern. However, if future CDRs are just as valuable as current ones (r_c=0), carbon dioxide removals will clearly be infinite as long as harvests continue in perpetuity (Table 6); if sites are not harvested, a limited number of carbon credits are created (Tables A1 and A4). With no weighting of carbon fluxes as to when they occur, forestry activities to increase CDRs can be delayed, perhaps into the far distant future. Forest landowners will still be able to count (paper-only) carbon offset credits as if they occurred today, although the number of CDRs to count will depend on arbitrary cutoff dates. Once physical carbon is weighted as to when removals from, or emissions to, the atmosphere occur, the picture changes dramatically. CDRs no longer depend on an arbitrary cutoff date, but the number of carbon offsets (CDRs) declines (Table 6), while the optimal rotation age generally declines (Table 4). Yet, there may be cases where the optimal rotation age actually increases, which depends on the stand type and species that are grown, the price of carbon, and the rate used to discount physical carbon (Tables A7–A9). That is, the rotation age may increase or decrease with an increase in the price of CO_2, although the tendency is for rotation age to decline.

Table 6: Carbon Offset Credits (CDRs) for Various Carbon Prices (P_c) and Weights on Physical Carbon (r_c), and a Financial Discount Rate (r) of 3%, Mt CO_2

Stand	$0/tCO2			$100/tCO2			$200/tCO2		
Type[a]	r_c=0%[b]	r_c=1%	r_c=5%	r_c=0%	r_c=1%	r_c=5%	r_c=0%	r_c=1%	r_c=5%
fir30N	inf	886	101	inf	764	84	inf	747	70
fir40N	inf	1,598	196	inf	1,482	159	inf	1,446	133
fir30P	inf	1,109	161	inf	1,038	143	inf	996	131
fir40P	inf	1,971	296	inf	1,802	233	inf	1,625	218
hem30N	inf	1,028	119	inf	879	102	inf	840	78
hem40N	inf	1,827	244	inf	1,664	212	inf	1,629	180
hem30P	inf	1,265	179	inf	1,118	149	inf	1,074	136
hem40P	inf	2,090	328	inf	2,024	288	inf	1,986	264
ced30N	inf	891	93	inf	816	86	inf	702	75
ced40N	inf	1,436	179	inf	1,436	177	inf	1,414	155
ced30P	inf	947	133	inf	947	130	inf	929	125
ced40P	inf	1,752	268	inf	1,673	226	inf	1,643	220
mix30N	inf	980	114	inf	867	99	inf	814	87
mix40N	inf	1,097	132	inf	1,002	115	inf	935	103
mix30P	inf	1,076	155	inf	1,045	142	inf	987	128
mix40P	inf	1,369	201	inf	1,234	170	inf	1,183	156
smix30P	inf	585	71	inf	548	65	inf	510	56
smix40P	inf	579	70	inf	532	65	inf	512	53
smixQN	inf	459	44	inf	432	43	inf	383	23
smix20N	inf	511	59	inf	471	55	inf	387	21

[a] Stand types are described in the footnotes to Table 2.
[b] If carbon is not discounted, an infinite (inf) amount of carbon is removed from the atmosphere by a forest that is regularly harvested with carbon stored in various post-harvest biomass pools. See also Appendix tables.
Source: Author's calculations.

Notice that the rotation age falls rapidly in several scenarios. Careful inspection of outcomes indicates that the value of commercial timber rises slowly but, at a carbon price of $200/tCO2, the annual component of overall income rises quickly; however, so does the penalty for releasing carbon upon harvest. In that case, the high annual payment can be 'continued' by planting new trees, while the carbon cost related to harvest is mitigated by cutting earlier, when less carbon is released.

Finally, when current carbon removals are weighted much higher than later carbon removals (r_c=5%), the carbon offsets that can be credited decline precipitously, especially in the case of slower-growing forests (Table 6). This is particularly the case for naturally occurring mixed forest stands.

