Economics of Old-growth Forest Conversion: The Carbon Storage Conundrum

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Abstract

Protection of old-growth forests is considered a promising way to mitigate climate change, but its cost-effectiveness needs to be carefully evaluated. This study investigates the costs and benefits of harvesting old-growth coastal forest in British Columbia and converting it into a sustainably managed forest. The analysis considers commercial and age-dependent environmental benefits plus the value of carbon fluxes—the Hartman-carbon rotation values. Economic efficiency is examined under various commercial timber and carbon sequestration prices, various social rates of time preference, differing weights on carbon values, and non-carbon environmental values. The analysis includes values related to commercial timber, carbon sequestration and CO_2 emissions, as well as the environment and ecological services of old growth and regrowth. Results indicate that even considering life-time dynamics, conversion of old growth will increase atmospheric CO_2 >93% of the time based on a Monte Carlo simulation, thereby supporting earlier arguments made by biologists. However, the cost to society of retaining old growth is significant because of foregone commercial timber benefits. Indeed, the tradeoff between the economic and carbon sequestration objectives increases with policymakers' increased desire to mitigate climate change. The sensitivity and Monte Carlo results also highlight the critical roles played by discount rates and the ratio of commercial versus carbon prices chosen in determining the overall societal value of harvesting and regenerating old-growth forests.

Keywords: Economic efficiency versus carbon sequestration; Protecting old-growth forests in British Columbia; Environmental and ecological service values of forests

Highlights:

- Conversion of an old growth (mature) forests in the Pacific Northwest will increases atmospheric CO2 as biologists have argued
- Preservation and environmental amenity values lost when converting old growth are large but partially offset by new growth
- Life cycle analysis suggests commercial timber values swamp all other forest values

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1. INTRODUCTION

Governments have come under increasing pressure to implement climate mitigation strategies that would enable them eventually to achieve carbon neutrality. Based on their Nationally Determined Contributions (NDCs) under the Paris Agreement, some 90% of new or updated NDCs submitted by December 2020 include the Land Use, Land-Use Change and Forestry (LULUCF) sector, marking an increase from 76% in the initial submissions (UN FCCC 2021).[1] About 57% of these updated NDCs explicitly reference forests as a domestic opportunity for reducing emissions, although only 11 of the NDCs analyzed between 2017 and 2023 contain quantified targets related to afforestation and reforestation (UNEP 2024).

In forest jurisdictions with much mature forest, the forest management strategy envisioned by government is often to increase carbon sequestration by sustainably harvesting old growth while seeking to retain many of the environmental amenities provided by the mature forests. As a strategy to address the commercial versus carbon-storage and other nonmarket amenities of mature forests, policymakers have recommended that available old growth be harvested over a period of 125 years, or, alternatively given that much of the original old growth would still be retained, a period of 70 years. This research examines whether and under which conditions a mature forest should be left standing or harvested, and the financial and carbon sequestration implications of the decision.

The objective of this paper is to address the following question: Can conversion of old-growth forests to commercial status contribute to the reduction of atmospheric CO_2? Or, more specifically, what are the optimal harvest strategies for integrating commercial and carbon considerations in managing old-growth timber? As an application, we investigate old growth stands in coastal British Columbia where the likelihood of wildfire is much less than elsewhere in the province. To do so, we develop a simulation model and use it to examine how an old-growth forest might be harvested and reforested in an optimal manner while attaining certain economic and carbon management objectives. The purpose of the research is to provide guidance to

[1] The registry of NDCs can be found at https://unfccc.int/NDCREG.

policymakers in choosing effective strategies for attaining carbon neutrality.

2. LITERATURE REVIEW

Early studies examining the feasibility of forest strategies neglected to consider the terrestrial carbon sequestration impacts, focusing only on direct economic costs and benefits. For instance, in comparing an afforestation program against an old-car buyback program (which reduced overall vehicle fleet emissions while maintaining fleet size), van Kooten et al. (1992) only examined the cost of planting trees and the associated carbon removed from the atmosphere versus the cost and reduction in CO_2 emissions from the buyback program. The authors concluded that the buyback program did more to reduce atmospheric CO_2 than afforestation.

More recent research recognized that forestry involves changes in land use, so that in addition to the financial cost of afforestation, the opportunity cost of land conversion had to be considered. Not only did one need to account for the commercial benefits of forestry activities, but environmental or ecological benefits and costs also had to be considered, including recreational benefits (see Hartman 1976; Calish et al. 1976; Amacher et al. 2009). Such benefits were taken to be a function primarily of the age of the forest or the volume of timber. Beginning in the early 1990s economists began to include carbon sequestration benefits in forest management models (Binkley and van Kooten 1994; van Kooten et al. 1995). Models generally subsumed the environmental benefits under the umbrella of carbon sequestration; rarely did the models attempt to integrate the two types of externality benefits (or costs).

Studies have also examined the cost effectiveness of afforestation on carbon sequestration in different countries and globally. Nordhaus (1991) found that the global cost of afforestation was between \$12 and \$31 per metric ton of carbon dioxide (tCO_2).[2] In contrast, Grafton et al. (2021) found that this cost ranged from a few cents to \$51/tCO_2. Most national studies focused on afforestation in the United States and Canada. For instance, Stavins (1999) found that afforestation on farmland in the U.S. would sequester carbon at a marginal cost of no more than \$37/tCO_2, while Obembe et al. (2022) found the cost to be \$10/tCO_2 for the U.S. Southeast. Van Kooten et al.

[2] Values are expressed in nominal U.S. dollars unless indicated otherwise.

(2000) investigated carbon sequestration by afforestation in Western Canada finding costs of carbon uptake to be less than \$14/tCO_2, while Hope et al. (2021) found them to be less than \$10/tCO_2 in the province of Ontario.

