Determining optimal forest rotation ages and carbon offset credits: Accounting for post-harvest carbon storehouses

G. Cornelis van Kooten

April 2023

This article was originally published at:

https://doi.org/10.1111/cjag.12333

Citation for this paper:

van Kooten, G. C. (2023). Determining Optimal Forest Rotation Ages and Carbon Offset Credits: Accounting for Post-Harvest Carbon Storehouses. Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie, 71, 255– 272. https://doi.org/10.1111/cjag.12333

Received: 29 July 2022 | Revised: 23 March 2023 | Accepted: 3 April 2023

DOI: 10.1111/cjag.12333

WILEY

REGULAR ARTICLE

Determining optimal forest rotation ages and carbon offset credits: Accounting for post-harvest carbon storehouses

G. Cornelis van Kooten

Department of Economics, University of Victoria, Victoria, British Columbia

Correspondence
G. Cornelis van Kooten, Department of Economics, University of Victoria, PO Box 1700, STN CSC, Victoria, BC V8W 2Y2.
Email: Kooten@uvic.ca

Funding information
Canada's Social Sciences and Humanities Research Council., Grant/Award Number: Grant SSHRC 435-2020-0034

Abstract

Sequestering carbon in forest ecosystems is important for mitigating climate change. A major policy concern is whether forests should be left unharvested to avoid carbon dioxide (CO_2) emissions and store carbon, or harvested to take advantage of potential carbon storage in post-harvest wood product sinks and removal of CO_2 from the atmosphere by new growth. The issue is addressed in this paper by examining carbon rotation ages that consider commercial timber as well as carbon values. 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 as a function of timber growth. 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. Using simple formulae for determining optimal rotation ages, we find that: (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 generally reduces the rotation age, but not in all cases. (3) As a corollary, an increase in the price of carbon increases or reduces rotation age depending on the weight chosen to discount future carbon fluxes. (4) Site characteristics and the mix of species on the site affect conclusions (2) and (3). (5) A large variety of carbon offset credits from forestry activities could be justified, which makes it difficult to accept any.

KEYWORDS
carbon dioxide removals, carbon sequestration, forest rotation age, life-cycle carbon, timing and decay of carbon pools

JEL CLASSIFICATION
Q54, F64, Q57, Q2

Résumé
La séquestration du carbone dans les écosystèmes forestiers est importante pour atténuer les changements climatiques. Une préoccupation politique majeure est de savoir si les forêts devraient être laissées en friche pour éviter les émissions de CO2 et stocker le carbone, ou exploitées pour tirer parti du potentiel de stockage du carbone dans les puits de produits ligneux post-récolte et de l'élimination du CO2 de l'atmosphère par une nouvelle croissance. La question est abordée dans le présent document en examinant les âges de rotation du carbone qui tiennent compte du bois commercial ainsi que des valeurs du carbone. Un modèle d'âge de rotation optimal en temps discret est développé qui utilise les données sur les flux de carbone stockés dans la biomasse vivante et morte par opposition au carbone en fonction de la croissance du bois. Le carbone est attribué à plusieurs bassins de produits écosystémiques et post-récolte qui se décomposent à différents taux au fil du temps. En outre, le calendrier des flux de carbone est pris en compte en pondérant les flux de carbone futurs comme moins importants que les flux actuels. En utilisant des formules simples pour déterminer les âges de rotation optimaux, nous constatons que : (1) Réduire le prix du bois tout en augmentant le prix du carbone augmentera l'âge de rotation, peut-être à l'infini (le peuplement reste non récolté). (2) Une augmentation du taux d'actualisation du carbone physique réduit généralement l'âge de rotation, mais pas dans tous les cas. (3) Comme corollaire, une augmentation du prix du carbone augmente ou réduit l'âge de rotation selon le poids choisi pour réduire les flux de carbone futurs. (4) Les caractéristiques du site et le mélange des espèces présentes sur le site influent sur les conclusions (2) et (3). (5) Une grande variété de crédits compensatoires de carbone provenant des activités forestières pourrait être justifiée, ce qui rend difficile d'en accepter.

1 | INTRODUCTION

As a result of various commitments made under the UN's Framework Convention on Climate Change and a special report on the need to prevent the globe's mean surface temperature from exceeding 1.5°C (IPCC, 2018), many countries now plan to eliminate carbon dioxide (CO_2) emissions by 2050—a policy known as "Net Zero." Since it is impossible to eliminate all emissions from fossil fuels by 2050, it will be necessary at some point to offset any remaining emissions. The forest sector has been identified as a major potential source for offsetting future emissions by removing CO_2 from the atmosphere through activities such as reforestation, afforestation, reduced deforestation, silvicultural investments, and improved forest management (Favero et al., 2020; Griscom et al., 2020; IPCC, 2000; Smith et al., 2014).

CO_2 is sequestered in forests 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 scrutiny for its potential to increase carbon dioxide removals (CDR) from the atmosphere. This study focuses on the determination of optimal forest rotation ages and calculation of CDR in the context of climate change mitigation.

Based on their Intended Nationally Determined Contributions under the Paris Agreement (UNFCC, 2015), many countries intend to rely on forestry activities to meet upwards of 25% of their self-determined, emission-reduction targets (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 considering carbon in the choice of an optimal rotation age (Ekholm, 2015, 2020; Sedjo & Sohngen, 2012; Sohngen & Brown, 2008; Thompson, et al., 2009; van Kooten et al., 1995).

Various papers have examined the impact of different rotation ages on carbon sequestration and storage, exploring the trade-offs between carbon sequestration and other forest management objectives such as wood production. Schlamadinger and Marland (1999), and Härtl et al. (2017), found that increasing rotation age leads to greater carbon sequestration, but that the relationship is not linear, with diminishing returns at longer rotation ages. Similarly, upon comparing the carbon sequestration potential of different forest management strategies, including different rotation ages and harvest intensities, Pukkala (2018) found that an increase in rotation age leads to higher carbon sequestration, but that other factors such as harvest intensity also have a significant impact. Both Assmuth et al. (2021) and Jarisch et al. (2022) provided meta-analyses of previous studies, focusing specifically on the relationship between carbon rotation ages and carbon sequestration in even-aged forests. They found that increasing rotation age leads to higher carbon sequestration, but that the relationship is nonlinear, with diminishing returns at longer rotation ages. While wood production declines as carbon sequestration increases, the trade-off between these two objectives is generally positive.

