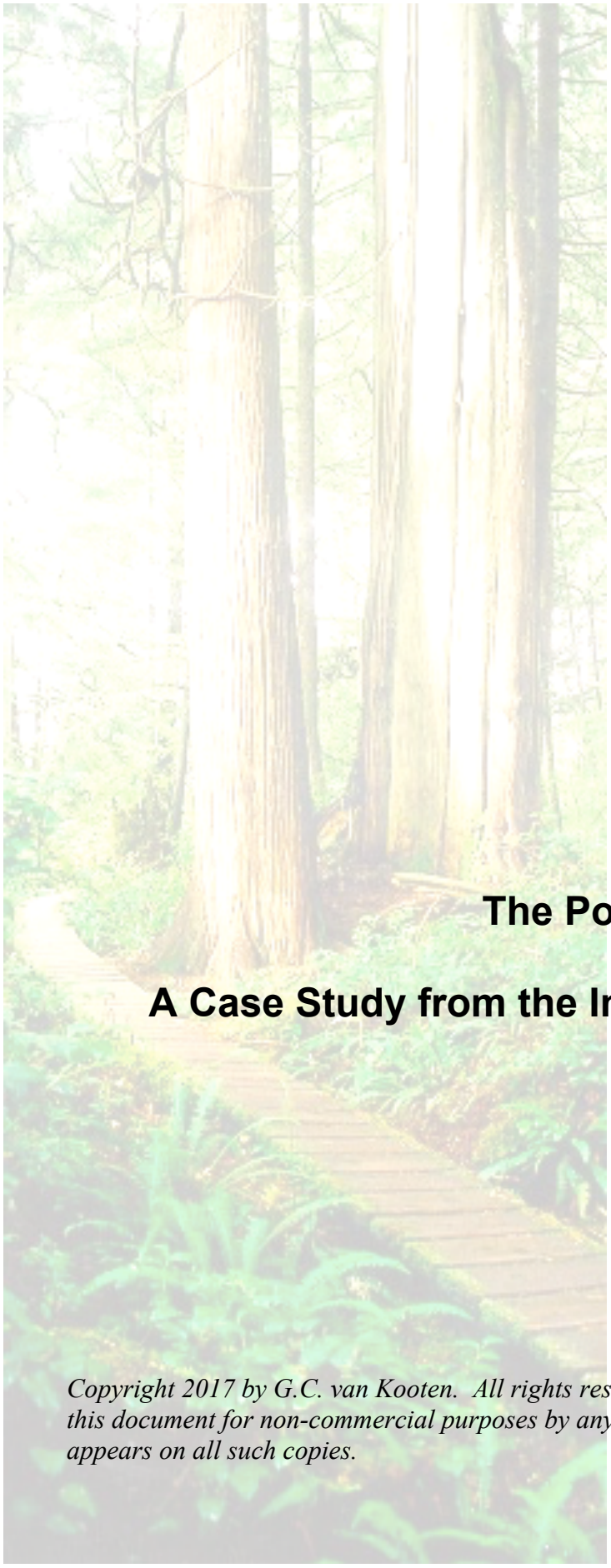

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The Policy Challenge of Creating Forest Offset Credits: A Case Study from the Interior of British Columbia

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The Policy Challenge of Creating Forest Offset Credits: A Case Study from the Interior of British Columbia

by

G Cornelis van Kooten

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Abstract

This paper provides an overview of the role that forestry activities can play in mitigating climate change. The price of carbon offset credits is used for incentivizing a reduction in the release of CO_2 emissions and an increase in sequestration of atmospheric CO_2 through forestry activities. Forestland owners essentially have two options for creating carbon offset credits: (1) avoid or delay harvest of mature timber; or (2) harvest timber and allow natural regeneration or regeneration with 'regular' or genetically-enhanced growing stock, storing carbon in post-harvest products, using sawmill and potentially logging residues to generate electricity. In this study, a model representative of the Quesnel Timber Supply Area (TSA) in the BC interior is developed. The objective is to maximize net discounted returns to commercial timber operations (and sale of downstream products) plus the benefits of managing carbon fluxes. The model tracks carbon in living trees, organic matter, and, importantly, post-harvest carbon pools and avoided emissions from substituting wood for non-wood in construction or wood bioenergy for fossil fuels. Model constraints ensure that commercial forest management is sustainable, while carbon prices incentivize sequestration to ensure efficient mitigation of climate change. The results are confirmed more generally by comparing the carbon fluxes derived from the integrated forest management model with those from a Faustmann-Hartman rotation age model that explicitly includes benefits of storing carbon. One other question is addressed: If carbon offsets are created when wood biomass substitutes for fossil fuels in power generation, can one count the saved emissions from steel/cement production when wood substitutes for non-wood materials in construction?

Keywords: climate change mitigation and forestry; carbon offsets and taxes; carbon life-cycle analysis; biomass energy; wood products versus cement and steel; forest rotation age

JEL categories: H23, Q23, Q42, Q54, G15

1. INTRODUCTION

To mitigate the effects of climate change, carbon reducing strategies are becoming increasingly important, including the role of forests in reducing atmospheric carbon dioxide. One debate about forest management strategies concerns whether to conserve forests as carbon sinks or to harvest them and process timber into wood products that store carbon. When trees are left standing, the carbon uptake rate slowly declines as growth exceeds maximum mean annual increment; eventually the unharvested forest simply stores carbon. Upon harvesting and processing trees, carbon can be stored in long-lived wood products that substitute for steel and cement in construction, including cross-laminated timber (CLT) that is increasingly used in multiple-purpose, multi-story buildings. Long-lived wood products constitute only a portion of the timber that is harvested, however, with remaining wood fiber used to produce short-lived products, such as pulp or fiber board, that release stored carbon much sooner after harvest. Logging and sawmill residues, on the other hand, can be burned to produce electricity, thereby reducing CO_2 emissions from fossil-fuel generating assets.