5. CONCLUDING DICUSSION

Forestry activities clearly have an impact on global emissions of CO_2 and carbon stored in ecosystems and harvested wood products. However, it is difficult to determine the optimal forest management strategy that maximizes carbon sequestration in British Columbia. It will clearly depend on the forest ecosystem, site quality, forest management practices, and post-harvest processing of timber. It depends on the species and varieties of trees; inventory and growth; the risk of natural disturbance; the extent to which harvested wood is converted to products; the rate of decay of such products; the economics of recovering and processing logging and roadside wastes, and sawmill residues; input and output prices; and a variety of policy levers, including log export policies, minimum utilization standards, and forest practices legislation or certification standards. As shown in this study, it also depends crucially on the rate used to discount physical carbon. "*As a result, a wide variety of forest offset values could be justified, which makes it difficult to accept any, particularly if one is serious about addressing climate change. This might have been a reason why Europe originally opposed the use of forest carbon offsets in lieu of actual CO_2 emissions reduction*" (van Kooten et al. 2015, p.379).

Outside of permanent land use changes where timber is not processed further and the land usually burned (viz., tropical deforestation), the carbon benefits from either conserving forests or sustainably harvesting them are not large enough to warrant reliance on forestry to meet national emission reduction targets. Estimates of forest carbon benefits are relative to an assumed counterfactual; for example, carbon benefits from forest conservation are to be measured relative to those associated with a sustainable commercial harvest (including carbon in post-harvest wood product sinks), while the carbon benefits from commercial harvests need to be compared to those of the unharvested forest. It is the difference in carbon sequestration between the proposed and the counterfactual that we need to determine. These differences are often small, but, more importantly, extremely difficult to measure without restrictive assumptions, which is why so few forestry projects have been improved under Kyoto's Clean Development Mechanism. Assumptions made in the political arena tip the decision one way or the other (van Kooten 2018). Society must choose whether carbon sequestration targets are more important than forest revenues from stumpage fees, forest-sector employment (including employment of indigenous peoples), community stability, exports and so on (Krcmar et al. 2005).

Based on the research presented in this study, we can conclude the following:

1. An increase in the price of timber has no effect on the Faustmann rotation age.

2. A decrease in the financial discount rate causes the optimal rotation age to increase.

3. An increase in the price of carbon can increase or reduce the optimal rotation age if any weight is placed on the timing of carbon fluxes (e.g., see Tables A7–A9). This depends on the quality of the timber on a site and the relationship between the price of carbon and the value of the timber.

4. An increase in the rate used to discount physical carbon generally lowers the optimal forest rotation age, although there may be cases where the rotation age actually increases—it depends on the characteristics of the forest stand. The general implication is that, if forestry is to be stop-gap measure while society implements a more permanent option for eliminating CO_2 emissions or lowering the atmospheric concentration of CO_2, early action is preferred. Post-harvest storage of carbon in wood product pools and the regeneration of the forest with younger, fast-growing trees are short-term actions that would help mitigate climate change. Delays in harvesting mature trees could lead to higher concentrations of atmospheric CO_2, but not on all forest stands.

Finally, the large differences across forest sites makes it difficult to determine the carbon fluxes over time from any one activity, let alone an activity measured against a counterfactual, while taking into account leakages and other pitfalls (Gifford 2020). Thus, the task of determining what might constitute true carbon offsets for any given scenario is almost impossible and certainly can be costly. Even with low carbon prices in voluntary or mandatory markets, verified carbon units can earn millions of dollars for their owners. Thus, rent seeking and corruption are unavoidable (Helm 2010). As a result, one can only conclude that forestry activities, while important, should not be relied upon to produce tradeable carbon offset credits.