Other studies concentrated on specific aspects of the carbon rotation age. Ekholm (2015) focused on the potential path of carbon prices, finding that the rotation age would increase with future increases in carbon prices. Ekholm (2020) subsequently examined the impact of natural disturbance on forest rotation ages when carbon was priced; he found that higher prices of carbon reduced the economic risks of disturbance. In contrast, Siebel-McKenna et al. (2020) found that the rotation age could be shortened when CO_2 emissions from timber harvesting and processing of post-harvest timber products were taken into account. Ekholm (2020) also pointed out that, in the determination of an optimal rotation age, the trade-off between carbon prices and timber values (and other land values) was important.

Li et al. (2022) used a multi-age class forest management model to examine the effect of various policy instruments on investments at the extensive (afforestation-deforestation) and intensive (on-site activities) margins, concluding that a carbon subsidy/tax scheme is a first-best policy instrument. Thompson et al. (2009) employed a carbon tax/subsidy scheme to investigate the impact that forest albedo (forest cover absorbs more of the sun's radiation) on forest rotation age.

In forest management models, the usual method is to include a price of carbon—subsidizing carbon uptake and taxing carbon release or, alternatively, providing the landowner with carbon offset credits to sell when carbon uptake occurs and requiring purchase of credits when emissions occur. If carbon fluxes are properly considered, the optimal forest 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, their 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 especially climate policies, along with life-cycle carbon dynamics, affect the optimal rotation age. One contribution is the explicit inclusion of physical discounting of carbon fluxes and decay factors into an analytic formulae for calculating the optimal rotation age.[1] Our results suggest that harvesting is generally optimal and that rotation ages generally increase when carbon fluxes are taken into account, although there are situations where these general results do not hold. Determination of an optimal rotation age and the carbon offset credits that a forest can produce are highly dependent on the characteristics of the particular forest site (e.g., site quality, type of species growing on a site), discount factors, and the prices of timber and carbon. Surprisingly, we also distinguish between privately and socially optimum rotation ages even though the price of carbon remains the same. Lastly, we provide simple equations for determining the optimal rotation age.

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.

---

[1] Discounting of future carbon fluxes was proposed by Schlamadinger and Marland (1999), and used by Johnston and van Kooten (2015) and Jarisch et al. (2022), while decay (or residence time) in product pools was modelled by Härtl et al. (2017). These studies did not, however, provide explicit analytic formulae for determining rotation age.

2 | BACKGROUND AND CHALLENGE

2.1 | 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, at COP7 in 2001 at Marrakech, Morocco, to the creation of carbon offset credits related to afforestation, reforestation and land use change (IPCC, 2000).[2] 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).[3]

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 activities removed from the atmosphere. To address the measurement problem, in this study we employ weights on carbon fluxes as to when they occur to make them somehow equivalent (see Assmuth et al., 2021; Li et al., 2022; Pukkala, 2018; Richards & Stokes, 2004). Indeed, given that carbon removed from the atmosphere today is much more important than that removed at a future date (Armstrong McKay et al., 2022), we discount carbon as to when it happens; however, the weighting scheme or discount rate on physical carbon to employ is a policy choice.

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).

2.2 | 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 management 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 4-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, or an average of 30.6 tCO_2 per ha. 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 harvests.

---

[2] See also the Marrakech Accords at https://unfccc.int/cop7/documents/accords_draft.pdf.

[3] For example, sustainable forest management reduced wasteful logging practices leading to lower CO_2 emissions. 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.

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 the SCC and come 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[4]

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, even negative on many timber stands (as shown below).

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 could potentially nullify much of the 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 CDR in forestry 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 an ecosystem or wood product sink (e.g., lumber used in construction).

3.1 | 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. In discrete rather than continuous time, the present value of commercial timber plus carbon values over a single rotation can be described for any stand age t as follows:

$$PV_{single} = \frac{P_F v_t}{(1+r)^t} + P_C \alpha \sum_{s=1}^{t} \frac{\Delta v_s}{(1+r)^s} - \frac{P_C \alpha (1-\beta) v_t}{(1+r)^t} \tag{1}$$

In Equation (1), P_F and P_c denote the net price of commercial timber (\$/m^3) and the price of carbon (\$/tCO$_2$), respectively; v_t denotes the volume of commercial timber (m^3) on the stand at age t and Δv_t denotes the change in volume between periods t–1 and t; α represents the carbon (measured as tCO$_2$) in a unit volume of timber; β is the proportion of carbon in timber that is transferred to post-harvest sinks—referred to as the "pickling factor"; r is the social discount rate; and s is a transitional variable. The first term in Equation (1) represents the return to commercial harvests at age t or,

---

[4] 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 (Dahlby, 2008; Sandmo, 1975, 1998). A good rule of thumb might be to divide the SCC by 2.0, which implies that a tax should not exceed \$160/tCO$_2$.

perhaps more appropriately, the stumpage value.[5] The second term denotes the discounted monetary payment provided the forestland owner in each period for sequestering carbon in the biomass that grows during that period. The third term consists of two components—the penalty for releasing CO_2 into the atmosphere upon harvest (a cost of harvesting trees) and an adjustment made for carbon stored in post-harvest wood product sinks.

To determine the present value of the financial plus carbon sequestration benefits over all rotation ages, we multiply PV_{single} by $(1+r)^t$ and divide by $(1+r)^t-1$ to get the following expression for the value function:[6]

$$V = \frac{1}{(1+r)^t - 1}\left[(P_F + \alpha\beta P_C - \alpha P_C)\,v_t + (1+r)^t P_C \alpha \sum_{s=1}^{t} \frac{\Delta v_s}{(1+r)^s}\right] \tag{2}$$

If $P_c = 0$, one gets the usual condition for finding the financial or Faustmann rotation age:[7]

$$V = \frac{P_F v_t}{(1+r)^t - 1} \tag{3}$$

To find the optimal rotation age numerically, one simply calculates the RHS values in Equation (2) or (3) for values of t (say, from 1 through 200 or more years). The optimal rotation age is then the year associated with the highest value of V. For a specified growth function (v_t) and discount rate (r), numerically solving Equation (3) results in the Faustmann rotation age, while solving Equation (2) for values of parameters α and β leads to the carbon-adjusted optimal rotation age.

Employing a continuous rather than discrete time version of the above analysis, van Kooten et al. 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 (i) the carbon associated with non-commercial elements of the forest ecosystem (carbon not a direct function of the volume of standing timber), (ii) a mechanism for counting decay of post-harvest wood-product pools that store carbon, and (iii) a method for addressing the fact that future removals of CO_2 from the atmosphere are less important than current removals.

3.2 | 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 extremely short-lived carbon sinks related to the use of wood biomass as an energy source. 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 but, rather, to the various forest-related carbon pools (although the option to correlate carbon with commercial volume remains).