One controversy concerns whether to count reduced emissions of greenhouse gases (GHGs) from lowered production of carbon-intensive materials (viz., concrete, steel) for which wood products substitute in construction. Clearly, if we allow wood biomass to substitute for fossil fuels in power generation, thereby counting the saved fossil fuel emissions, then we should also count the saved emissions from not producing steel and cement when wood substitutes for non-wood materials in construction. The question arises: Should the CO_2 savings from not burning fossil fuels, or not producing concrete and steel when wood substitutes for non-wood in construction, be attributed to forestry activities? How important are such savings for forest management?

The current paper contributes to the debate about how forestry might best contribute to mitigating climate change. We compare carbon uptake, storage and release under various forest management strategies, including the possibility of 'leaving the forest unmanaged.' Importantly, we take into account the life-cycle of carbon through the vertical chain of processing wood. A forest management model developed by van Kooten et al. (2015) for a small forest in southeastern BC is adapted to the Quesnel Timber Supply Area (TSA) in the BC interior. The model maximizes net discounted returns to commercial timber operations (and sale of

downstream products) plus the benefits of managing carbon fluxes – a carbon price is used to incentivize carbon management. We can then determine the costs of reducing CO_2 emissions via different forestry activities.

We employ the existing forest inventory for the Quesnel TSA and the provincial government's TIPSY (Table Interpolation Program for Stand Yields) model to forecast timber growth and yield based on the topographical and environmental conditions of the forests in the interior of British Columbia (BC Ministry of Forests, Lands and Natural Resource Operations, hereafter MFLNRO, 2016). The Canadian Forest Service's Carbon Budget Model CBM-CFS3 is applied to investigate how carbon fluxes vary with the growth of the forest (Kull et al. 2011). Greater effort will be made to manage forests for their carbon fluxes if the substitution rate of wood products for concrete and cement is deemed to be high, while the opposite is true if it is low. By valuing carbon, forest managers are incentivized to choose strategies that promote carbon sequestration and storage, but they would need to take the wood product substitution rate as given. By pricing carbon and specifying the 'rules of the game', forest managers are able to balance the trade-offs between leaving forests to grow and harvesting them for wood products, including bioenergy products.

We proceed as follows. In the next section, we provide a background to the debate about how forestry policies can best be used to mitigate climate change. The main controversy relates to the role of forest conservation and the life-cycle of carbon. The model used in the study is described in section 3, followed by the results of various scenarios in section 4. We conclude by providing answers to the questions raised above and with a discussion of policy implications regarding the management of forests.

2. BACKGROUND TO MEASUREMENT OF CARBON FLUXES

An important consideration when managing forests for climate change mitigation relates to the timing of carbon fluxes. How do forest management activities and post-harvest uses of fiber affect the stream of CO_2 release to and removals from the atmosphere? This is important for the simple fact that forestry activities should be incentivized to mitigate climate change to the greatest extent possible at the lowest potential cost. While the mitigation objective might be interpreted to mean 'sequester the greatest amount of carbon in forest ecosystems and wood

product pools,' this objective is not as straightforward as it might seem. There are two reasons: One relates to the life-cycle of carbon while the other relates to the emissions avoided when wood fiber is used in construction or as a fuel, and both relate to the urgency to address global warming (Johnston and van Kooten 2015).

2.1 Life Cycle of Carbon

Consider first the carbon life-cycle analysis (LCA) debate in the context of wood biomass for generating electricity. For Massachusetts, Walker et al. (2013) determined that, if the source of biomass is dedicated harvests of mixed wood, it takes 45 to more than 90 years for the carbon debt to be recovered in the case of coal plants and gas electric plants, respectively. But if the only source of biomass energy is logging residues, it takes only 10 to 30 years to recover the carbon debt. This is because the carbon associated with harvesting of whole trees for burning would otherwise have remained on site sequestering carbon. In the case of logging residues, the trees have already been cut and the carbon in the residues would have been released to the atmosphere through decay if not used as bioenergy. However, just as with sawmill residues, logging residues can be used to make products, such as oriented strand board (OSB), medium density fiber board (MFB) and pulp, that store carbon. The only problem is that logging residues are costly to remove from the forest (Stennes et al. 2010), activities to collect them emit CO_2, and they are often needed in situ to provide ecosystem services (Johnston and Crossley 2002).

The Walker et al. approach has intuitive appeal because of its simplicity: CO_2 emissions from fossil fuels "can be captured in biomaterials and vegetation, but only with the effect of reducing the opportunities for future capture, since the world's carbon sequestration potential is presumably limited. In contrast, at any future point in time carbon dioxide in the biosphere will be lower if wood biomass is allowed to substitute for fossil fuels" (Sedjo 2011; also Sedjo and Tian 2012). Several studies have subsequently proposed alternative LCAs for carbon fluxes associated with biomass burning.

McKechnie et al. (2011) also consider the changes in forest carbon resulting from biomass harvest for bioenergy, and carbon flux when biomass is converted to wood pellets and co-fired with coal to produce electricity. Their conclusion is similar: the benefits of generating electricity from biomass depend on whether standing timber or forest floor residuals are used for bioenergy.

For the Great Lakes-St. Lawrence forest region of Ontario, they find that, if pellets are produced from standing trees, the time taken to eliminate the carbon debt from biomass burning takes 38 years; if pellets are produced from forest residuals, the break-even point occurs after 16 years. However, if 15% of biomass is not needed to dry the wood (as originally assumed), the time required to yield any net climate mitigation benefit is reduced from 38 to 29 years in the case of whole trees and from 16 to 11 years for residuals. Again, based on LCA considerations, forest residuals would decay over time, releasing carbon, whereas standing trees would continue to sequester carbon.