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7. APPENDIX

Table A1: Rotation Ages, Land Value and CDRs for Various Carbon Prices, Financial Discount Rate of 5% and No Weighting of Physical Carbon, Log Prices based on ESSA

Stand Type[a]	$0/tCO$_2$[b]			$100/tCO$_2$			$200/tCO$_2$		
	Age	PV[c] ($/ha)	CDR (tCO_2)	Age	PV[c] ($/ha)	CDR (tCO_2)	Age	PV[c] ($/ha)	CDR (tCO_2)
fir30N	40	1,118	inf	40	1,120	inf	40	1,122	inf
fir40N	39	2,242	inf	39	2,246	inf	39	2,250	inf
fir30P	31	1,965	inf	31	1,969	inf	31	1,973	inf
fir40P	31	3,566	inf	31	3,573	inf	31	3,581	inf
hem30N	inf	-	2,804	inf	-	2,804	inf	-	2,804
hem40N	inf	-	3,070	inf	-	3,070	inf	-	3,070
hem30P	inf	-	2,828	inf	-	2,828	inf	-	2,828
hem40P	inf	-	3,057	inf	-	3,057	inf	-	3,057
ced30N	42	6,128	inf	42	6,129	inf	42	6,131	inf
ced40N	39	13,499	inf	39	13,503	inf	39	13,506	inf
ced30P	36	10,237	inf	36	10,240	inf	36	10,244	inf
ced40P	26	20,769	inf	26	20,776	inf	26	20,784	inf
mix30N	40	1,354	inf	40	1,356	inf	40	1,359	inf
mix40N	39	1,620	inf	39	1,623	inf	39	1,625	inf
mix30P	33	2,007	inf	33	2,011	inf	33	2,015	inf
mix40P	32	2,594	inf	32	2,599	inf	32	2,604	inf
smix30P	43	1,178	inf	43	1,180	inf	43	1,181	inf
smix40P	44	1,980	inf	44	1,982	inf	44	1,983	inf
smixQN	53	407	inf	53	408	inf	53	408	inf
smix20N	50	422	inf	50	423	inf	50	424	inf

[a] Stand types are described in the footnotes to Table 2.
[b] Faustmann or financial rotation age occurs when price of carbon is $0/tCO$_2$; 'inf' refers to infinite.
[c] PV refers to the net discounted financial return.
Source: Author's calculations.

Table A2: Rotation Ages, Land Value and CDRs for Various Carbon Prices, Financial Discount Rate of 5% and No Weighting of Physical Carbon, Log Prices based on BC Billing Data

Stand Type[a]	$0/tCO$_2$[b]			$100/tCO$_2$			$200/tCO$_2$		
	Age	PV[c] ($/ha)	CDR (tCO$_2$)	Age	PV[c] ($/ha)	CDR (tCO$_2$)	Age	PV[c] ($/ha)	CDR (tCO$_2$)
fir30N	40	1,608	836,477	40	1,610	836,477	40	1,612	836,477
fir40N	39	3,223	1,599,563	39	3,227	1,599,563	39	3,231	1,599,563
fir30P	31	2,824	1,064,908	31	2,829	1,064,908	31	2,833	1,064,908
fir40P	31	5,126	1,868,936	31	5,134	1,868,936	31	5,142	1,868,936
hem30N	41	1,857	980,328	41	1,859	980,328	41	1,861	980,328
hem40N	34	4,302	1,772,397	34	4,308	1,772,397	34	4,314	1,772,397
hem30P	32	2,900	1,152,023	32	2,904	1,152,023	32	2,909	1,152,023
hem40P	29	6,174	2,090,566	29	6,184	2,090,566	29	6,193	2,090,566
ced30N	42	3,410	757,258	42	3,412	757,258	42	3,413	757,258
ced40N	39	7,512	1,493,083	39	7,516	1,493,083	39	7,519	1,493,083
ced30P	36	5,697	1,003,044	36	5,700	1,003,044	36	5,703	1,003,044
ced40P	26	11,557	1,511,532	26	11,565	1,511,532	26	11,573	1,511,532
mix30N	40	2,188	907,140	40	2,191	907,140	40	2,193	907,140
mix40N	39	2,618	1,036,323	39	2,620	1,036,323	39	2,623	1,036,323
mix30P	33	3,243	1,057,119	33	3,247	1,057,119	33	3,251	1,057,119
mix40P	32	4,192	1,287,059	32	4,197	1,287,059	32	4,202	1,287,059
smix30P	43	1,564	562,541	43	1,565	562,541	43	1,566	562,541
smix40P	44	1,486	566,429	44	1,488	566,429	44	1,489	566,429
smixQN	53	767	462,497	53	768	462,497	53	768	462,497
smix20N	50	905	509,457	50	905	509,457	50	906	509,457