In what follows, 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, forest landowners can be incentivized to take carbon fluxes into account using either a tax/subsidy scheme or a carbon market.[8] Thus, there are four components to the present value function: (i) the commercial value of logs at the time of harvest; (ii) the annual payment the landowner receives for CO_2 removed from the atmosphere by growing trees during that period; (iii) the penalty the landowner pays

---

[5] 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.

[6] The optimal rotation age, t^*, is the value of t that maximizes V. It is found by assuming the RHS of Equation (1) constitutes regular payments that occur in the present (first time period) and continue every t^* periods into perpetuity. If the payments are not discounted to the present period but are compounded to the end of harvest (rotation age t^*), then we do not multiply the RHS of (1) by $(1+r)^t$ but only divide by $(1+r)^t-1$.

[7] Setting $P_F = 0$ in Equation (2) gives the rotation age that optimizes the carbon-only benefits of the stand; that is, even if the forest site has no commercial timber benefits, it might be optimal to harvest the site for its carbon benefits.

[8] 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 an appropriate forest growth model (which also tracks carbon fluxes) so only land use needs to be remotely 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.

at the time of harvest when all the carbon on the site is released; and (iv) 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). The costs of these activities, including the carbon tax if any, are included in the net price of logs, P_F.

In discrete form, we can then re-write the present value function over a single rotation (Equation 1) as:[9]

$$PV_{single} = \frac{P_F v_t}{(1+r)^t} + P_c \sum_{s=1}^{t} \frac{\Delta C_s}{(1+r+r_c)^s} - \frac{P_C C_t}{(1+r+r_c)^t}\left(1 - \sum_{k=1}^{K} \frac{\delta_k}{r_c+\delta_k}\gamma_k\right) \tag{4}$$

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 term is self-explanatory, while the other terms require further discussion. The first term in Equation (4) is the net return to commercial harvests, while the second term refers to the value of carbon (in the form of CO_2) that gets stored in the forest ecosystem as a stand develops. In each growth period s, the second term 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 and falling debris, an amount ΔC_s carbon removed from the atmosphere.

In each period ΔC_s is valued at the price of carbon. If the objective is to maximize the value of the forest stand to the private owner, the value of the carbon at time s is discounted to the present at the financial rate. However, if the perspective of society is taken and future carbon uptake is considered less valuable than current uptake, the future carbon flux must also be weighted less, which explains why ΔC_s is weighted by $(1+r+r_c)^{-s}$ rather than by $(1+r)^{-s}$. As a consequence, even if the private forestland owner is paid to take account of the climate externality, a potential divergence exists between the private and socially optimal rotation age.

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 (transferred) 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.

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 $\frac{\delta_k}{r_c+\delta_k}$,[10] 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. Notice that more carbon is retained as the weight on future carbon fluxes increases (as r_c rises).[11] Further, if 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.

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;[12] and (iv) carbon left on-site and stored in the forest ecosystem. In Equation (4), it is

---

[9] For convenience and without loss of generality, we follow van Kooten et al. (1995) and do not include the cost of regenerating sites, thereby assuming natural regeneration or that such costs are directly proportional to volume harvested. Then the Faustmann age is not sensitive to P_F. If regeneration costs, R, are included, the first term in (4) and in square brackets in (5) becomes $\frac{P_F v_t - R}{(1+r)^t}$ and the Faustmann age could vary with P_F (see Montgomery & Adams, 1995). Regardless of whether R is included, the carbon rotation age remains sensitive to changes in P_F, which, along with the price of carbon, facilitates the current focus on the trade-off between carbon and commercial benefits.

[10] See van Kooten (2018) for a derivation of this formula.

[11] For example, suppose 25 kg of carbon enters a lumber pool and decays at a rate of 2% ($\delta = 0.02$). With $r_c = 1\%$, 8.3kg [= 25kg × (1–0.02/(0.01+0.02))] of carbon is assumed to enter permanently into the lumber product pool, but this rises to 10.7kg if $r_c = 1.5\%$.

[12] 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.

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.

To find the age at which to cut trees for a one-time benefit, we find the value of t that maximizes Equation (4). To account for regeneration and future harvests, we again multiply (4) by $(1+r)^t$ and divide by $(1+r)^t - 1$. The value function over all rotations is thus given by:

$$V = \frac{(1+r)^t}{(1+r)^t - 1}\left[\frac{P_F v_t}{(1+r)^t} + P_c \sum_{s=1}^{t} \frac{\Delta C_s}{(1+r+r_c)^s} - \frac{P_C C_t}{(1+r+r_c)^t}\left(1 - \sum_{k=1}^{K} \frac{\delta_k}{r_c+\delta_k}\gamma_k\right)\right], \tag{5}$$

where t refers to the optimal rotation age. The optimal rotation age can be found numerically by incrementing the RHS of (5) for a period of 250 years, say, and determining the t for which V is maximized. If changes in carbon found in living and dead biomass are not available (say, from the Canadian Forest Service's Carbon Budget Model), it is possible to make carbon fluxes a function of v_t, as in van Kooten et al. (1995).

Finally, to calculate the carbon sequestered over multiple rotations, we first find the optimal rotation age using Equation (5). Then we employ the CDR associated with the optimal rotation age and the following equation to derive the total carbon offsets at the current time:

$$CDR = \frac{(1+r_c)^n\, \mathrm{C}^n}{(1+r_c)^n - 1}, \tag{6}$$

where n refers to the (optimal) rotation age and C^n is the decay-adjusted carbon removed at age n.

4 | FOREST MANAGEMENT AND CARBON: APPLICATION

For any given forest stand, if the required information is available, the easiest means of solving the rotation age problem is to calculate the value of V given in Equation (5) for each year over a sufficiently long time horizon. The year in which V attains a maximum represents the optimal rotation age. If $V < 0$ 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.

4.1 | Data

We employ data from BC Ministry of Forests' (2021) open-access growth and yield model, known as TIPSY. Information on the carbon sinks found in the various components of forest ecosystems is available from the Canadian Forest Service's Carbon Budget Model (Government of Canada, 2021; Kull et al., 2011), which has been integrated into TIPSY. The modeling software includes the growth and yield of commercial timber (Nigh & 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, partly because stumpage value might change with the size of logs (stand age) and with lumber and other wood product prices. Therefore, we conduct sensitivity analysis over different stumpage values, using data from the Vancouver log market (which include harvesting and marketing costs), the provincial government's billing system, and Morton et al. (2021), which we refer to as the ESSA data. The latter used information from TIPSY to calculate average stumpage value, grade-weighted over 1 year, for species found on southern Vancouver

TABLE 1 Log values, by source of data, \$/m^3

Species	Vancouver log Market[a]	BC billing System[b]	ESSA[c] Forest level	At mill
Alder	89.68	0.99	41.68	−37.58
Birch	57.25	40.98	––	––
Cedar	257.15	74.14	212.49	133.23
Cypress	117.83	33.6	98.81	19.55
Fir	219.66	46.91	111.89	32.63
Hemlock	71.62	38.28	68.21	−11.05
Maple	59.44	0.99	29.41	−49.85
Pine	46.90	63.51	62.79	−16.47
Spruce	102.31	102.69	102.23	22.97

[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. These are stumpage fees that companies pay to harvest trees on public lands.