Cherubini et al. (2011) use the notion of global warming potential (GWP) to determine the prospective carbon dividend from biomass burning. The GWP of CO_2 from fossil fuel burning is taken to equal 1 regardless of the time horizon. Thus, there is a distinction between CO_2 molecules released by burning fossil fuels and ones released when burning biomass; CO_2 emitted from biomass is denoted bioCO_2 to distinguish it from CO_2 emitted by fossil fuels. Because CO_2 from fossil fuel burning cannot be removed from the atmosphere, the GWP_{bio} is a measure of the relative benefit of burning biomass. It is given by the ratio of the absolute global warming potential (AGWP) of bioCO_2 to that of CO_2 (Cherubini et al. 2011, p.418):

$$\text{(1)} \qquad \mathrm{GWP_{bio}} = \frac{\mathrm{AGWP_{bioCO2}}}{\mathrm{AGWP_{CO2}}} = \frac{C_0 \int_0^T \alpha_{bioCO2} f(t)dt}{C_0 \int_0^T \alpha_{CO2} y(t)dt},$$

where C_0 refers to the initial pulse of CO_2 entering the atmosphere at t=0. T is the time horizon, and α_{CO2} and α_{bioCO2} are the radiative efficiencies of CO_2 and bioCO_2, respectively, which depend on the ratio of the concentration of CO_2 in the atmosphere after a small perturbation to the initial concentration. Coal releases an average of 0.94-1.02 tCO_2/MWh with wood biomass releasing much more (see section 3.2 below); therefore, $\alpha_{bioCO2} > \alpha_{CO2}$. The functions $y(t)$ and $f(t)$ are CO_2-decay functions that represent the fraction of the initial emission that is still found in the atmosphere at time t. Since CO_2 originating with fossil fuels is assumed not to decay, $y(t)$ = GWP_{CO2} = 1, while GWP_{bio} depends on $f(t)$, which measures the fraction of bioCO_2 removed from the atmosphere by the ocean and biosphere sinks.

Cherubini et al. argue that a bioCO_2 molecule released to the atmosphere by burning biomass can be removed by growing new trees (vegetation), by the ocean carbon sink, or by a terrestrial sink. The speed at which a bioCO_2 molecule would be removed from the atmosphere, or function $f(t)$, depends on the atmospheric concentration of CO_2 at time t, and the rates that each of the three sinks sequester carbon, which they determine using the Bern 2.5CC climate model. The authors find that, if the forest rotation age is 40 years and the time horizon is 100 years, the narrow approaches of Walker et al. (2013) and McKechnie et al. (2011) would result in a GWP_{bio} of 0.43 compared to 0.16 if all sinks were considered; for a forest with rotation age of 80 years, the comparable GWP_{bio} values are 0.86 and 0.34, respectively. Since GWP_{bio} values are less than 1.0, bioenergy is preferred to fossil fuels.

The forgoing analysis neglects the temperature uptick that occurs because the initial pulse of CO_2 from biomass burning is greater than that from coal or gas in generating electricity. Because $\alpha_{bioCO2} > \alpha_{CO2}$, the initial carbon debt results in an increase in temperature, which implies that biomass burning is carbon neutral before it is climate neutral (Helin et al. 2013). That is, the GWP_{bio} is greater than indicated by Cherubini et al. (2011). Indeed, Miner et al. (2014, p.598) calculate that, for loblolly pine harvested every 20 years and a 100-year time horizon, the GWP_{bio} would be 0.12 if carbon neutrality is to be achieved, but it is 0.26 if the objective is climate neutrality. Since GWP_{bio} never declines completely to zero, one could consider biomass to be a better alternative to coal or even natural gas for generating electricity, but not a final solution to the climate problem.

2.2 Economics of Carbon Fluxes

Scientists clearly favor the use of radiative forcing as the appropriate method for measuring the climate impacts of bioenergy. The "advantage of the GWP_{bio} approach is that it provides a kind of *physically based discounting factor* by which the biomass emissions with deviating timing can be transformed into a permanent fossil carbon emission whose cumulative warming impact within a given time horizon is the same" (Helin et al. 2013, p.481, emphasis added). The concept of radiative forcing is not useful from a policy perspective, however (Lemprière et al. 2013, p.301). To analyze the benefits of bioenergy, for example, policy analysts would argue that "assessments of mitigation must go beyond just considering the C [carbon] pools in forest ecosystems: it is important to also consider C use and storage in HWPs [harvested wood

products] and landfills, substitution of wood for more emissions-intensive products and fossil fuels, and land-use change involving forests. Such activities are highly interconnected, [and] … need to be based on an integrated assessment of the various mitigation possibilities" (Lemprière et al. 2013, p.298).

Canadian Forest Service (CFS) scientists (Kurz et al. 2013; Lemprière et al. 2013; Smyth et al. 2014) take a systems approach that measures the carbon fluxes associated with the interaction between human activities (planting, fertilizing, thinning, harvesting) and the forest ecosystem dynamics, which includes weather, wildfire, pests and disease. A systems approach considers carbon stored in long-lived product pools, and CO_2 emissions avoided when wood replaces steel and cement in construction and/or wood biomass replaces fossil fuels in energy production.[1] In their LCA of carbon in boreal ecosystems, for example, they note that "the age-class structure currently found in North America's boreal forests is a transient, non-sustainable phenomenon arising from a period with higher disturbance rates followed by a period with lower disturbance rates," with carbon stocks currently greater than their long-term sustainable maximum (Kurz et al. 2013, p.263). If left undisturbed, these forests will inevitably become net emitters of CO_2.

It is not surprising that in their study of how Canada's forest resources can best be used to mitigate climate change, the CFS scientists find that commercial harvesting of trees to produce wood products is preferred to the option of storing carbon in unmanaged forests, and that production of wood products leads to a greater carbon dividend than the use of wood biomass for energy. Indeed, Lemprière et al. (2017) find that intensive forest management, including "increased recovery of harvested biomass, increased salvage, extraction of harvest residues for bioenergy and increased production of longer-lived wood products," could account for 9.8% to 14.7% of Canada's annual CO_2-emissions reduction target of 112 Mt CO_2 between 2014 and 2020, and at a cost of less than \$50/tCO_2. At the provincial level, British Columbia could rely on forestry activities to achieve 35% of its targeted emissions reduction by 2050 at a cost of less than \$100/tCO_2 (Xu et al. 2017). In BC, improved utilization of harvests (including harvest of pine beetle killed timber), greater production of long-lived wood products, and use of logging residues for bioenergy are needed to achieve these mitigation goals. Missing from these large-landscape scale

[1] Concrete requires five times and steel 24 times more energy to produce than an equivalent amount of sawn softwood. Wood is also five times more insulating than concrete and 350 times more than steel.

studies are the economic incentives that landowners, logging companies and wood processors require to implement the needed activities. Importantly, the incentives must also include the carbon accounting rules – particularly substitution rates for emissions avoided and how carbon fluxes are to be weighted over time.