A limited number of studies have examined the conversion of old-growth forests into sustainably managed commercial forests. An influential study by Harmon et al. (1990) concluded that harvests of old-growth (mature) forests should be avoided because it would be preferable from a climate standpoint to prevent the release of this vast carbon sink to the atmosphere as CO_2 (see also Morton et al. 2021). The alternative perspective argues that an old-growth forest would sequester very little carbon as vegetation growth is limited and largely offset by decay. Further, mature forests are susceptible to wildfire (especially in drier regions), pests and disease that could release large amounts of carbon, as illustrated by the devastation caused by the mountain pine beetle in Colorado and the interior of British Columbia.

Biologists generally concur that harvests from old growth should be avoided. Forest carbon researchers concluded that carbon accumulation in old-growth forests eventually declined to zero, largely based on the idea that as trees get older their growth tapers off so that additional carbon sequestration eventually fell to zero—standing old growth was considered carbon neutral, but a large store of carbon (Odum 1969; Keeton 2018). The carbon-neutral narrative was challenged by Luyssaert et al. (2008), who conducted a meta-analysis of carbon-flux estimates from 519 study sites worldwide (70 percent in temperate forests and 30 percent in boreal forests). The authors discovered that even when forests reach maturity (defined as 200+ years old), they continue to be net carbon accumulators. Luyssaert et al. (2008) estimated that old-growth forests cover 15% of the global forest area while accounting for at least 10% of global carbon accumulation. Similar conclusions were drawn by Kohl et al. (2017), who found that tropical forests maintain high carbon sequestration rates even as they approach maturity. Regardless of whether mature forests continue to be net sequesters of carbon, carbon storage by old-growth forests makes their conversion into commercial forests an untenable climate change strategy from a strictly carbon perspective.

Beyond carbon storage benefits, old growth forests provide commercial timber benefits, and preserve biodiversity, and ecosystem and ecological service benefits that other forests cannot replicate (BC Ministry of Forests 2024). Additionally, old growth forests contribute environmental, cultural, spiritual, and religious value to various communities (BC Ministry of Forests 2024). Therefore, it is essential to have information about non-carbon costs and benefits that can better inform decision-makers. The information is also critical to enable policymakers to gain support from communities concerned about potential lost income and overlooked costs associated with any given strategy.

Recent economic studies have argued that the CO_2 released by harvesting mature forests can be offset by a combination of carbon storage in post-harvest wood products (PHWP) and carbon dioxide removals (CDR) from the atmosphere by fast-growing, newly planted trees (Lemprière et al. 2013; van Kooten et al. 2015; Li et al. 2022). To implement this, Assmuth et al. (2018, 2021), for example, treated carbon storage as a positive externality, with forestland owners paid a subsidy for carbon sequestered by growing trees and charged for carbon emitted as CO_2 due to harvest and mortality. In this regard, a study by Zhang et al. (2024) examined whether carbon uptake considerations would enhance the forestation of natural areas identified as capable of growing trees (or having grown trees in the past) in Northwest China. The authors found it was economic to forest 10.2% of these lands, and carbon considerations increased the proportion of economic plantings to 11.2% at a carbon price of USD 200 per tCO_2.

Conclusions concerning the conservation of mature forest stands depend on various factors that include, among others, the carbon dynamics of the stand, its location, the growth rate of newly planted trees, prices of timber, the price of carbon, conversion of biomass to various post-harvest products, discount rates, nonmarket (environmental/ecological) values, and the potential for natural disturbance. As a result, it is difficult to generalize whether mature or old growth (OG) forests should be left unharvested, although many studies suggest that, when PHWP storage is considered, reforestation occurs and older sites are vulnerable to natural disturbance, sustainable forestry remains the best option for maximizing carbon sequestration and commercial benefits. In this study, we employ field measurement data from British Columbia to examine the costs and benefits of harvesting an old- growth forest.

3. MODELING CONVERSION OF OLD-GROWTH FOREST

Forestry activities are economically feasible only if the net benefits from the activity exceed the opportunity costs. In the current study, we examine the economic and carbon sequestration benefits of protecting an old-growth forest versus those of converting the forest into a sustainably managed and productive commercial forest. The protection of old-growth forests provides annual existence, ecosystem, and other environmental benefits, most of which are nonmarket in nature; a possible exception relates to water retention benefits that prevent flooding, and which might be estimated from market data. Another consideration is the benefit from storing carbon—preventing release of CO_2 into the atmosphere. The opportunity cost of retaining an old-growth forest constitutes the net benefits of commercial wood products and the value of CDRs from the atmosphere by the new generation of trees planted post-harvest (e.g., Lemprière et al. 2013). Also included as a benefit is the value of the carbon stored in post-harvest products, minus any CO_2 emissions resulting from harvesting and processing of timber that is not subsequently stored in PHWPs. Finally, there may be nonmarket benefits associated with newly planted forests, with annual benefits potentially increasing as newly planted forests mature.

To model the conversion of OG into a sustainably managed forest, it is necessary to distinguish between the stand level and the forest level. At the stand level, it is necessary to first consider the commercial value of timber plus or minus any values associated with CO_2 uptake and emissions. At the second level it is necessary to consider what happens to amenity values. The marginal existence value of old growth increases as more land is converted; further, as the regenerated forest grows, environmental or ecological service values increase as a function of the volume (age) of the stand.

Consider first the immediate value of converting a mature, ready-to-harvest forest, without considering future harvests. The forest is assumed to be in equilibrium with decay balancing growth, so no additional carbon is sequestered, and timber growth is considered static.[3] The benefit of a one-time harvest (PV_0) is then given by:

[3] A private landowner should liquidate the forest as its growth in value is less than the interest rate on money.

(1) $$PV_0 = (P_F v(M) - K) - \left(1 - \frac{d}{r_c + d}\right) p_C C(M),$$

where M is the current age of a mature (old growth) stand and v_M is the volume of commercial timber on that stand. Further, P_F is the financial return of commercial timber or price of logs ($/m^3), p_c is the price of carbon ($/t$CO_2$), r is the intergenerational discount rate (or social rate of time preference), r_c is the rate used to discount carbon values, d is a decay factor ($0 \leq d < 1$), and K is the replanting cost, where replanting is a sustainability requirement. At the time of harvest, all wood biomass is assumed to enter various post-harvest wood product and ecosystem (dead matter) pools of which there are N, with each separate proportion γ_n decaying at rate δ_n. Then the weighted decay factor (d) is determined as $d = \sum_{n=1}^{N} \delta_n \gamma_n$.