[c] *Source*: Morton et al. (2021, pp18-19, Table 5). The authors subtract a constant "marketing cost" of \$79.26/m^3. Some species have negative values, but this may not translate into negative stand values because multiple species co-exist on a particular stand.

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.[13] 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. [14] 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 (Dymond, 2012; Harmon et al., 1986; Krankina & Harmon, 1995).

4.2 | Optimal harvest decisions

Should mature forests be left unharvested to prevent the release of CO_2 to the atmosphere? As noted earlier, non-carbon environmental benefits of forests in the study region are ignored as they tend to be insignificant at the margin compared to their commercial benefits (van Kooten & Bulte, 1999). For each of the sites identified in Table 2, we solved Equation (5) to find the optimal rotation age and the expected discounted net returns using a discount rate on monetary values of 3%. Then, Equation (6) was used to determine the CO_2 removals that could be counted as carbon offset credits. In Table 4, for each of the 20 sites we provide the Faustmann (financial) rotation age and rotation ages for selected assumptions about the price of carbon—\$50/tCO_2 and \$200/tCO_2—and two carbon weighting schemes—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 (IPCC, 2022; van Kooten et al., 2021).

Since lumber prices have more than doubled over the past 2 years, we assume that the values represented by the Vancouver log market are best representative of actual stumpage values; we also assume that financial data are discounted at a rate of 3%. In Table 5, we present the net present value of the forestry operations for these assumed parameters, while the associated CDR are provided in Table 6. Additional scenarios are available in the Appendix Tables A1 to A3.

Rotation ages are provided in Table 4. The Faustmann rotation ages are determined by ignoring carbon sequestration, with the only concern being the commercial value of the standing timber. In the model, the interplay between monetary

---

[13] 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.

[14] Greater detail about the individual sites is available upon request.

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 (δ_k)
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
Average weighted decay rate, δ	0.02793	

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

discount rates and the weighting of carbon, and the prices of commercial timber and carbon, lead to quite large differences in optimal forest rotation ages. In addition, although not shown here, faster decay of post-harvest wood product and ecosystem sinks leads to a longer rotation age.

As expected, the Faustmann rotation age is reduced when the monetary discount rate is increased. When the authority uses a subsidy/tax scheme to incentivize forestland owners to take into account carbon fluxes, this will increase the rotation age depending on the size of the subsidy (measured in $/tCO$_2$). This is indicated by comparing columns (1), (3), and (6). Indeed, when the price of CO$_2$ is sufficiently high, the net value of the standing timber (i.e., after harvest and sale of manufactures) is less than the tax imposed for releasing the stored carbon into the atmosphere as CO$_2$. As a result, the stand would remain unharvested (see column (6), Table 4, and results in Table 5).

TABLE 4 Rotation ages for various carbon prices (P_c) and weights on physical carbon fluxes (r_c), stumpage values (P_F) based on vancouver log market data, and a financial discount rate (r) of 3% (unless otherwise indicated), number of years.[a]

	Faustmann[c]		**$P_c = \$50/tCO_2$**			**$P_c = \$200/tCO_2$**		
Stand type[b]	**3% (1)**	**5% (2)**	**$r_c = 0\%$ (3)**	**$r_c = 1\%$ (4)**	**$r_c = 5\%$ (5)**	**$r_c = 0\%$ (6)**	**$r_c = 1\%$ (7)**	**$r_c = 5\%$ (8)**
fir30N	49	40	58	55	50	*	66	50
fir40N	44	39	53	50	44	*	63	48
fir30P	37	31	45	44	37	*	55	38
fir40P	37	31	39	37	37	*	51	37
hem30N	49	41	104	61	49	*	108	52
hem40N	40	34	68	50	42	*	91	45
hem30P	42	32	70	49	43	*	96	45
hem40P	32	29	45	42	33	*	81	37
ced30N	56	42	59	57	56	93	61	56
ced40N	42	39	52	51	42	75	59	42
ced30P	37	36	47	47	37	71	54	39
ced40P	36	26	38	37	36	58	48	36
mix30N	50	40	60	54	50	*	73	50
mix40N	47	39	56	53	47	*	70	50
mix30P	38	33	51	46	38	*	59	43
mix40P	40	32	47	43	41	*	60	41
smix30P	52	43	59	54	52	*	72	52
smix40P	52	44	62	55	52	*	73	52
smixQN	61	53	73	66	61	*	87	61
smix20N	58	50	69	64	58	*	73	60

[a] * indicates stand of trees remains unharvested.

[b] Stand types are described in the footnotes to Table 2.

[c] Faustmann or financial rotation age occurs when price of carbon is $0/tCO_2$; for comparison, financial rotation ages are provided for monetary discount rates of 3% and 5%.

Source: Author's calculations.

If there is some urgency to mitigate climate change, society is interested in the timing of CO_2 removals from the atmosphere. This translates into a desire for early removals and delayed emissions, which can be addressed by weighting carbon fluxes as to when they occur. This is done using a discount parameter denoted r_c. If $r_c = 1\%$, one tCO_2 removed from the atmosphere 25 years from now is considered to be worth only 0.78 of a tCO_2 sequestered today; if $r_c = 5\%$, then the future removal would be worth only 0.30 tCO_2 today. Determination of the appropriate weighting scheme is a policy decision based upon society's perceived damages from future climate change.

Note that policies about the urgency of addressing climate change lead to a divergence between the private and social objective. In Table 4, columns (4) and (5), and (7) and (8), provide the socially desirable rotation ages for different carbon prices and different desires for immediate or delayed mitigation. The socially desirable forest rotations are at least the same or longer than the private ones. While the social rotation age rises with higher carbon prices (greater damages from climate change), forests are generally to be harvested somewhat faster as the perceived increases in damages rises (as determined by the increase in the weight on carbon fluxes).