Economic agents need to know how many carbon offset credits they can expect to earn or be required to purchase as a result of the decisions they make regarding harvest utilization and logging methods (size of trees, residuals), transportation (roadside waste), processing (products to produce), and regeneration, among others. Subject to technical and institutional constraints, price signals determine how much timber a rights holder will harvest and how much lumber, plywood, wood chips, et cetera, are produced. Whether through the issuance of carbon offset credits for sale in carbon markets or through a tax/subsidy scheme, the introduction of carbon prices signals agents to alter their harvesting practices, choice of product mix, and overall use of wood fiber to take into account carbon flux. However, agents need to know the carbon credits they will receive at each stage. They need to know whether and how many offsets they will earn when wood substitutes for fossil fuels in electricity generation, or when wood substitutes for concrete and cement in construction. They need to know how much carbon is credited to their account in each period if trees are left unharvested, or if they plant faster-growing trees. That is, economic agents need to know the rules of the game, and that may require the use of models to establish the carbon fluxes related to various forestry activities.

The length of time that incremental carbon is stored in forest ecosystems, product pools or in the atmosphere may be on the order of decades. As noted, release of CO_2 to the atmosphere contributes to climate forcing, while removals do the opposite. Thus, if there is some urgency to remove CO_2 from the atmosphere to avoid climate forcing, the timing of emissions and removals of carbon are important, with current emissions and removals from the atmosphere more important than later ones (e.g., see Helin et al. 2013, p.476). This is a policy decision and implies that carbon fluxes need to be weighted as to when they occur, with future fluxes discounted relative to current ones (Richards 1997; Schlamadinger and Marland 1999).

The weights used to discount carbon fluxes can be thought of as discount rates that can be used to put into practice the urgency of policy to address climate change (Johnston and van Kooten 2015). If global warming is not considered a problem, the economist might use a zero discount rate, in which case it really does not matter if biomass growth removes CO_2 from the atmosphere

today or sometime in the future – it only matters that the CO_2 is eventually removed. If, on the other hand, global warming is an urgent problem, we would want to weight current reductions in emissions and removals of CO_2 from the atmosphere much higher than those in future years. This is the same as discounting future uptake of CO_2, with higher discount rates suggesting greater urgency in dealing with global warming. In the next section, we develop a model of the Quesnel TSA in the interior of British Columbia. A key component of the model is how we apply the concept of urgency to various carbon sinks.

3. MANAGING FOR CARBON: FOREST MANAGEMENT MODEL OF QUESNEL TSA

In this section, we employ the same holistic approach used by the CFS. We examine forest conservation that prevents emissions of CO_2, the use of residual wood for energy and engineered wood products, and the processing of wood into long-lived products. Unlike these studies, however, we employ economic incentives to implement forest management activities that sequester carbon and the rules regarding how much carbon can be credited. We also addition to wood for energy and we also consider activities that cause carbon to enter various forest ecosystem and post-harvest wood product pools.

In this section, we develop a forest management model that employs the same holistic approach used by Lemprière et al. (2017) and Xu et al. (2017), but unlike them employs economic incentives to implement such forest management. The application is to the Quesnel Timber Supply Area in the interior of British Columbia.

3.1 Forest Management Model

Following van Kooten et al. (2015), let $x_{s,a,z,m,t}$ denote the hectares of timber species s of age a in zone z that are harvested in period t and managed according to regime m, which refers in this case to the type of post-harvest silviculture (basic or enhanced regeneration). Let $v_{s,a,z,m,t}$ be the associated total merchantable volume (m^3/ha) of the stand at time t that is to be converted to lumber, wood chips (used in pulp mills or the manufacture of OSB, MDF, etc.), or for production of energy; and assume the stand's initial volume is given by $v_{s,a,z,m,0}$. Then we define total harvest in period t as follows:

(2) $$H_t = \sum_{s=1}^{S}\sum_{a=1}^{A}\sum_{z=1}^{Z}\sum_{m=1}^{M} v_{s,a,z,t} x_{s,a,z,t}, \forall t,$$

where S is the total number of tree species,[2] A the number of age classes, Z the number of zones and M the management regimes. Zones constitute a combination of eight bio-geoclimatic sub-zones and 17 slope categories, so there are effectively 136 different forest land types in the model. The time horizon is 200 years divided into decades, while age classes begin as 'bare' (recently harvested) and increase by decadal increments to old-growth (≥200 years). Finally, the landowner decides when to harvest trees, which land types to harvest, and how much to harvest; following harvest, she must determine whether basic or enhanced silviculture is employed, where the latter employs genetically-improved species of the same mix as that of the harvested sites.

We define the total costs (K_t) in period t as:

(3) $$K_t = K_t^{log} + K_t^{haul} + K_t^{silv} + K_t^{admin} + K_t^{proc}.$$

K_t^{log} are logging costs (\$/m^3) that vary by the size of trees; $K_t^{haul} = c^{truck} \times H_t$ are trucking costs (\$/m^3) that vary with harvest levels H_t (although an average constant haul distance and truck speed is applied for convenience); K_t^{silv} are regeneration costs (\$/ha) that vary according to biogeoclimatic zone and whether regeneration is basic or enhanced; and K_t^{admin} are administrative and development costs (\$/ha) that are assumed to be constant. Processing or manufacturing costs K_t^{proc} relate to sawmilling and production of engineered wood products.

Assuming that timber throughout the Quesnel TSA is relatively homogenous, the same proportion ε_1 of all the harvested timber is converted to lumber, a proportion ε_2 is sold as chips and a proportion ε_3 is used to generate electricity or for space heating, while the remainder is left to decay at the harvest site. The price of chips is the same regardless of how chips are used. Let p_{lum}, p_{chip} and p_{fuel} be the respective fixed prices of lumber, chips and bioenergy fiber.