$C(M)$ is the carbon on the mature stand (tCO_2) and is given by:[4] $C(M) = \alpha\, \eta(M) v(M)$, where α translates a cubic meter of tree growth into its CO_2 equivalent (tCO_2/m^3). The parameter $\eta(M)$ expands the growing commercial volume (bole) component to include the living biomass in branches and leaves and to account for the carbon in roots, as well as dead biomass that eventually enhances soil organic matter; this value changes as the forest grows (see section 4 below).

The first term in (1) represents the net commercial benefit of harvesting a mature forest stand, while the second term represents the associated externality cost of releasing CO_2. It is assumed that all the biomass on the stand emits its CO_2 to the atmosphere at the time of harvest but then credits carbon entering post-harvest pools, which then decay over time (see van Kooten 2018, p.5). Parameter r_c discounts the value of the decaying carbon stores because future carbon fluxes are worth less than current ones, although, potentially, $r_c = 0$ in which case carbon values are discounted at the same intergenerational rate r (see Arrow et al. 2012; van Kooten and Johnston 2016; van Kooten 2023).

It is also necessary to account for future harvests. Then the stream of all future benefits is as follows (van Kooten 2025, eqn. (A8)):

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[4] This applies only to conversion of the first stand. As future stands of old growth are harvested, it is necessary to discount the first and subsequent terms in the equation.

(2) $$PV_T = \frac{1}{1-e^{-rT}}\left[(P_F v(T)-K)e^{-rT} + \alpha\eta(T)p_c\left(1-\frac{d}{r_c+d}\right)v(T)e^{-(r+r_c)T} + \alpha p_c(r+r_c)\int_0^T v(s)e^{-(r+r_c)s}ds\ + H(v_t)\right],$$

where T represents the fixed rotation age specified in the conversion of old-growth forest into a sustainably harvested forest, and s is an integration variable. The first term in square brackets in (2) counts the discounted commercial value of future harvests, while the second term addresses the value of the carbon fluxes because of harvest. The second term consists of two components. The first represents an assumed release of all carbon as CO_2 at the time of future harvest, while the second represents the carbon that is sequestered in post-harvest wood product or ecosystem pools that decay over time. Then the third term in square brackets can be considered the present value of CO_2 attributable to reforestation; it counts the accrued value of carbon in each period as a newly planted forest grows. In essence, the second and third terms in square brackets can be considered the present value of CO_2 attributable to reforestation.

The final term in (2) counts the annual nonmarket or amenity values. As a forest grows, it provides increasing annual environmental or ecological service values, such as those related to water retention, atmospheric cooling, and wildlife habitat. These values are a function of the stand volume (or age) and are given by the following equation:

(3) $$H(v(t)) = \int_{s=0}^{T} u(v(s))e^{-rs}ds$$

where the annual amenity value of the stand, $u(v)$, is summed over the period from planting to harvest, with $u'(v)\geq 0$ and $u''(v)\leq 0$.

If the old-growth forest remains unharvested, then we count the carbon sequestered according to equation (2) and its one-time value as $p_c C_M$, where M represents the current age of the old-growth forest (van Kooten 2000; Zhang et al. 2024).

The net social benefit of converting the forest consists of the conversion value of the forest, PV_0 given by equation (1), plus the value of future harvests, PV_T given by equation (2). Included are the amenity values that are a function of the volume of standing timber plus the carbon sequestration benefits (with CDRs a function of the change in the volume of timber from one year to the next). The sum of the conversion and future values do not include the value of old growth, however. Old-growth values are related to the entire forest, depending on area remaining in the old-growth state; the marginal value of old growth changes as more area is converted to sustainable forestry.

Assume that the total area of OG available for conversion (but not necessarily converted) is given by $\bar{G}$ and $A(s)$ refers to the area of OG converted to a sustainably managed forest at time $s \leq t$. Then, at any given time, the annual benefits of leaving forestland in its original old-growth state are given by:

(4) $$w(G(t)) = w\left(\bar{G} - \int_{s=0}^{t} A(s)ds\right),$$

where $w(G(t))$ represents the ecological value of the land as old growth, which is a function of the available land remaining in the old-growth state, namely $\bar{G} - \int_{s=0}^{t} A(s)ds$. It is assumed that $w'(G)>0$ and $w''(G)<0$, so that the existence value of a hectare of OG rises as area in old growth is reduced. Assuming all stands are identical, only the value $w(G)$ will differ according to how the forest evolves.

Finally, to calculate the carbon sequestered over multiple rotations, we employ the present tonne equivalent of carbon dioxide removals (PTE_{CDR}) to derive the total carbon offsets at the current time. From van Kooten (2018, p.5), we determine the total carbon sequestered from converting a hectare of mature forest to a sustainably managed commercial forest as:

(5) $$PTE_{CDR} = \left(\frac{1 - e^{-r_c}}{\left(1 - e^{-r_c}\right) + de^{-r_c}}\right)\alpha\left[\eta(M)v(M) + \eta(R)v(R)\left(\frac{1}{1 - e^{-r_c R}}\right)\right].$$ [5]

The first term in (5) represents the immediate carbon sequestered as a result of the immediate conversion of old growth, while the second term calculates the PTE carbon sequestered over all

[5] In discrete time, the first term can be written as: $\left(1 - \frac{d}{r_c + d}\right)$ (van Kooten 2018). For a decay rate d=2.9% and a carbon discount r_c = 1%, the discrete version gives 0.2564103 and the continuous version give 0.2573655.

future rotations.