Now consider Table 5 which presents the discounted net values of various timber stands. Not surprisingly, the net discounted value received by the forestland owner increases with a rise in timber prices. But when landowners are paid to sequester carbon, the rotation age that results in the highest net returns may not be the Faustmann rotation age. Net discounted returns increase when carbon is priced, but only when carbon is discounted at a low rate; with higher weights on carbon, the net return from timber stands then declines as prices received for CO_2 offsets are increased further, regardless of stand type. This is the result of the penalty that the forestland owner must pay when carbon is released at the time of harvest. The harvest penalty is only partially offset by the payment received for carbon entering post-harvest ecosystem and wood product sinks, because these storehouses decay over time with landowners losing the associated carbon benefits.

TABLE 5 Discounted net values of timber stands for selected carbon prices (P_c) and weights on physical carbon (r_c), based on vancouver log market data, and monetary discount rate (r) of 3%, compared to a base case scenario where $P_C = 0$, $r_c = 0\%$ and $r = 3\%$, \$C per ha.[a]

	$P_c = \$50/tCO_2$			$P_c = \$200/tCO_2$		
Stand type	$r_c = 0\%$	$r_c = 1\%$	$r_c = 5\%$	$r_c = 0\%$	$r_c = 1\%$	$r_c = 5\%$
fir30N	4,657	5,493	2,233	34,860	24,666	8,962
fir40N	8,221	10,392	4,763	61,310	47,172	19,229
fir30P	5,590	7,947	4,773	42,768	36,711	19,128
fir40P	8,881	13,911	9,155	69,945	62,076	36,620
hem30N	7,004	6,676	2,683	56,510	33,712	10,776
hem40N	11,717	13,191	6,579	101,778	65,760	26,642
hem30P	8,440	9,508	5,070	70,011	45,732	20,334
hem40P	12,036	16,764	10,937	117,167	81,497	44,024
ced30N	4,344	5,065	1,863	22,982	21,275	7,451
ced40N	6,774	8,903	4,454	40,027	41,953	17,814
ced30P	4,735	6,640	3,779	27,592	30,745	15,242
ced40P	7,920	12,563	8,482	42,921	54,563	33,929
mix30N	5,219	6,109	2,622	41,462	28,062	10,488
mix40N	5,933	7,127	3,142	47,037	32,593	12,659
mix30P	6,085	8,010	4,597	47,388	36,578	18,469
mix40P	7,327	10,141	6,006	56,362	44,788	24,050
smix30P	3,299	3,840	1,677	23,746	16,861	6,710
smix40P	3,207	3,743	1,635	23,594	16,842	6,539
SmixQN	2,595	2,618	850	19,408	11,718	3,399
smix20N	3,343	3,446	1,379	22,779	14,819	5,515

[a] See Table 4 for footnotes.

Source: Author's calculations.

Net revenues tend to decline when future carbon fluxes are discounted at a higher rate, but not in all cases. This is due to the fact that, as the weight of future carbon fluxes is reduced, future losses of carbon-related income are considered less valuable at the time of harvest—the landowner is penalized less for future carbon losses. As a corollary, the number of CDRs that can be attributed to any forest stand falls with increases in the rate used to discount carbon (Table 6).

If carbon is not discounted, an infinite amount of carbon is removed from the atmosphere by a forest that is regularly harvested as carbon is subsequently stored in various post-harvest biomass pools. The maximum CDRs available from any site occur with the Faustmann rotation age, except when commercial timber prices are so low that harvest is not warranted (as with hemlock stands).

Consider Table 6. With the exception of cedar (marked with *), trees are not worth harvesting. In that case, the CO_2 removed equals the carbon stored on the site when the stand achieves ultimate growth—where decay offsets new growth. When trees are harvested on a regular basis (indicated by *), an infinite amount of CO_2 is removed from the atmosphere as carbon is not weighted ($r_c = 0\%$).

Notice that rotation ages, net present values and the number of CDRs (carbon offsets) 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 trees thereby enabling society to make a sizable dent in its CO_2 mitigation targets (e.g., Grassi et al., 2017). Site quality and choice of species matter a great deal, although this issue is often neglected.

The timing of carbon removals from the atmosphere is also important. 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. Forestland owners 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 (see Groen et al., 2006). 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) (Table 6) generally declines as future carbon fluxes are considered worth less than current fluxes.

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% (unless otherwise indicated), vancouver log market timber prices, tCO_2 per hectare

	$P_c = \$0/tCO_2$			$P_c = \$50/tCO_2$		$P_c = \$200/tCO_2$		
Stand type[a]	$r = 5\%$, $r_c = 1\%$ (1)	$r_c = 1\%$ (2)	$r_c = 5\%$ (3)	$r_c = 1\%$ (4)	$r_c = 5\%$ (5)	$r_c = 0\%$[b] (6)	$r_c = 1\%$ (7)	$r_c = 5\%$ (8)
fir30N	747	886	101	962	102	2,152	1,043	102
fir40N	1,446	1,598	196	1,739	196	2,460	1,927	206
fir30P	996	1,109	161	1,205	161	2,235	1,297	163
fir40P	1,763	1,971	296	1,971	296	2,517	2,199	296
hem30N	879	1,028	119	1,160	119	2,807	1,341	122
hem40N	1,629	1,827	244	2,072	250	3,072	2,290	258
hem30P	1,074	1,265	179	1,349	180	2,831	1,500	183
hem40P	1,986	2,090	328	2,332	332	3,059	2,497	346
ced30N	668	891	93	904	93	*	945	93
ced40N	1,352	1,436	179	1,637	179	*	1,771	179
ced30P	929	947	133	1,091	133	*	1,161	136
ced40P	1,433	1,752	268	1,773	268	*	1,964	268
mix30N	814	980	114	1,029	114	2,046	1,169	114
mix40N	935	1,097	132	1,187	132	2,080	1,330	136
mix30P	987	1,076	155	1,177	155	1,955	1,268	163
mix40P	1,208	1,369	201	1,414	203	2,116	1,549	203
smix30P	510	585	71	597	71	1,211	661	71
smix40P	512	579	70	596	70	1,277	662	70
smixQN	400	459	44	486	44	1,236	557	44
smix20N	455	511	59	541	59	904	572	60

[a] Stand types are described in the footnotes to Table 2.

[b] Only those sites indicated by * are harvested, other sites remain unharvested.

Source: Author's calculations.

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. Yet, there may be cases where CDRs actually increase, depending on the stand type and species that are grown, the relative prices of timber and carbon, and the rate used to discount physical carbon.