Finally, we need to account for carbon. First, assume that, since the price of fuel is fixed in the analysis as is the efficiency of equipment, CO_2 emissions (E_t) are fixed proportions of the logging, hauling and silvicultural costs. In addition, there are costs associated with processing logs into products. Thus, CO_2 emissions are derived as follows:

[2] Each site is classified by a dominant and a secondary species. There are 11 species, of which seven are considered dominant and 10 secondary (some dominant species may be secondary species on other sites).

(4) $$E_t = e_1\ c_t^{log} + e_2\ c_t^{\text{haul}} + e_3\ c_t^{\text{silv}} + e_4\ c_t^{\text{proc}},\ \forall t,$$

where e_1, e_2, e_3 and e_4 are parameters that, respectively, convert the costs associated with logging, hauling, silvicultural and manufacturing/processing activities into CO_2 emissions.

Following Malmsheimer et al. (2011), we determine the amount of carbon that is sequestered in each period in the above-ground biomass (leaves, branches, litter) and soil organic matter. We denote the total carbon stored in the ecosystem at any given time, as measured in terms of CO_2, by C_t^{eco}. The ecosystem carbon fluxes are calculated using the Canadian Forest Service's Carbon Budget Model (Kull et al. 2011).

We measure the CO_2 that is not emitted immediately at harvest time but is slowly released over many decades as post-harvest wood decays as if it were released at the time of harvest. This is done by determining the carbon flux in each future period after harvest, applying a weight (discount factor), denoted r_c, to the CO_2 flux in each of those periods, and aggregating the infinite sum. This weighted sum can then be credited at the time of harvest – the physical stream of carbon flux is discounted to the time of harvest. If the price of carbon is non-zero, the CO_2 emitted or accumulated at time of harvest, say t, is then multiplied by the price of carbon and, since the landowner receives payment (for uptake) or pays a penalty (for emissions) at time t, discounted to the present at the financial rate of discount. The weighted current carbon released from and stored in a post-harvest wood product pool is given by (see Appendix for a proof):

(5) $$V_{Crelease} = \left(\frac{d}{r_c + d}\right)\varepsilon\, C \text{ and } V_{Cstored} = \left(\frac{r_c}{r_c + d}\right)\varepsilon\, C,$$

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

We consider the carbon stored in three product pools – (i) lumber; (ii) pulp and engineered wood products made from wood chips; and (iii) logging, sawmill and other residues that are used to

produce bioenergy (e.g., wood pellets for power generation, biomass for heating).[3] In addition, the carbon stored in dead organic matter and material left at roadside is treated separately as is the carbon in living matter (which does not decay). Denote the rates of decay for each of the three product pools and the dead organic matter pool by d_1, d_2, d_3 and d_4, respectively, and assume that decay begins at the time of harvest. Then, from equation (5), the amount of carbon stored in the three pools as a result of harvest H_t is given as follows:

$$(6)\quad C_t^{product} = \varphi \sum_i \frac{r_c}{r_c + d_i} \varepsilon_i H_t,\ i \in \{\text{lumber, chips, residuals/waste}\},$$

where parameter φ (= 44/12) converts carbon to CO_2. Notice that C_t refers to the net CO_2 removed from the atmosphere at time t after taking into account future emissions from decay.

Lastly, we consider the avoided fossil fuel emissions when wood products substitute for non-wood products (viz., aluminum studs, concrete) in construction (Hennigar et al. 2008):

$$(7)\quad C_t^{ff} = \varphi\, \xi\, \varepsilon_1\, H_t\,,$$

where ξ is a parameter denoting the emissions avoided when wood substitutes for other products. Total carbon removed from the atmosphere at any time is then given by the sum:

$$(8)\quad C_t = C_t^{eco} + C_t^{product} + C_t^{ff}.$$

The constrained optimization problem can now be formulated as a linear programming model with the following objective:

$$(9)\quad \text{NPV} = \sum_{t=1}^{T} \beta^t \left[\left(\sum_{i=1}^{N} p_i \varepsilon_i \right) H_t - K_t - p_C \left(E_t - C_t - S_t \right) \right],$$

where p_C refers to the price of carbon (\$/tCO_2), p_i to the price of forest product i, ε_i is the proportion of the harvest processed into product i, and $\beta = 1/(1+r)$ is the discount factor, with r the discount rate on monetary values. For simplicity and given fixed product prices and proportions ε_i, we assume that the price of logs (\$/m^3) (= $p_{lum}\, \varepsilon_{\text{lum}} + p_{chip}\, \varepsilon_{\text{chip}} + p_{fuel}\, \varepsilon_{\text{fuel}}$) is the value of interest in the objective function (9). Finally, S_t refers to the CO_2 emissions avoided because of the reduced production of cement and steel if wood substitutes for these materials in

[3] Sawmill residues are often burned on site (at a mill) to reduce energy costs.

construction, or if wood biomass substitutes for fossil fuels in the generation of electricity.

Objective function (9) is maximized subject to equations (2), (3), (4) and (8), which define H_t, K_t, E_t and C_t, respectively, plus a variety of technical constraints. The latter relate to the limits on harvest imposed by the available inventory in any period as determined by tree species, bio-geoclimatic zones, slope and age characteristics; a total area constraint; growth from one period to the next (which is affected by management practices); reforestation (management) options; limits on the minimal merchantable volume that must stocked before harvest can occur; sustainability constraints (viz., sustainable management certification standards); non-negativity constraints; and other constraints relating to the specific scenarios that are investigated (including avoided emissions related to substitution of wood for non-wood in construction and wood biomass for fossil fuels in energy). The constrained optimization model is constructed in GAMS (General Algebraic Modeling System) and solved using the CPLEX solver (Rosenthal 2008).