4. APPLICATION TO OLD GROWTH IN BRITISH COLUMBIA

The model described above is implemented for the management of old-growth forest in British Columbia. Comparing the net carbon balance of conservation and harvesting scenarios, forest clear-cuts with 70- and 125-year rotation periods are applied to the landscape assuming that mature trees are 250 years old. In the harvest scenarios, the substitution benefits of the PHWPs are estimated using a constant substitution factor. Inducing clear-cuts could turn an old-growth landscape into a significant carbon source or sink, depending on whether and which post-harvest carbon storehouses are included or excluded. Forest regrowth increases carbon sequestration in the ecosystem, while PHWPs retain a proportion of the carbon released at harvest. However, it is not clear whether regrowth and the subsequent cradle-to-grave carbon fluxes from PHWPs and future rotations can offset the initial CO_2 emissions from the harvest of old growth. If not, the harvested landscapes could be a net carbon source. In the model, we balance the climate considerations against the net income over an infinite time horizon, with the results informing forest management decision making.

4.1 Study region

Approximately 88.7 million hectares of land in British Columbia are publicly owned as 'crown land', of which 67 percent is covered by forest (BC Ministry of Forests, Lands and Natural Resource Operations 2011). The forests located mainly in low lying areas west of the Coastal Mountains but also along river bottoms into the interior are among the most productive natural forests in North America. These constitute some 10.8 million ha, of which approximately three-quarters are protected or uneconomic to harvest (CFCG 2025). Some 68% of the protected area constitutes old growth (>120 years), with 67% of trees >120 years currently protected compared with only 3% of trees <60 years, 7% between 60 and 120 years, and 17% non-forested natural lands. To mitigate climate change, one aspect of forest management in BC focuses on the role of old-growth in reducing or offsetting carbon fluxes.

The current application focuses on the Coastal Western Hemlock (CWH) biogeoclimatic ecological zone located along the western coast of British Columbia (BC Ministry of Forests 1999; CFCG 2024). The biogeoclimatic zone consists primarily of western hemlock and western red cedar, but it also includes less abundant amabilis fir, yellow cedar, Douglas fir, grand fir, lodgepole pine, Sitka spruce, and broad-leaf species such as maple, red alder, and cottonwood. We assume that 1 million ha of CWH old growth are identified for conversion to sustainable commercial forest management.

Using this approach, the ecological or amenity values of old-growth forest and reforested lands need to be specified; denote the functions as $w(G)$ and $u(A)$, respectively. Using data from van Kooten (1995) adjusted for inflation, we find the discounted marginal willingness to pay (WTP) per ha in old growth as follows:

(6) $w'(G) = 1327.06 - 0.2715\, G$,

where G is measured in thousands of ha. There are about three million ha of old growth in British Columbia, which implies that old growth is worth \$512.56/ha.[6] Further, we assume any site converted from old growth and replanted gains amenity value as follows:

(7) $u(v(s)) = \frac{v(s)}{v_{Max}} \cdot\ 512.56/\text{ha}$,

where v_{Max} refers to the maximum volume a mature timber stand can achieve. The ecological value of a converted and sustainably managed forest increases with the volume of timber or forest age.

4.2 Model parameterization and data

It is assumed that timber growth on afforested land is represented by the following Gompertz functional form:

(8) $v(t) = Ue^{-ke^{-gt}}$,

where the volume of stem wood (m^3/ha) is a function of stand age t. Parameter U represents the

[6] Although there are 11.1 million ha of old growth in British Columbia, the "Timber Harvesting Land Base is approximately 22.3 million hectares, of which about 3 million hectares is old-growth forest" (Government of British Columbia 2024).

maximum volume (asymptote) that will grow on the site given its biogeoclimatic characteristics,[7] k is the growth range, and g is the growth rate. The change in $v(t)$ with respect to t in discrete time is given by $\Delta v(t) = v(t+1) - v(t)$, which is useful for determining carbon fluxes on afforested land as trees grow. Using the functional form (8), regression parameters were estimated for two growth functions based on data from two hypothetical sites, with site indexes of 19 and 29, respectively. As described below, the data were generated by LANDIS-II, a simulation model for forest landscapes (The LANDIS-II Foundation 2024). A site index (SI) represents the potential forest productivity of a site, with higher values corresponding to greater potential productivity (Nussbaum 1996). This is reflected in Table 1 where the SI_29 has a maximum volume at an age of 250 years (1343.7 m^3) that exceeds that of SI_19 (1163.2 m^3). The estimated growth functions are plotted in Figure 1, with SI_19 stands reaching 1000 m^3/ha at 250 years compared with 1220m^3/ha for SI_29. The observed data for SI_19 fit the Gompertz functional form (8) slightly better than the data for SI_29, but the underlying growth function in LANDIS is likely Gompertz.

Table 1: Parameters for Gompertz Functional Form

Parameter	Symbol	Site Index 19	Site Index 29
Maximum Volume	*U*	1163.197***	1343.714***
Growth Range	*K*	5.274***	4.054***
Growth Rate	G	0.014***	0.015***
Residual Standard Error	*RSE*	3.926	23.61
(Degrees of freedom)		(12,396 df)	(12,364 df)

*** indicates significant at 0.1% level; ** at 1% level, and * at 5% level.
Source*:* Authors' calculations

The forest simulation model LANDIS-II does not provide ready estimates of merchantable volume because the focus is on carbon per m^2. Thus, it was necessary to use wood density measures to retrieve merchantable volume (m^3/ha). This was done for a hypothetical 100,000-ha forest consisting of 500 mixed hemlock-amabilis fir stands. The formula used to convert the carbon measure (tC/m^2) in LANDIS-II is:

(9) $$MV = \omega_1 \cdot C_B \cdot \omega_2 \cdot Prop \cdot \frac{1}{density},$$

[7] This is the value of v_{Max} used in equation (7).