5 | CONCLUDING DICUSSION

Forestry activities clearly have an impact on global emissions of CO_2, and on the amount of carbon stored in ecosystems and harvested wood products. However, it is difficult to determine the optimal forest management strategy that maximizes carbon sequestration. 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 (not modeled here); 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 whether the decay of post-harvest carbon storehouses is taken into account, and, to a lesser extent, on the rate used to discount physical carbon. While rates of decay are scientifically determinable, the weighting of carbon fluxes as to when they occur is a policy decision (Richards & Stokes, 2004). Depending on these choices, a large variety of carbon offset values from forestry activities could be justified, which makes it difficult to accept any (see also Gifford, 2020).

Based on the research presented in this study, we can further summarize 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 generally reduces the rotation age.
3. As a corollary, an increase in the price of carbon increases or reduces rotation age depending on the weight chosen to discount future carbon fluxes.
4. Site characteristics and the mix of species on the site affect conclusions (2) and (3).

Overall, almost any number of carbon offset credits could be justified through forestry activities, depending on the authority's choice of a weighting scheme for future carbon fluxes, a carbon tax/ subsidy (or rules regarding a carbon market), and policies pertaining to forest operations (e.g., authority setting non-optimal harvest rates on public land). This then makes it difficult to accept carbon credits as an offset against fossil fuel emissions of CO_2.

While this study has not examined the impact on rotation age of uncertainty related to natural disturbance (see Ekholm, 2020; Siebel-McKenna et al., 2020), it has also ignored the potential effect of harvests on reducing natural disturbance. Likewise, the impact of climate change itself, including the effect of increased atmospheric CO_2 on tree growth, has not been accounted for in the determination of optimal rotation ages. These are clearly areas requiring further inquiry.

ACKNOWLEDGMENTS

Funding for this research was provided by Canada's Social Sciences and Humanities Research Council, grant SSHRC 435-2020-0034. The author is the sole researcher and declares that there exist no competing interests.

ORCID

G. Cornelis van Kooten https://orcid.org/0000-0003-1780-7065

REFERENCES

Angelsen, A. (2014). The economics of REDD+. Chapter 19 in (Kant, A. & Alavalapati, J.R.R. Eds.). *Handbook of forest resource economics*. Routledge, pp. 290–306.

Armstrong McKay, D. I., Staal, A., Abrams, J. F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S. E., Rockström, J., & Lenton, T. M. (2022). Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science*, *377*, eabn7950. https://doi.org/10.1126/science.abn7950

Assmuth, A., Rämö, J., & Tahvonen, O. (2021). Optimal carbon storage in mixed-species size-structured forests. *Environmental and Resource Economics*, *79*, 249–275. https://doi.org/10.1007/s10640-021-00559-9

BC Ministry of Forests. (2021). Growth and yield modelling software. *TIPSY*. https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/forest-inventory/field-forms-and-software/software-download

BC MFLNRO (Ministry of Forests, Lands, and Natural Resource Operations). (2021). Harvest billing system. Mark monthly billing history report. Report generated December 23, 2021.

Butler, R. A. (2012). REDD (Reducing Emissions from Deforestation and forest Degradation in developing countries). Mongabay blog. https://rainforests.mongabay.com/redd/

Dahlby, B. (2008). *The marginal cost of public funds: Theory and applications*. MIT Press.

Dymond, C. C. (2012). Forest carbon in North America: Annual storage and emissions from British Columbia's harvest, 1965–2065. *Carbon Balance and Management*, *7*, (Article 8).

Ekholm, T. (2020). Optimal forest rotation under carbon pricing and forest damage risk. *Forest Policy and Economics*, *115*, 102131.

Ekholm, T. (2015). Optimal forest rotation age under efficient climate change mitigation. *Forest Policy and Economics*, *62*, 62–68. https://doi.org/10.1016/j.forpol.2015.10.007

Faustmann, M. (1995). (1849). On the determination of the value which forest land and immature stands possess for forestry. *Journal of Forest Economics*, *1*(1), 7–44.

Favero, A., Daigneault, A., & Sohngen, B. (2020). Forests: Carbon sequestration, biomass energy, or both? *Science Advances*, *6*(13), eaay6792. https://doi.org/10.1126/sciadv.aay6792

Gifford, L. (2020). 'You can't value what you can't measure': A critical look at forest carbon accounting. *Climatic Change*, *161*, 291–306.

Government of Canada. (2021). Carbon budget model. https://www.nrcan.gc.ca/climate-change/impacts-adaptations/climate-change-impacts-forests/carbon-accounting/carbon-budget-model/13107

Grassi, G., House, J., Dentener, F., Federici, S., den Elzen, M., & Penman, J. (2017). The key role of forests in meeting climate targets requires science for credible mitigation. *Nature Climate Change*, *7*, 220–226.

Griscom, B. W., Busch, J., Cook-Patton, S. C., Ellis, P. W., Funk, J., Leavitt, S. M., Lomax, G., Turner, W. R., Chapman, M., Engelmann, J., Gurwick, N. P., Landis, E., Lawrence, D., Malhi, Y., Schindler Murray, L., Navarrete, D., Roe, S., Scull, S., Smith, P., … Worthington, T.

(2020). National mitigation potential from natural climate solutions in the tropics. *Philosophical Transactions of the Royal Society B*, *375*, 20190126. https://doi.org/10.1098/rstb.2019.0126

Groen, T., Nabuurs, G. - J., & Schelhaas, M. (2006). Carbon accounting and cost estimation in forestry projects using CO2Fix V.3. *Climatic Change*, *74*, 269–288.

Harmon, M. E., Ferrell, W. K., & Franklin, J. F. (1990). Effects on carbon storage of conversion of old-growth forests to young forests. *Science*, *247*, 699–702.

Harmon, M. E., Franklin, J. F., Swanson, F. J., Sollins, P., Gregory, S. V., Lattin, J. D., Anderson, N. H., Cline, S. P., Aumen, N. G., Sedell, J. R., Lienkaemper, G. W., Cromack, K., & Cummins, K. W. (1986). Ecology of coarse woody debris in temperate ecosystems, in: (MacFadyen, A., Ford, E.D. Eds.) *Advances in ecological research*. Academic Press, Inc., pp. 133–302.

Härtl, F. H., Höllerl, S., & Knoke, T. (2017). A new way of carbon accounting emphasizes the crucial role of sustainable timber use for successful carbon mitigation strategies. *Mitigation and Adaptation Strategies for Global Change*, *22*, 1163–1192. https://doi.org/10.1007/s11027-016-9720-1

Hartman, R. (1976). The harvesting decision when a standing forest has value. *Economic Inquiry*, *16*, 52–58.

Helm, D. (2010). Government failure, rent-seeking, and capture: The design of climate change policy. *Oxford Review of Economic Policy*, *26*(2), 182–196.