3.2 Study Area and Data Description

British Columbia is Canada's most important timber producing province with 95 million ha of forestland, constituting of 27.3% of the nation's total forest area, a harvest of 66.5 million m^3 (2014), or 43.4% of Canada's total harvest, and exports of more than $10.8 billion, or 50.4% of the nation's total forest product exports (Natural Resources Canada–Canadian Forest Service 2016). The Quesnel TSA is located in the Northern Cariboo Forest Region in the Southern Interior of BC and covers some 1.4 million ha, of which 965,700 ha are in the harvest land base, consisting of Lodgepole pine (85%), spruce (10%) and Douglas-fir (3%) with the remainder consisting of hemlock, balsam and deciduous species (Snetsinger 2011).

In this study, we distinguish forest sites in the Quesnel TSA according to the following characteristics: bio-geoclimatic zones (2)[4] and subzones (4), slope classes (17), major species (7), secondary species (10), and age class (21). While this potentially gives nearly 200,000 combinations of site possibilities, species other than pine and spruce rarely occur as major or secondary species, so three hardwood species (Aspen and two types of Birch) were classified together as were the two remaining softwoods (Douglas fir and Balsam). To keep the model

[4] The two main zones are Montane Spruce (MS) and Sub-Boreal Pine Spruce (SBPS), with costs of regeneration higher in MS (https://www.for.gov.bc.ca/hfd/library/documents/treebook/biogeo/biogeo.htm [accessed January 10, 2017]).

manageable, we used GIS data for Quesnel TSA to identify 538 sites, although the proportions of major and secondary species were not available from the GIS data. We then varied the percentages of major and secondary species, and used the TIPSY model[5] to estimate growth and yield for a period of 200 years (using a decadal time step) and for two treatments after harvest – stands managed intensively after harvest (with 1,200 genetically-improved stems planted per ha over a two-year period) and stands managed extensively (basic silviculture with 600 stems/ha planted within six years of harvest).[6] In this way, the 538 sites were expanded into 6,205 stands covering an area of 20,266.4 ha.

The Carbon Budget Model CBM-CFS3 is a landscape-level model of forest ecosystem carbon dynamics that can be used to assess the carbon stocks and changes in carbon stocks in a forest ecosystem as trees grow (Kull et al. 2011). The carbon fluxes in living biomass and dead biomass generated by the CBM-CFS3 model were used to ascertain this component of the overall carbon budget.

The costs of converting standing trees into lumber, sawmill residues and chips is the sum of the harvesting costs, road and infrastructure costs, transportation costs, manufacturing costs, and costs of post-harvest treatment of the site (basic versus enhanced silvicultural treatment). These are also available from TIPSY and are summarized in Table 1. Average lumber prices have varied from a low of \$70/m^3 in 2009 to more than \$170/m^3 before the recession and about \$160/m^3 in 2015. The price of engineered wood products is assumed to be \$200/m^3. It is assumed that the only processing costs relate to sawmilling and the production of engineered products such as CLT; these costs are provided in Table 1. Sawmilling leads to the production of lumber and sawmilling residuals that can be used to produce chips or biomass fuel, as discussed below.

[5] TIPSY (Table Interpolation Program for Stand Yields) is a growth and yield model developed by the BC Ministry of Forests that provides yield tables for stands under different management regimes using TASS (Tree and Stand Simulator) and economic data using SYLVER (Silviculture on Yield, Lumber Value, and Economic Return) (BC Ministry of Forests, Lands and Natural Resource Operations 2016).

[6] From TIPSY, younger stands under age 60 consisted primarily of pine or spruce as the primary species with a hardwood species as secondary. This is indicative of harvested stands planted to either pine or spruce with hardwoods subsequently invading, as expected since hardwoods are generally the first species to re-populate a stand.

Table 1: Price, Cost, Harvest and Other Parameters, Quesnel TSA[a]

General parameters		**Transportation**	
Monetary discount	2.5%	Fixed costs ($/ha)	295.0
Carbon discount	varies	Hauling ($/m^3 per cycle hour)	6.67
Price lumber ($/m^3)	160.0	Hauling distance (km)	150
Price engineered products ($/m^3)	200.0	Speed of trucks (km/hour)	50
Price chips ($/m^3)	145.0	**Silviculture regeneration ($/ha)**	
Price of fuel ($/m^3)	155.0	Basic (SBPS, MS)	1000, 1200
		Enhanced (SBPS, MS)	1500, 1800
Logging costs ($/m^3)		**Manufacturing costs ($/m^3)**[b]	
Non-variable:	22.20	Sawmilling per harvested log	72.00
Variable: $2.04 - 0.005V$ if $V < 251$ m^3; $0.79 - 0.001V$ if $V \geq 251$ m^3		Engineered products (over-and-above sawmilling costs)	50.00

[a] Source: Data on prices come from Random Lengths (2016). Cost data come from Wiltshire and Associates Forestry (2014); Renzie and Han (2002, 2008); and TIPSY model (BC Ministry of Forests, Lands & Natural Resource Operations 2016). Data on conversion factors are from http://www.globalwood.org/tech/tech_wood_weights.htm [accessed November 21, 2016].
[b] Milling costs are $335 per thousand board feet (mbf). Log cost ($/m^3) = [lumber recovery (215 bf/m^3)] × $0.335/bf =$72.00/m^3. Costs for engineered wood products from chips are over and above sawmilling costs.

Wholesale electricity price data are available only for the province of Alberta. Electricity in Alberta traded for an average price of $49.50/MWh in 2014; because biomass is a renewable energy source and often granted implicit or explicit subsidies, we assume the BC producer would receive a subsidized price of $75/MWh, which translates into a price for wood residues for fuel of about $155/m^3.[7] The price of wood chips is simply assumed to be $145/m^3.[8] Prices used in the study are also given in Table 1.

[7] Conversions: 1 megawatt hour (MWh) = 3.6 giga joules (GJ = 10^{12} J) of energy. There are 1.86 m^3 per bone dry tonne (BDt) of wood, with a calorific value of about 21 GJ (Fonseca 2012). Thus, each m^3 of timber has a heat value of 11.3 GJ, and can produce 3.14 MWh of power. Adjusting for the moisture content of harvested timber leads to only 2.1 MWh of electricity per m^3 of green timber, or a value of about $155/m^3 if the price is $75/MWh. Note that Xu et al. (2017) employ a "generic electricity price" of $120/MWh.
[8] Wood chips for delivery in the U.S. have recently varied in price from US$110 to over $150/BDt. With an exchange rate of 1.35C/US and 1.86 m^3/BDt, the price might be $C110/m^3. We assume a higher Canadian price as chips could be used for bioenergy.