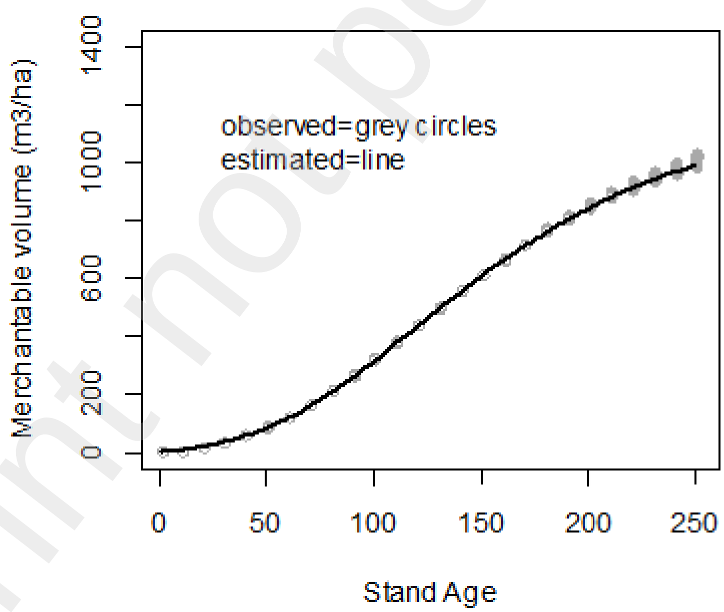
where MV refers to merchantable volume, $\omega_1$converts grams to tonnes (tC/gC), ω_2 converts meters to hectares (m^2/ha), C_B refers to the carbon in wood biomass (gC/m^2) on the stand (both living and dead), and *density* refers to the carbon in a cubic meter of wood (tC/m^3). Then,

(10) $$Prop = h_1 \cdot (1 - h_2{}^t),$$

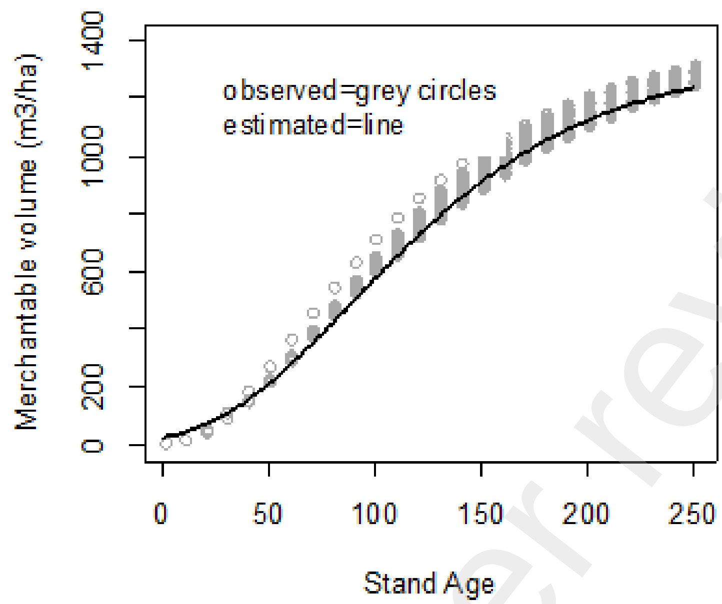
where $h_1 = \{0.6519, 0.7546\}$ and $h_2 = \{0.992, 0.983\}$ are pre-specified parameters (Dymond 2024), and t refers to the age of the trees on the stand. Equation (9) is solved for C_B, which, after adjusting for units of measurement, simplifies to:

(11) $$C_B = \frac{MV \cdot density}{Prop} (\mathrm{tC/m^3}).$$

Finally, to obtain carbon not included in the merchantable component, denoted C_N, C_B is multiplied by $(1 - Prop)$:



(a) Site Index 19



(b) Site Index 29
***Figure 1:** Growth Functions and Observed Data*
Source: Calculations based on data from LANDIS-II Simulation (2023)

(12) $$C_N = \left(\frac{1 - Prop}{Prop}\right) \cdot MV \cdot density \text{ (tC/m}^3\text{)}.$$

During the growth stage carbon will also be sequestered in the branches, leaves, and roots. To account for all the living above-ground biomass plus root biomass, the commercial component is multiplied by $\eta_t = 2 - a(1 - b^t)$, where a=0.7546, b=0.983 (Dymond 2024). If each cubic meter of biomass contains 0.20 tonnes of carbon, then α = 0.73 tCO_2/m^3.[8] Further, we employ average decay rates for four post-harvest carbon pools: lumber; long-lived engineered products; sawmill residues and waste, and the carbon in biomass left at the site after harvesting. The allocations of the stand's biomass to the various pools are provided in Table 2, with the average decay rate for the different carbon pools equal to 2.9263% (δ=0.02926).

[8] The average density of softwoods is approximately 400 kg per m^3 (Jessome 1977); given that about 50% of wood biomass is carbon, there are 0.2 tC/m^3, which is then multiplied by 44/12.

Table 2: Post-harvest allocation of biomass to four pools and associated decay rates

Post-harvest carbon pool	Allocation of biomass to post-harvest pools	Decay rates of post-harvest pools (δ_n)
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	0.029263	

Source*:* van Kooten (2023)

Other key parameters for the analysis include the prices of carbon and logs, planting costs, the rate of discount (or social rate of time preference), and the discount rate used for carbon values if it differs from the social rate of time preference (van Kooten 2025). The rate used to discount carbon values (r_c) varies from 1% to 3%, depending upon the urgency to address climate change, and the market discount rate (r) is taken to be 5%. The carbon prices considered here are summarized in Table 3.

We use a log price of \$194.96/m^3, which was the average of the Vancouver Log Market Average prices for December 2024.[9] Carbon prices reflect the current tax of \$80/tCO_2 in effect in British Columbia (Ministry of Environment and Climate Change Strategy 2024), with the federal carbon tax scheduled to reach \$170/tCO_2 in 2030 (Greenhouse Gas Pollution Pricing Act 2024). Costs of re-planting a harvested site in the CWH study region are available from the BC Ministry of Forests (2025, p.5-29). For 2024, these were estimated to range from a low of \$1411/ha to \$3691/ha, with an average of \$2328/ha.