[a] Stand types are described in the footnotes to Table 2.
[b] Faustmann or financial rotation age occurs when price of carbon is $0/tCO$_2$; ‘inf’ refers to infinite.
[c] PV refers to the net discounted financial return.
Source: Author’s calculations.

Table A3: Rotation Ages, Land Value and CDRs for Various Carbon Prices, Financial Discount Rate of 5% and No Weighting of Physical Carbon, Log Prices based on Vancouver Log Market Data

	$0/tCO$_2$[b]			$100/tCO$_2$			$200/tCO$_2$		
Stand Type[a]	Age	PV[c] ($/ha)	CDR (tCO$_2$)	Age	PV[c] ($/ha)	CDR (tCO$_2$)	Age	PV[c] ($/ha)	CDR (tCO$_2$)
fir30N	40	7,528	836,477	40	7,530	836,477	40	7,532	836,477
fir40N	39	15,094	1,599,563	39	15,098	1,599,563	39	15,102	1,599,563
fir30P	31	13,225	1,064,908	31	13,229	1,064,908	31	13,233	1,064,908
fir40P	31	24,003	1,868,936	31	24,011	1,868,936	31	24,019	1,868,936
hem30N	41	3,473	980,328	41	3,476	980,328	41	3,478	980,328
hem40N	34	8,049	1,772,397	34	8,055	1,772,397	34	8,060	1,772,397
hem30P	32	5,425	1,152,023	32	5,430	1,152,023	32	5,434	1,152,023
hem40P	29	11,552	2,090,566	29	11,561	2,090,566	29	11,571	2,090,566
ced30N	42	11,828	757,258	42	11,829	757,258	42	11,831	757,258
ced40N	39	26,054	1,493,083	39	26,058	1,493,083	39	26,062	1,493,083
ced30P	36	19,759	1,003,044	36	19,762	1,003,044	36	19,765	1,003,044
ced40P	26	40,086	1,511,532	26	40,094	1,511,532	26	40,102	1,511,532
mix30N	40	7,056	907,140	40	7,058	907,140	40	7,061	907,140
mix40N	39	8,440	1,036,323	39	8,443	1,036,323	39	8,446	1,036,323
mix30P	33	10,456	1,057,119	33	10,460	1,057,119	33	10,464	1,057,119
mix40P	32	13,517	1,287,059	32	13,522	1,287,059	32	13,528	1,287,059
smix30P	43	4,175	562,541	43	4,176	562,541	43	4,177	562,541
smix40P	44	4,188	566,429	44	4,189	566,429	44	4,190	566,429
smixQN	53	2,181	462,497	53	2,182	462,497	53	2,182	462,497
smix20N	50	2,260	509,457	50	2,261	509,457	50	2,262	509,457

[a] Stand types are described in the footnotes to Table 2.
[b] Faustmann or financial rotation age occurs when price of carbon is $0/tCO$_2$; 'inf' refers to infinite.
[c] PV refers to the net discounted financial return.
Source: Author's calculations.