Given the study region already includes logging roads and other infrastructure as the area has been harvested in the past, fixed costs are lower than might be the case in other mountainous regions. Transportation costs vary with distance, while post-harvest treatment costs vary by bio-geoclimatic zone and type of silviculture. The information on these costs is provided in Table 1.

A typical distribution of lumber and residues in the lumber manufacturing process is available for the BC Interior from the annual mill survey (BC Ministry of Forests, Lands and Natural Resource Operations, hereafter MFLNRO, 2015). In 2014, the Interior harvest was 48,074,000 m^3, with 39,531,000 m^3 (82.2%) processed by lumber mills and 4,343,000 m^3 (9.0%) by veneer and OSB mills; the remainder went directly to pulp mills for chipping (1.3%), chip and other mills (5.1%), and log exports (2.4%, 1.15 million m^3). Of the log volume allocated to lumber mills, 44.4% was processed into lumber with 53.4% constituting sawmill residues (sawdust and shavings) and 2.2% shrinkage. Neglecting shrinkage because TIPSY output is assumed to account for shrinkage and assuming no log exports, the log harvest is adjusted to 46,924,000 m^3, which is then allocated as indicated in Table 2. Sawdust is primarily used as fuel, burned on site to generate heat or electricity, or made into wood pellets although chips can also be used. Chips are used to make pulp, produce OSB, MDF and other engineered wood products, or manufacture wood pellets to generate electricity; sawdust can also be used for some of these purposes as well.

Table 2: Disposition of Harvested Logs: Production of Lumber, Sawmill Residues and Other Products, BC Interior, 2014[a]

Category of Use and Sub-category	Volume ('000s m^3)	Proportion of Harvest (%)[b]	Within Category (%)
Lumber	*18,174.6*	*38.7*	
Sawmill residues	*21,335.4*	*45.5*	
• *Sawdust*	12,161.2	25.9	57.0
• *Chips*	9,174.2	19.6	43.0
Other products	*7,414.0*	*15.8*	
• *Engineered wood products*	4,343.0	9.3	58.6
• *Chipped in pulp mills*	620.0	1.3	8.4
• *Other chips from whole logs*	2,451.0	5.2	33.1
Logging residues & roadside waste[c]	*0*	n.a.	
Total Harvest	**46,924.0**		

[a] Data from annual mill report for 2014 (MFLNRO 2015), adjusted to remove shrinkage and log exports.
[b] Numbers may not add to 100% due to rounding.
[c] Logging residuals are left in the forest and as are roadside wastes, which result from trimming logs to fit trucks optimally. These are too costly to remove (Stennes et al. 2010).

As indicated in Table 2, lumber is the most valuable wood product, and sawmill residues are the most important source of fiber for pulp mills, engineered wood manufacturers and bioenergy producers (wood pellets). Since lumber recovery from harvested logs varies by species, age and site characteristics, the TIPSY model is used to obtain the volumes of lumber, sawmill residues, and other residuals, all measured in m^3, for each of these characteristics. Since TIPSY provides lumber volume in thousands of board feet (mbf), the board feet measure is converted to m^3 using the average conversion factor of 1.61 m^3/mbf available from the latest survey of mills (MFLNRO 2015). As a check, the TIPSY data for Quesnel, the observed conversion factor from the mill survey and a minimal harvest of 80 m^3/ha are used to find that 36.7% of the timber harvest in our data set would be processed into lumber; this compares favorably to the Interior average of 36.5% reported in the 2014 mill survey.

We construct a base case scenario from the mill survey information and the above allocation of fiber for the BC interior. Assuming 2.183 m^3 of wood is required to produce one bone dry unit (BDU) of fiber (Fonseca 2012), and using data from the mill survey, pulp mills in the Interior consumed 9.18 million BDU, or 20.038 million m^3, of wood fiber. Pellet plants consumed 2.0 million BDUs, or 4.366 million m^3 of fiber. This implies that pulp mills and pellet plants

respectively consumed 69.7% and 15.2% of the total available residual fiber in the Interior (28,749,400 m^3), with engineered wood manufacturers employing the remaining 15.1%. Thus, in our model, we allocate 42.7% of available timber to pulp production, with the remainder allocated to lumber (38.7%), wood pellets (9.3%) and other wood products (9.3%); the latter and lumber are employed in construction, with lumber potentially used to produce CLT.

The amount of CO_2 released when producing a megawatt hour (MWh) of electricity varies by fuel type. Natural gas releases about 0.55 tCO_2/MWh of power, while coal releases about 0.94 tCO_2/MWh. Burning wood biomass provides 6.6 GJ of heat per m^3 if the moisture content is 40% (Kofman 2010), which translates into 1.83 MWh/m^3. Thus, the burning wood in lieu of natural gas would save 1.01 tCO_2/m^3 (=0.55 tCO_2/MWh × 1.83 MWh/m^3), while it would save 1.72 tCO_2/m^3 if bioenergy replaced coal. Assuming wood burning is carbon neutral, emission reductions from burning wood in lieu of a 50-50 mix of natural gas and coal to generate electricity amount to 1.365 tCO_2/m^3.

Other parameters include decay rates for organic matter left on the ground after harvest and the various post-harvest carbon pools, plus financial discount rates, costs of harvesting, gathering and hauling biomass to downstream facilities, and costs of processing and manufacturing, and rates of CO_2 emissions at each stage of the stump-to-products process. The CO_2 emission rates and decay rates for various components of the forest ecosystem and product pools used in this study are provided in Table 3.