5. RESULTS AND ANALYSIS

Our interest is to determine the impacts of the rotation age (70 years or 125 years) along with the carbon prices and carbon discount rates on the net discounted economic (social rather than private) returns to tree planting and the total carbon benefits. Finally, we examine the tradeoffs between net economic returns versus the carbon sequestration benefits using some discrete sensitivity

[9] Historical coast log market reports available at https://www2.gov.bc.ca/gov/content/industry/forestry/competitive-forest-industry/timber-pricing/coast-timber-pricing/coast-log-market-reports/2024 [accessed 05 March 2025]

analysis and, much more broadly, Monte Carlo simulation.

5.1 Harvest to reforestation benefits: Sensitivity analysis

The results of our analysis in the base case scenario for the 70- and 125-year rotation periods for SI_29 are provided in Table 3. Our base case scenario for both site indexes assumes that the price of timber is \$194.96/m^3, the price of carbon is \$80.00/tCO_2, and the weighted average decay rate of post-harvest carbon pools is 2.926% (Table 2). Further, the weight for discounting physical fluxes of carbon is taken to be 1% and the intergenerational rate of discount is 3%.

Consider a forest with site index 29 (SI_29). In the base case scenario, society gains a present net benefit of some \$3.01 billion from the conversion of 1 million ha of old-growth forest to a sustainable forest that is harvested every 70 years, but only after including a loss of about \$250 million of existence and ecological values from harvesting old growth. Also included is a recovery of some ecological value as new forests grow to maturity.

Table 3: Discounted Values of Various Forest Components and Present Ton Equivalent of Carbon Dioxide Removals for SI-29 and SI_19 Sites, Base Case Scenario, (P_F=\$194.96/m^3, p_c=\$80/tCO_2, r=3%, r_c=1%) [a]

	SI_29: Rotation Age		SI_19: Rotation Age	
Item	70 years	125 years	70 years	125 years
Total stand value (\$ 10^6)	\$3,257.3	\$1,791.0	\$2,557.5	\$1,423.3
Commercial timber value (\$ 10^6)	\$3,490.6	\$1,913.2	\$2,787.3	\$1,545.5
Ecological value (\$ 10^6)	\$16.8	\$13.3	\$7.5	\$6.9
Net carbon value (\$ 10^6)	-\$250.2	-\$135.6	-\$237.2	-\$129.2
PTE_{CO2} (Mt CO_2)	-6.64	-4.32	-2.09	-0.57
Lost old-growth value (\$ 10^6)	\$249.6	\$148.8	\$249.6	\$148.8

[a] Values in Canadian dollars. Decay rate determined in Table 2.
Source: Authors' calculations.

If the current old-growth forest is to be converted over a period of 125 years, so that the sustainable rotation age becomes 125 years, the present net benefit is reduced to \$1.64 billion. The reason is that, with the extended rotation age, it takes longer to achieve the associated benefits which are then less in present value terms.

The commercial timber value of the standing forest constitutes the greatest benefit of harvesting old growth. Nonetheless, the overall benefit to society is reduced because of carbon sequestration (climate mitigation) considerations. In this regard, the results are somewhat supportive of arguments by Harmon et al. (1990) and Morton et al. (2021), who maintain harvests of mature forests lead to an overall increase in CO_2 emissions. Depending on site index and rotation age, conversion of old-growth forest could result in a present tonne equivalent increase in emissions of 0.6 to 6.6 Mt CO_2. This result is thus contrary to the argument that harvests increase carbon sequestration because carbon is stored in product sinks while new growth removes additional CO_2 from the atmosphere (see Howard et al. 2021; Smyth et al. 2020; Lemprière et al. 2013).[10] Given that the net climate effect was positive once a sustainably-harvested forest was newly planted, it was the initial harvest of mature timber and transfer of carbon to post-harvest wood product and other carbon pools that was crucial. In this regard, the decay rate and rate used to weight current carbon fluxes more than future ones affect the PTE values in Table 3.

These results suggest that, from a commercial timber standpoint, longer rotation periods and thus a longer period for converting old-growth forests lower the net present timber value due to discounting. However, from a carbon management perspective, a longer rotation period is better because it reduces the annual CO_2 emitted from harvesting mature timber, delaying some emissions to the future so as they are not considered as important as more recent emissions—they are effectively discounted.

Suppose that carbon is not priced, and future carbon fluxes are considered equal to current ones, but still accounting for decay of post-harvest fiber. For SI_29 this leads to an increase in total stand values of $259.1 million and $135.5million, respectively, for the 70-year and 125-year rotations. The reason for this increase in value is that there is no longer a cost of increased CO_2 emissions caused by the initial harvest, subsequent storage of carbon in post-harvest pools, and new growth—carbon has no value even though the registered storage of carbon is considered infinite since there is no distinction as to when a carbon flux occurs.

If future carbon fluxes are discounted at 1%, however, the present tonne equivalent CO_2 is negative; there is a release of 1.571 and 0.280 Mt CO_2 for the 70- and 125-year rotations,

[10] However, some of these studies focused on temperate and boreal forests rather than coastal rain forests.

respectively. If the carbon were priced at \$80/tCO_2, the value of the stand would be reduced by \$250.2 million and \$135.6 million for the respective rotation ages; with a carbon price of \$170/tCO2, the reductions would amount to \$531.7 and \$288.1 million, respectively. Finally, the value of timber must be significantly below the value of carbon before it is no longer socially desirable to harvest timber; at a carbon price of \$80/tCO_2 it is economic to harvest timber as long as the net return to logs exceeds approximately \$15/m^3.