Table A4: Rotation Ages, Land Value and CDRs for Various Carbon Prices, Financial Discount Rate of 3% and No Weighting of Physical Carbon, Log Prices based on ESSA

Stand	$0/tCO$_2$[b]			$100/tCO$_2$			$200/tCO$_2$		
Type[a]	Age	PV[c] ($/ha)	CDR (tCO_2)	Age	PV[c] ($/ha)	CDR (tCO_2)	Age	PV[c] ($/ha)	CDR (tCO_2)
fir30N	49	3,106	inf	49	3,111	inf	49	3,116	inf
fir40N	44	6,083	inf	44	6,093	inf	44	6,103	inf
fir30P	37	4,744	inf	37	4,754	inf	37	4,763	inf
fir40P	37	8,612	inf	37	8,629	inf	37	8,646	inf
hem30N	inf	-	2,804	16	neg	inf	16	neg	inf
hem40N	inf	-	3,070	12	neg	inf	12	neg	inf
hem30P	inf	-	2,828	12	neg	inf	12	neg	inf
hem40P	inf	-	3,057	inf	neg	3,057	inf	neg	3,057
ced30N	56	18,122	inf	56	18,126	inf	56	18,129	inf
ced40N	42	36,438	inf	42	36,448	inf	42	36,458	inf
ced30P	37	25,688	inf	37	25,696	inf	37	25,704	inf
ced40P	36	48,551	inf	36	48,567	inf	36	48,583	inf
mix30N	50	3,838	inf	50	3,843	inf	50	3,848	inf
mix40N	47	4,509	inf	47	4,515	inf	47	4,522	inf
mix30P	38	4,985	inf	38	4,994	inf	38	5,003	inf
mix40P	40	6,281	inf	40	6,292	inf	40	6,303	inf
smix30P	52	3,393	inf	52	3,396	inf	52	3,399	inf
smix40P	52	5,784	inf	52	5,787	inf	52	5,790	inf
smixQN	61	1,391	inf	61	1,392	inf	61	1,394	inf
smix20N	58	1,368	inf	58	1,370	inf	58	1,372	inf

[a] Stand types are described in the footnotes to Table 2.
[b] Faustmann or financial rotation age occurs when price of carbon is $0/tCO$_2$; 'inf' refers to infinite.
[c] PV refers to the net discounted financial return.
Source: Author's calculations.

Table A5: Rotation Ages, Land Value and CDRs for Various Carbon Prices, Financial Discount Rate of 3% and No Weighting of Physical Carbon, Log Prices based on BC Billing Data

Stand Type[a]	$0/tCO$_2$[b]			$100/tCO$_2$			$200/tCO$_2$		
	Age	PV[c] ($/ha)	CDR (tCO_2)	Age	PV[c] ($/ha)	CDR (tCO_2)	Age	PV[c] ($/ha)	CDR (tCO_2)
fir30N	49	4,466	inf	49	4,471	inf	49	4,475	inf
fir40N	44	8,745	inf	44	8,755	inf	44	8,765	inf
fir30P	37	6,820	inf	37	6,830	inf	37	6,840	inf
fir40P	37	12,381	inf	37	12,398	inf	37	12,415	inf
hem30N	49	5,337	inf	49	5,343	inf	49	5,348	inf
hem40N	40	10,864	inf	40	10,878	inf	40	10,891	inf
hem30P	42	7,283	inf	42	7,293	inf	42	7,302	inf
hem40P	32	14,316	inf	32	14,337	inf	32	14,358	inf
ced30N	56	10,085	inf	56	10,088	inf	56	10,092	inf
ced40N	42	20,277	inf	42	20,287	inf	42	20,297	inf
ced30P	37	14,295	inf	37	14,303	inf	37	14,311	inf
ced40P	36	27,018	inf	36	27,034	inf	36	27,049	inf
mix30N	50	6,202	inf	50	6,207	inf	50	6,212	inf
mix40N	47	7,286	inf	47	7,293	inf	47	7,299	inf
mix30P	38	8,056	inf	38	8,065	inf	38	8,074	inf
mix40P	40	10,150	inf	40	10,161	inf	40	10,172	inf
smix30P	52	4,503	inf	52	4,506	inf	52	4,509	inf
smix40P	52	4,341	inf	52	4,344	inf	52	4,347	inf
smixQN	61	2,621	inf	61	2,622	inf	61	2,624	inf
smix20N	58	2,929	inf	58	2,931	inf	58	2,933	inf