Howard, C., Dymond, C. C., Griess, V. C., Tolkien-Spurr, D., & van Kooten, G. C. (2021). Wood product carbon substitution benefits: A critical review of assumptions. *Carbon Balance Management*, *16*, 9. https://doi.org/10.1186/s13021-021-00171-w

IPCC. (2022). Summary for policymakers, in: Climate change 2022: Impacts, adaptation, and vulnerability. *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_SummaryForPolicymakers.pdf

IPCC. (2018). Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Geneva: U.N. Intergovernmental Panel on Climate Change.

IPCC. (2000). *Land use, land-use change, and forestry*. Cambridge University Press.

Jarisch, I., Bödeker, K., Bingham, L. R., Friedrich, S., Kindu, M., & Knoke, T. (2022). The influence of discounting ecosystem services in robust multi-objective optimization – An application to a forestry-avocado land-use portfolio. *Forest Policy and Economics*, *141*, 102761. https://doi.org/10.1016/j.forpol.2022.102761

Johnston, C. M. T., & van Kooten, G. C. (2015). Back to the past: Burning wood to save the globe. *Ecological Economics*, *120*, 185–193. https://doi.org/10.1016/j.ecolecon.2015.10.008

Kaimowitz, D. (2008). The prospects for reduced emissions from deforestation and degradation (REDD) in Mesoamerica. *International Forestry Review*, *10*(3), 485–495.

Krankina, O. N., & Harmon, M. E. (1995). Dynamics of the dead wood carbon pool in northwestern Russian boreal forests. *Water, Air, & Soil Pollution*, *82*, 227–238.

Kull, S. J., Rampley, G. J., Morken, S., Metsaranta, J., Neilson, E. T., & Kurz, W. A. (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., Shaw, C. H., Boisvenue, C., Stinson, G., Metsaranta, J., Leckie, D., Dyk, A., Smyth, C., & Neilson, E. T. (2013). Carbon in Canada's boreal forest—A synthesis. *Environmental Reviews*, *21*, 260–292.

Lemprière, T. C., Kurz, W. A., Hogg, E. H., Schmoll, C., Rampley, G. J., Yemshanov, D., McKenney, D. W., Gilsenan, R., Beatch, A., Blain, D., Bhatti, J. S., & Krcmar, E. (2013). Canadian boreal forests and climate change mitigation. *Environmental Reviews*, *21*, 293–321.

Li, R., Sohngen, B., & Tian, X. (2022). Efficiency of forest carbon policies at intensive and extensive margins. *American Journal of Agricultural Economics*, *104*(4), 1243–1267.

Malmsheimer, R. W., Bowyer, J. L., Fried, J. S., Gee, E., Izlar, R. L., Miner, R. A., Munn, I. A., Oneil, E., & Stewart, W. C. (2011). Managing forests because carbon matters: Integrating energy, products, and land management policy. *Journal of Forestry*, *109*(7S), 7–50.

Montgomery, C. A., & Adams, D. M. (1995). Optimal timber management policies. Chapter 17 in *The handbook of environmental economics* (pp.379–404) edited by Bromley, D. Blackwell.

Morton, C., Trenholm, R., Beukema, S., Knowler, D., & Boyd, R. (2021). Economic valuation of old growth forests on Vancouver Island: Pilot Study; Phase 2 – Port Renfrew Pilot. ESSA Technologies Ltd. for the Ancient Forest Alliance. Vancouver, BC. https://www.ancientforestalliance.org/wp-content/uploads/2021/06/Economic-Value-of-Old-Growth-Report.pdf

Nigh, G. D., & Mitchell, M. G. E. (2003). Development of height-age models for estimating juvenile height of coastal Douglas-fir in British Columbia. *Western Journal of Applied Forestry*, *18*(3), 207–212.

Pukkala, T. (2018). Carbon forestry is surprising. *Forest Ecosystems*, *5*, 11. https://doi.org/10.1186/s40663-018-0131-5

Richards, K. R., & Stokes, C. (2004). A review of forest carbon sequestration cost studies: A dozen years of research. *Climatic Change*, *63*, 1–48.

Sandmo, A. (1998). Redistribution and the marginal cost of public funds. *Journal of Public Economics*, *70*, 365–382.

Sandmo, A. (1975). Optimal taxation in the presence of externalities. *Scandinavian Journal of Economics*, *77*(1), 86–98.

Schlamadinger, B., & Marland, G. (1999). Net effect of forest harvest on CO_2 emissions to the atmosphere: A sensitivity analysis on the influence of time. *Tellus B: Chemical and Physical Meteorology*, *51*(2), 314–325. https://doi.org/10.3402/tellusb.v51i2.16289

Sedjo, R., & Sohngen, B. (2012). Carbon sequestration in forests and soils. *Annual Review of Resource Economics*, *4*(1), 127–144.

Siebel-McKenna, A., Johnston, C. M. T., & van Kooten, G. C. (2020). Knock on wood: The effects of suboptimal decision-making on forest carbon sequestration in the presence of uncertainty in wildfire risk. *Spatial Economic Analysis*, *15*(3), 299–310.

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E. A., Tubiello, F. (2014). Agriculture, forestry and other land use (AFOLU), Chapter 11, in: (Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., … Minx J.C. Eds.), *Climate* *change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Smyth, C. E., Stinson, G., Neilson, E., Lemprière, T. C., Hafer, M., Rampley, G. J., & Kurz, W. A. (2014). Quantifying the biophysical climate change mitigation potential of Canada's forest sector. *Biogeosciences*, *11*, 3515–3529.

Sohngen, B., & Brown, S. (2008). Extending timber rotations: Carbon and cost implications. *Climate Policy*, *8*(5), 435–451.

Thompson, M. P., Adams, & Sessions, J. (2009). Radiative forcing and the optimal rotation age. *Ecological Economics*, *68*(10), 2713–2720.

UNFC. (2015). Intended nationally determined contributions. 1447pp. https://unfccc.int/files/adaptation/application/pdf/all__parties_indc.pdf

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. (2017). Forest carbon offsets and carbon emissions trading: Problems of contracting. *Forest Policy and Economics*, *75*, 83–88.

van Kooten, G. C., & Bulte, E. H. (1999). How much primary coastal temperate rainforest should society retain? Carbon uptake, recreation and other values. *Canadian Journal of Forest Research*, *29*(12), 1879–1890.

van Kooten, G. C., Withey, P., & Johnston, C. M. T. (2021). Climate urgency and the timing of carbon fluxes. *Biomass and Bioenergy*, *151*, 106162.

van Kooten, G. C., Binkley, C. S., & Delcourt, G. (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.