5.2 Harvest to reforestation benefits: Monte Carlo Simulation

To shed further light on the robustness of our results, we conduct Monte Carlo simulation over the key parameters in the model, as identified in Table 4. For each parameter in the table and for each of 10,000 iterations, we sample from a binomial, uniform or triangle distribution as indicated. A summary of the results is provided in Table 5. These indicate that the conversion of 1 million ha of old-growth forest on the BC Coast could be expected to increase the social value of the forest by some \$2.9 billion with the greatest benefit associated with the commercial value of the harvest as reflected in log value.

Table 4: Distributions used in Sampling Parameters for Monte Carlo Simulation

Item	Distribution	Minimum	Maximum	Mode
Growth function indicator[a]	binomial	0	1	Prob. = 0.5%
Rotation age (yrs)	uniform	60	125	n.a.
Rate of time preference (%)	triangle	2Z%	7%	7%
Discount rate on carbon value (%)	triangle	0%	6%	1%
Price of logs (\$/m^3)	triangle	\$185.50	\$374.43	\$257.14
Price of carbon (\$/tCO_2)	triangle	\$0	\$200	\$80
Regeneration cost (\$/ha)	triangle	\$1411	\$3691	\$2328
Decay rate of post-harvest carbon pools (%)	triangle	0.25%	3.50%	1.75%
Amenity value (\$/ha)	triangle	\$300.00	\$750.00	\$512.56

[a] Determines whether SI-19 or SI_20 growth function (Figure 1) is chosen with 50-50 probability.

Table 5: Summary of Monte Carlo Results with 10,000 Iterations

Item	Mean	Standard Deviation
Forest value ($ mil)	2,910.48	945.39
Timber value ($mil)	3,439.45	986.34
Ecological Value ($mil)	8.30	5.38
Lost old-growth value ($ mil)	165.09	52.79
Carbon value ($ mil)	-537.27	351.95
PTE carbon removed (Mt CO_2)	-3.35	2.27
Price of logs ($/m^3)	272.64	38.64
Price of carbon ($/t$CO_2$)	93.58	41.16

[a] Stand value does not include lost old-growth value.
Source: Authors' calculation

The present value of commercial timber is expected to be approximately $3.4 billion, but its exploitation will lead to a reduction in the forest's environmental value to society. The loss in old-growth value of an expected $165 million will be offset to some degree by an anticipated ecological value of $8 million as newly planted trees grow. The principal loss is associated with early carbon release in the form of CO_2 emissions. The probability that the harvest of old growth, with subsequent storage of carbon in wood-product sinks and increased rates of carbon uptake due to regeneration of timber stands, results in an overall reduction in atmospheric CO_2 ($PTE_{CO2} > 0$) is only 6.97% (see Appendix for calculation). Exploiting old growth will lead to a net release of stored carbon in the form of CO_2 as argued by Harmon et al. (1990) and others.

If either the net social value of the forest or its net commercial timber value is maximized, the discounted timber is worth $7592 million while society values the coastal forest at $7421 million. In this outcome, the price of logs is $371.92/m^3, while that of carbon is $33.09/t$CO_2$; the present tonne equivalent loss of carbon from harvesting equals 3.602 Mt CO2, with the lost CO_2 valued at $184.8 million. The outcome that maximizes carbon sequestration occurs when the log price is $277.58/m^3 and the carbon is (surprisingly) priced at only $16.39/t$CO_2$; 5.041 PTE_{CO2} is prevented from entering the atmosphere, but society still values the carbon negatively (–$24.12 million) because of the ill timing of the carbon fluxes—the value of the initial pulse of CO_2 released to the atmosphere dwarfs the value of the later uptake. In this outcome, the timber is still valued at $3489 million, approximately equal to the average value of 10,000 random outcomes.

If one wishes to determine the potential cost of sequestering carbon, it is necessary to recognize that net sequestration occurs only 7% of the time. Further, although the ratio of the average log price to the average carbon price in the simulation is 2.91 (see Table 5), the ratio of the two prices is significantly higher—namely, 22.69 (=277.58/16.39)—when the simulation attains maximum sequestration of carbon. Overall, one can only conclude that, while the conversion of old growth to a sustainably managed forest leads to a net increase in atmospheric CO_2, the benefits of doing so are large—the cost of reducing emissions of CO_2 by conserving old growth forest is prohibitive, even when other environmental costs are considered.

6. CONCLUSION AND POLICY IMPLICATIONS

The conversion of old-growth forests into sustainably managed, commercial forests presents a complex interplay between economic returns, carbon sequestration dynamics, and ecological trade-offs. Our analysis of coastal British Columbia's old-growth systems underscores the inherent tensions between these objectives and offers critical insights for policymakers tasked with balancing short-term economic gains against long-term environmental sustainability.

There is a tradeoff between maximizing commercial timber value and achieving net carbon dioxide removals from the atmosphere. While immediate timber harvesting generates significant financial returns (averaging $3.4 billion NPV in simulations), it results in a net release of 3.35 Mt CO_2 equivalent over time. This challenges the argument that post-harvest regrowth and wood product storage offset initial emissions, particularly in carbon-rich coastal ecosystems. Managing old-growth forests in this respect might be akin to balancing a portfolio: preserving ancient 'blue-chip' carbon stocks while investing in younger, faster-growing 'startups'—with carbon pricing acting as the risk-adjusted return metric.

Carbon discount rates (r_c) reflect the time sensitivity of carbon values, or the urgency of climate action, with the choice of an appropriate rate significantly altering outcomes. Higher discount rates reduce the perceived value of future carbon uptake, favoring shorter rotations (e.g., 70 years) for timber profits but exacerbating long-term emissions. Conversely, lower discount rates prioritize carbon sequestration but diminish present economic gains. The policy dilemma thus centers on the ethical calculus of discount rates: should present generations prioritize immediate economic gains from timber harvests, or invest in future climate benefits by preserving old-growth carbon sinks?

The research indicates that the ratio of commercial values to carbon values affects the economic viability of net CO_2 emissions. Conversion of old growth remains economically viable even with a high carbon price (e.g., \$170/tCO_2). Indeed, only if the value of timber is significantly below the value of carbon does conservation become financially competitive.