[a] Stand types are described in the footnotes to Table 2.
[b] Faustmann or financial rotation age occurs when price of carbon is $0/tCO$_2$; 'inf' refers to infinite.
[c] PV refers to the net discounted financial return.
Source: Author's calculations.

Table A6: Rotation Ages, Land Value and CDRs for Various Carbon Prices, Financial Discount Rate of 3% and No Weighting of Physical Carbon, Log Prices based on Vancouver Log Market Data

Stand Type[a]	$0/tCO_2$[b]			$100/tCO_2$			$200/tCO_2$		
	Age	PV[c] ($/ha)	CDR (tCO_2)	Age	PV[c] ($/ha)	CDR (tCO_2)	Age	PV[c] ($/ha)	CDR (tCO_2)
fir30N	49	20,912	inf	49	20,917	inf	49	20,922	inf
fir40N	44	40,948	inf	44	40,958	inf	44	40,968	inf
fir30P	37	31,937	inf	37	31,947	inf	37	31,957	inf
fir40P	37	57,973	inf	37	57,991	inf	37	58,008	inf
hem30N	49	9,986	inf	49	9,991	inf	49	9,997	inf
hem40N	40	20,327	inf	40	20,340	inf	40	20,354	inf
hem30P	42	13,627	inf	42	13,636	inf	42	13,645	inf
hem40P	32	26,784	inf	32	26,806	inf	32	26,827	inf
ced30N	56	34,978	inf	56	34,982	inf	56	34,985	inf
ced40N	42	70,330	inf	42	70,340	inf	42	70,350	inf
ced30P	37	49,580	inf	37	49,588	inf	37	49,596	inf
ced40P	36	93,710	inf	36	93,725	inf	36	93,741	inf
mix30N	50	19,998	inf	50	20,003	inf	50	20,008	inf
mix40N	47	23,494	inf	47	23,500	inf	47	23,507	inf
mix30P	38	25,975	inf	38	25,984	inf	38	25,993	inf
mix40P	40	32,729	inf	40	32,740	inf	40	32,751	inf
smix30P	52	12,021	inf	52	12,025	inf	52	12,028	inf
smix40P	52	12,231	inf	52	12,234	inf	52	12,237	inf
smixQN	61	7,452	inf	61	7,454	inf	61	7,455	inf
smix20N	58	7,319	inf	58	7,321	inf	58	7,323	inf

[a] Stand types are described in the footnotes to Table 2.
[b] Faustmann or financial rotation age occurs when price of carbon is $0/tCO_2$; 'inf' refers to infinite.
[c] PV refers to the net discounted financial return.
Source: Author's calculations.

Table A7: Rotation Ages, Land Value and CDRs for Various Timber Prices, Carbon Prices and Weightings on Physical Carbon using a Financial Discount Rate of 3%, Log Prices based on ESSA Data