How to cite this article: van Kooten, G. C. (2023). Determining Optimal Forest Rotation Ages and Carbon Offset Credits: Accounting for Post-Harvest Carbon Storehouses. *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie*, *71,* 255–272. https://doi.org/10.1111/cjag.12333

APPENDIX

TABLE A1 Faustmann and carbon rotation ages for various stumpage values (P_F) and selected carbon price (P_c) of \$200/tCO$_2$, weights on physical carbon fluxes (r_c) of 0% and 1%, and financial discount rate (r) of 3%, number of years

	$P_c = \$0/\mathrm{tCO}_2, r_c = 0\%$[a]			$P_c = \$200/\mathrm{tCO}_2, r_c = 1\%$		
Stand type	**BC billing**	**ESSA**	**VLM**	**BC billing**	**ESSA**	**VLM**
fir30N	49	49	49	136	158	66
fir40N	44	44	44	*	*	63
fir30P	37	37	37	116	135	55
fir40P	37	37	37	*	*	51
hem30N	49	*	49	144	*	108
hem40N	40	*	40	129	*	91
hem30P	42	*	42	130	*	96
hem40P	32	*	32	114	*	81
ced30N	56	56	56	97	78	61
ced40N	42	42	42	85	68	59
ced30P	37	37	37	84	70	54
ced40P	36	36	36	75	57	48
mix30N	50	50	50	125	152	73
mix40N	47	47	47	123	*	70
mix30P	38	38	38	111	134	59
mix40P	40	40	40	107	132	60
smix30P	52	52	52	107	126	72
smix40P	52	52	52	110	98	73
smixQN	61	61	61	133	171	87
smix20N	58	58	58	127	*	73

[a] These are Faustmann rotation ages that occur when $P_c = \$0/\mathrm{tCO}_2$; * indicates an infinite rotation age implying no harvest.

Source: Author's calculations.

TABLE A2 Net discounted values for various carbon prices (P_c), weights on physical carbon fluxes (r_c), and a financial discount rate (r) of 3% (unless otherwise indicated), $/ha

Stand type	$P_c = \$0/tCO_2$				$P_c = \$50/tCO_2$			$P_c = \$200/tCO_2$		
	$r = 5\%$, $r_c = 0\%$	$r_c = 0\%$	$r_c = 1\%$	$r_c = 5\%$	$r_c = 0\%$	$r_c = 1\%$	$r_c = 5\%$	$r_c = 0\%$	$r_c = 1\%$	$r_c = 5\%$
fir30N	7,528	20,912	20,912	20,912	25,569	26,405	23,145	55,772	45,578	29,875
fir40N	15,094	40,948	40,948	40,948	49,169	51,340	45,711	102,258	88,120	60,177
fir30P	13,225	31,937	31,937	31,937	37,528	39,885	36,710	74,705	68,649	51,065
fir40P	24,003	57,973	57,973	57,973	66,854	71,884	67,128	127,918	120,049	94,594
hem30N	3,473	9,986	9,986	9,986	16,990	16,662	12,668	66,496	43,698	20,761
hem40N	8,049	20,327	20,327	20,327	32,044	33,517	26,906	122,105	86,087	46,969
hem30P	5,425	13,627	13,627	13,627	22,067	23,135	18,697	83,638	59,359	33,961
hem40P	11,552	26,784	26,784	26,784	38,821	43,549	37,721	143,952	108,281	70,808
ced30N	11,828	34,978	34,978	34,978	39,322	40,043	36,841	57,960	56,253	42,429
ced40N	26,054	70,330	70,330	70,330	77,105	79,234	74,784	110,358	112,284	88,145
ced30P	19,759	49,580	49,580	49,580	54,315	56,221	53,359	77,173	80,325	64,822
ced40P	40,086	93,710	93,710	93,710	101,629	106,273	102,192	136,630	148,272	127,639
mix30N	7,056	19,998	19,998	19,998	25,217	26,107	22,620	61,460	48,060	30,486
mix40N	8,440	23,494	23,494	23,494	29,427	30,621	26,636	70,531	56,087	36,153
mix30P	10,456	25,975	25,975	25,975	32,060	33,985	30,572	73,363	62,553	44,444
mix40P	13,517	32,729	32,729	32,729	40,056	42,869	38,735	89,091	77,517	56,779
smix30P	4,175	12,021	12,021	12,021	15,320	15,862	13,699	35,768	28,883	18,731
smix40P	4,188	12,231	12,231	12,231	15,438	15,974	13,866	35,825	29,073	18,770
smixQN	2,181	7,452	7,452	7,452	10,047	10,070	8,302	26,860	19,170	10,851
smix20N	2,260	7,319	7,319	7,319	10,662	10,765	8,698	30,098	22,138	12,834

Source: Author's calculations.

TABLE A3 Carbon dioxide removals (= carbon offset credits) for various stumpage values (P_F) and carbon prices (P_c), weights on physical carbon fluxes (r_c), and financial discount rate (r) of 3%, tCO$_2$/ha[a].

	$P_c = \$0/\text{tCO}_2, r_c = 1\%$			$P_c = \$200/\text{tCO}_2, r_c = 1\%$		
Stand type	**BC Billing**	**ESSA**	**VLM**	**BC Billing**	**ESSA**	**VLM**
fir30N	886	886	886	1,085	1,061	1,043
fir40N	1,598	1,598	1,598	776	776	1,927
fir30P	1,109	1,109	1,109	1,271	1,238	1,297
fir40P	1,971	1,971	1,971	826	826	2,199
hem30N	1,028	236	1,028	1,322	236	1,341
hem40N	1,827	763	1,827	2,201	763	2,290
hem30P	1,265	235	1,265	1,465	235	1,500
hem40P	2,090	783	2,090	2,388	783	2,497
ced30N	891	891	891	1,129	1,064	945
ced40N	1,436	1,436	1,436	1,944	1,860	1,771
ced30P	947	947	947	1,281	1,249	1,161
ced40P	1,752	1,752	1,752	2,137	2,055	1,964
mix30N	980	980	980	1,215	1,187	1,169
mix40N	1,097	1,097	1,097	1,378	468	1,330
mix30P	1,076	1,076	1,076	1,288	1,256	1,268
mix40P	1,369	1,369	1,369	1,552	1,504	1,549
smix30P	585	585	585	688	681	661
smix40P	579	579	579	694	693	662
smixQN	459	459	459	597	592	557
smix20N	511	511	511	624	246	572

[a] For $r_c = 0\%$ and finite rotation age, carbon uptake is infinite. In the case of the highlighted rows (stands of hemlock), stands remain unharvested for the parameterizations so the carbon uptake is given by the weighted value of carbon uptake from the time of stand establishment to the time when biomass growth equals decay. See Table A1.

Source: Author's calculations.