As an ecological cost, conversion erodes old-growth existence values, with limited compensation from regrowth amenity benefits. Monte Carlo simulations indicate only a 7% probability that there is net carbon sequestration, emphasizing the ecological risks of large-scale conversion.

To address the complex tradeoffs between economic returns, climate goals, and ecological preservation identified in this study, policymakers must adopt a cohesive strategy that integrates carbon valuation, forest protection, and economic incentives. First, reforming carbon accounting frameworks is imperative to reflect the true costs of old-growth conversion. Current models undervalue standing forests by neglecting full lifecycle emissions from harvested biomass decay and the irreversible loss of carbon sequestration capacity in intact ecosystems. A recalibration of carbon discount rates, aligning them with climate urgency (e.g., r_c=1%), would better prioritize intergenerational equity by assigning greater weight to long-term carbon storage and biodiversity benefits.

Second, targeted conservation policies should prioritize protecting high-carbon coastal rainforests, where old-growth stocks far exceed regrowth potential. But, as this study indicates, protection of old growth comes at a very high cost. Expanding protected areas could be funded through innovative mechanisms such as ecologically weighted carbon credits, which recognize old-growth forests' dual role in carbon storage and provision of ecological service and non-use benefits. However, results indicate that, even when ecological (or environmental) benefits are considered, the economically efficient strategy is to convert old growth—the commercial timber benefits simply swamp the carbon sequestration and environmental benefits of retaining old growth. The existence of some 3 million ha of old growth of which 1 million is to be harvested over a long period of time likely contributes to this—at the margin, environmental benefits of retaining old growth are small.

Finally, our analysis fails to consider the impact of disturbances on stand values and the rotation ages as considered in Ekholm (2020) and Siebel-McKenna et al. (2020). That is, we fail to account for the interactions between harvesting and natural disturbances such as wildfires. Including this would make for a more comprehensive analysis. Such an analysis would require collaboration between scientists, policymakers, and Indigenous communities, whose traditional knowledge and stewardship practices offer critical insights into resilient forest management.

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APPENDIX: CALCULATION THAT PTE > 0

To find the probability that an outcome is positive ($PTE > 0$) for a normal distribution with mean $\mu = -3.35$ and standard deviation $\sigma = 2.27$, we standardize the value using the **z-score** formula:

$$Z = \frac{PTE - \mu}{\sigma}$$

For $PTE = 0$:

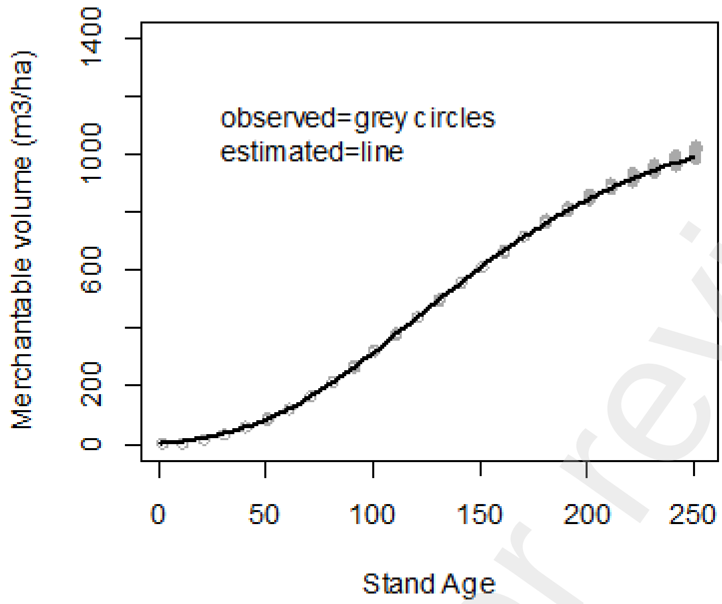
$$Z = \frac{0 - (-3.35)}{2.27} = \frac{3.35}{2.27} \approx 1.476$$

Now, we look up the cumulative probability $P(Z \leq 1.476)$ from the standard normal distribution table:

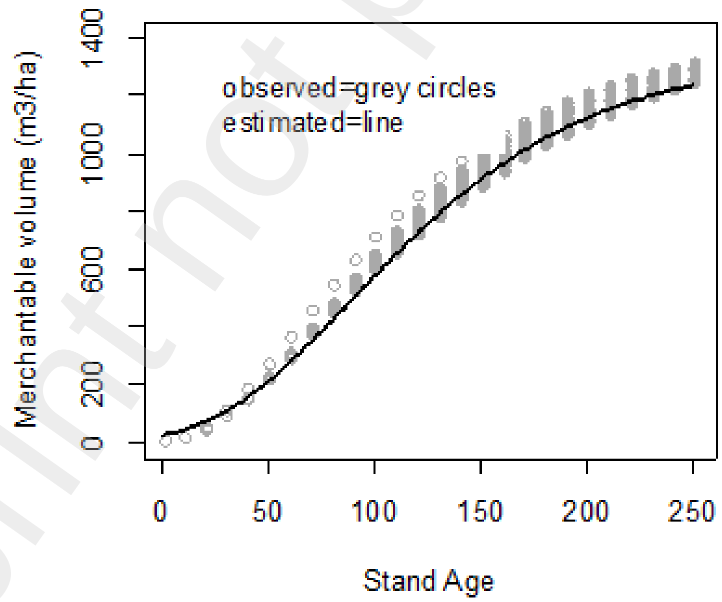
$$P(Z \leq 1.476) \approx 0.9303$$

Since we need $P(PTE > 0)$, we take the complement:

$$P(PTE > 0) = 1 - P(Z \leq 1.476) = 1 - 0.9303 = 0.0697.$$



(a) Site Index 19



(b) Site Index 29

Figure 1: *Growth Functions and Observed Data*

Source: Calculations based on data from LANDIS-II Simulation (2023)