	Carbon price = $100/tCO$_2$						Price of carbon = $200/tCO$_2$					
	Carbon discount rate = 1%			Carbon discount rate = 5%			Carbon discount rate = 1%			Carbon discount rate = 5%		
Stand Type[a]	Age	PV[c] ($/ha)	CDR (tCO$_2$)	Age	PV[c] ($/ha)	CDR (tCO$_2$)	Age	PV[c] ($/ha)	CDR (tCO$_2$)	Age	PV[c] ($/ha)	CDR (tCO$_2$)
fir30N	40	4,309	747	35	1,923	77	38	5,654	707	28	1,512	50
fir40N	39	8,830	1,446	31	4,805	144	36	11,846	1,317	27	5,016	120
fir30P	32	8,123	1,018	29	5,583	140	30	11,676	971	23	7,256	109
fir40P	31	14,818	1,763	24	11,599	226	27	21,565	1,585	22	16,112	209
hem30N	28	802	500	19	210	17	30	2,436	581	20	517	22
hem40N	23	2,405	1,028	17	1,017	68	26	7,003	1,227	19	2,877	98
hem30P	24	2,188	798	18	1,252	66	26	5,864	887	20	3,139	84
hem40P	20	5,262	1,501	16	4,495	183	22	13,756	1,635	17	11,178	201
ced30N	51	18,608	816	51	16,174	87	50	19,217	801	44	14,429	78
ced40N	42	38,960	1,436	42	34,496	179	42	41,481	1,436	40	32,649	174
ced30P	37	28,211	947	37	25,411	133	37	30,735	947	36	25,185	130
ced40P	35	53,967	1,729	33	49,811	258	33	59,696	1,673	26	52,585	226
mix30N	41	5,125	833	37	2,552	93	39	6,636	793	29	2,271	66
mix40N	40	6,148	958	34	3,264	103	37	8,066	891	29	3,088	83
mix30P	33	8,031	987	29	5,520	132	32	11,305	965	26	6,975	118
mix40P	32	10,339	1,208	28	7,549	166	30	14,665	1,156	24	9,865	144
smix30P	44	4,146	520	43	2,521	64	43	5,026	510	33	2,134	50
smix40P	48	6,447	549	48	4,788	67	46	7,203	532	43	3,981	63
smixQN	51	1,511	383	43	401	32	47	1,777	341	19	433	5
smix20N	43	1,784	387	19	1,168	21	37	2,460	321	17	1,766	19

Notes: Footnotes are identical to those in Table A1. With the exception of the shaded areas, the rotation age declined or remained the same with an increase in the discount factor on physical carbon.
Source: Author's calculations.

Table A8: Rotation Ages, Land Value and CDRs for Various Timber Prices, Carbon Prices and Weightings on Physical Carbon using a Financial Discount Rate of 3%, Log Prices based on BC Billing Data

	Carbon price = $100/tCO_2$						Price of carbon = $200/tCO_2$					
	Carbon discount rate = 1%			Carbon discount rate = 5%			Carbon discount rate = 1%			Carbon discount rate = 5%		
Stand Type[a]	Age	PV[c] ($/ha)	CDR (tCO_2)	Age	PV[c] ($/ha)	CDR (tCO_2)	Age	PV[c] ($/ha)	CDR (tCO_2)	Age	PV[c] ($/ha)	CDR (tCO_2)
fir30N	41	5,618	764	38	3,142	84	40	6,938	747	33	2,423	70
fir40N	40	11,434	1,482	34	7,012	159	39	14,341	1,446	29	6,932	133
fir30P	33	10,153	1,038	30	7,505	143	31	13,667	996	27	8,826	131
fir40P	32	18,474	1,802	25	14,847	233	28	25,025	1,625	23	19,133	218
hem30N	41	6,557	879	39	3,714	102	39	8,095	840	31	2,974	78
hem40N	35	15,100	1,664	32	10,364	212	34	19,633	1,629	27	11,228	180
hem30P	34	10,515	1,118	30	7,516	149	32	14,110	1,074	27	8,781	136
hem40P	30	22,165	2,024	25	18,360	288	29	30,290	1,986	22	24,416	264
ced30N	51	10,624	816	50	8,196	86	44	11,401	702	42	6,813	75
ced40N	42	22,799	1,436	41	18,371	177	41	25,387	1,414	35	16,985	155
ced30P	37	16,818	947	36	14,032	130	36	19,353	929	34	13,931	125
ced40P	33	32,567	1,673	26	28,852	226	32	38,415	1,643	25	32,492	220
mix30N	43	7,402	867	40	4,727	99	40	8,854	814	35	3,893	87
mix40N	42	8,828	1,002	38	5,786	115	39	10,655	935	34	5,081	103
mix30P	36	11,033	1,045	32	8,322	142	33	14,219	987	28	9,399	128
mix40P	33	14,129	1,234	29	11,079	170	31	18,352	1,183	26	13,030	156
smix30P	47	5,227	548	44	3,591	65	43	6,085	510	37	3,002	56
smix40P	46	5,018	532	46	3,375	65	44	5,825	512	36	2,747	53
smixQN	57	2,682	432	58	1,513	43	51	2,875	383	35	713	23
smix20N	52	3,257	471	50	1,987	55	43	3,730	387	19	2,418	21

Notes: Footnotes are identical to those in Table A1. With the exception of the shaded areas, the rotation age declined or remained the same with an increase in the discount factor on physical carbon.
Source: Author's calculations.

Table A9: Rotation Ages, Land Value and CDRs for Various Timber Prices, Carbon Prices and Weightings on Physical Carbon using a Financial Discount Rate of 3%, Log Prices based on Vancouver Log Market Data

	Carbon price = $100/tCO_2$						Price of carbon = $200/tCO_2$					
	Carbon discount rate = 1%			Carbon discount rate = 5%			Carbon discount rate = 1%			Carbon discount rate = 5%		
Stand Type[a]	Age	PV[c] ($/ha)	CDR (tCO_2)	Age	PV[c] ($/ha)	CDR (tCO_2)	Age	PV[c] ($/ha)	CDR (tCO_2)	Age	PV[c] ($/ha)	CDR (tCO_2)
fir30N	47	21,865	858	47	19,223	99	43	22,955	795	42	17,808	91
fir40N	43	43,516	1,572	43	38,650	194	42	46,135	1,544	41	36,592	188
fir30P	34	35,121	1,056	34	32,185	154	34	38,469	1,056	33	32,647	152
fir40P	36	63,725	1,944	34	58,760	285	34	69,709	1,880	32	60,412	275
hem30N	46	11,127	978	45	8,118	113	41	12,465	879	39	6,801	102
hem40N	36	24,410	1,696	34	19,478	222	34	28,835	1,629	32	19,415	212
hem30P	36	16,719	1,161	34	13,458	161	34	20,124	1,118	30	14,187	149
hem40P	31	34,581	2,059	29	30,084	314	30	42,502	2,024	24	35,062	281
ced30N	53	35,386	846	53	32,949	90	51	35,958	816	51	31,090	87
ced40N	42	72,852	1,436	42	68,388	179	42	75,374	1,436	42	66,446	179
ced30P	37	52,104	947	37	49,303	133	37	54,627	947	37	49,027	133
ced40P	36	99,063	1,752	35	94,684	265	35	104,547	1,729	33	96,259	258
mix30N	48	21,030	951	47	18,207	111	45	22,220	902	43	16,738	104
mix40N	46	24,945	1,081	46	21,691	131	45	26,440	1,063	41	20,126	121
mix30P	36	28,851	1,045	36	25,921	152	36	31,873	1,045	34	26,067	147
mix40P	35	36,538	1,275	34	33,194	187	34	40,579	1,255	32	34,062	181
smix30P	48	12,722	556	48	11,052	68	48	13,447	556	47	10,111	68
smix40P	48	12,844	549	48	11,186	67	48	13,551	549	48	10,234	67
smixQN	59	7,490	446	59	6,326	44	58	7,551	440	59	5,224	44
smix20N	56	7,575	499	56	6,308	58	52	7,940	471	52	5,394	56

Notes: Footnotes are identical to those in Table A1. With the exception of the shaded areas, the rotation age declined or remained the same with an increase in the discount factor on physical carbon.
Source: Author's calculations.