Table 3: Rates of CO_2 emissions and decay rates for various forest carbon pools

Carbon emissions	Value	Item	Value
Activity (tCO_2/m^3)		**Decay rate of:**	
Harvesting (tCO_2/m^3)	0.01173	Dead organic matter	0.0718
Trucking (tCO_2/m^3)	0.000078	Softwood lumber	0.0082
Production of:		Engineered wood products	0.0080
Sawlogs (tCO_2/m^3)	0.0293	Chips and pulp wood	0.0234
Engineered wood (tCO_2/m^3)	0.0660	Fuel[b]	1.0
Pulp wood (tCO_2/m^3)[a]	0.1000	Biofuel[b]	0.7

[a] Average of mechanical and chemical pulp.
[b] Decay rates for fuel and biofuel indicate that, respectively, 100% and 70% of the CO_2 is emitted in the first year after harvest.
Source: Healy et al. (2009)

3.3 Managing for Carbon

Economic incentives are the best way to encourage public and private forestland owners, loggers and wood processors to consider the climate impacts of forest management decisions. With appropriate incentives, forests could be left unmanaged or managed for their commercial plus carbon benefits. This requires carbon prices. With carbon offset trading, economics agents can be required to purchase carbon offsets for emissions to the atmosphere while they receive carbon credits for sale in the carbon market for CO_2 sequestered in ecosystem sinks, growing vegetation or product pools. For example, carbon credits can be issued for carbon entering wood product pools and these can be used to offset emissions from fossil fuels used in logging. Lumber and engineered wood products are the most important product pools, because technological advances in engineered products have led to the construction of state-of-the-art multipurpose and multi-story wood buildings that are now less vulnerable to fire and pests, and require less energy to heat or cool thereby further reducing CO_2 emissions (Green and Karsh 2012).

To overcome issues related to measurement and monitoring, carbon offset credits/debits can be based on an agreed upon forest management (growth and yield) model and observed changes in land use (van Kooten 2009). The forest management model would specify the annual carbon uptake in the various components of the forest ecosystem from the time trees are planted until they are harvested, if at all. Each year, the landowner would receive a credit for the carbon removed from the atmosphere, which would depend on site characteristics and pre-specified rates of tree growth and ecosystem carbon fluxes. At the time of harvest, the owner would purchase offsets based on the amount of CO_2 released from decaying residues left on the site, decaying residues resulting from processing and manufacturing, and decaying short- and long-lived products. It will, however, be necessary to determine how much roundwood and other biomass is harvested and how this wood is utilized. Decay rates for each carbon pool can be established a priori and the carbon fluxes resulting over infinite time can be discounted to the present (using equation 5) to determine the credits to be purchased to cover emissions at the time of harvest.

It is also possible to specify and provide credits for the CO_2 emissions avoided when biomass is burned in lieu of fossil fuels or the emissions avoided from producing non-wood materials when wood is substituted for steel or concrete in construction, or even the emissions avoided when

heating wood buildings as opposed to concrete and steel ones. These are more controversial aspects of a forest carbon uptake scheme because it could result in double counting. For example, when biomass substitutes for fossil fuels in generation of electricity, the utility is no longer charged for the emissions associated with the burning of fossil fuels, which is a benefit counted outside forestry. The same is true of the emissions saved from not producing steel and cement when wood substitutes for non-wood materials in construction. In that case, the only carbon savings that can be credited occur because carbon is stored in a product pool. Nonetheless, if CO_2 emissions avoided are credited when bioenergy is burned instead of fossil fuels, then it is just as appropriate to credit the fossil fuel emissions avoided when wood substitutes for non-wood materials in construction (and fossil fuel emissions avoided when less energy is required to heat or cool wood buildings as opposed to concrete and steel ones).

4. MANAGING FOR CARBON: RESULTS

Carbon flux outcomes depend on the management regime chosen, which, in turn, depends on the price of carbon, biophysical constraints and sustainability requirements. Outcomes also depend on the weight attached to future carbon fluxes – that is, on the perceived urgency of addressing climate change. Finally, the carbon flux is impacted by the extent to which wood substitutes for non-wood in construction and the accreditation of CO_2-emission reductions, and the emissions savings when wood biomass is burned to produce energy in lieu of fossil fuels. In this section, we use the model developed in the previous section to examine various scenarios based on the following three management regimes:

1. No harvest (NF) or forest conservation – not harvesting the forest whatsoever;
2. Even-flow management (EF) – harvests in any decade cannot vary by more than 10% from the endogenously determined harvest in the first decade; and
3. Commercial management (CM) – harvest is unconstrained except that areas harvested must be regenerated using basic or enhanced silviculture (as is the case under even-flow management), with only product and carbon prices as incentives.

For each management regime, we consider carbon prices of \$0 and \$50 per tCO_2,[9] and carbon discount rates of 0%, 1.5% and 15.0%, which represent 'no urgency', 'some urgency' and 'great urgency' in mitigating climate change. In addition, we examine three cases that include reduced

[9] The social cost (price) of carbon used by the U.S. EPA is approximately \$37/tCO_2, but there remain questions about its meaning (see Pindyck 2015; Dayaratna et al. 2016).

emissions from substituting biomass for fuel in generating electricity (Table 4); in two of these we assume a low ability to substitute wood products for non-wood in construction (lo sub) and one where substitution is high (hi sub). In the latter case, we implicitly count the saved emissions from not producing steel or concrete. Even so, substitution rates of 0.25 tCO_2 per m^3 (lo) and 2.5 tCO_2/m^3 (hi) are well below the 3.3 tCO_2/m^3 found by Hennigar et al. (2008).[10]

The results for nine scenarios are provided in Figures 1 and 2 and Table 4. The total net (discounted) carbon produced by each scenario is provided in Figure 1. If climate change is considered an urgent policy issue, future carbon fluxes are discounted at 15%; then forestry activities in the BC interior are capable of doing little to mitigate climate change. Forest conservation essentially continues to store the carbon already in the ecosystem and future contributions to ecosystem carbon are too distant to be considered, while total carbon attributable to even-flow or commercial management is essentially zero because the CO_2 emissions released early on as a result of logging, transportation and processing offset the future carbon sequestered by fast-growing (young) trees or stored in products.

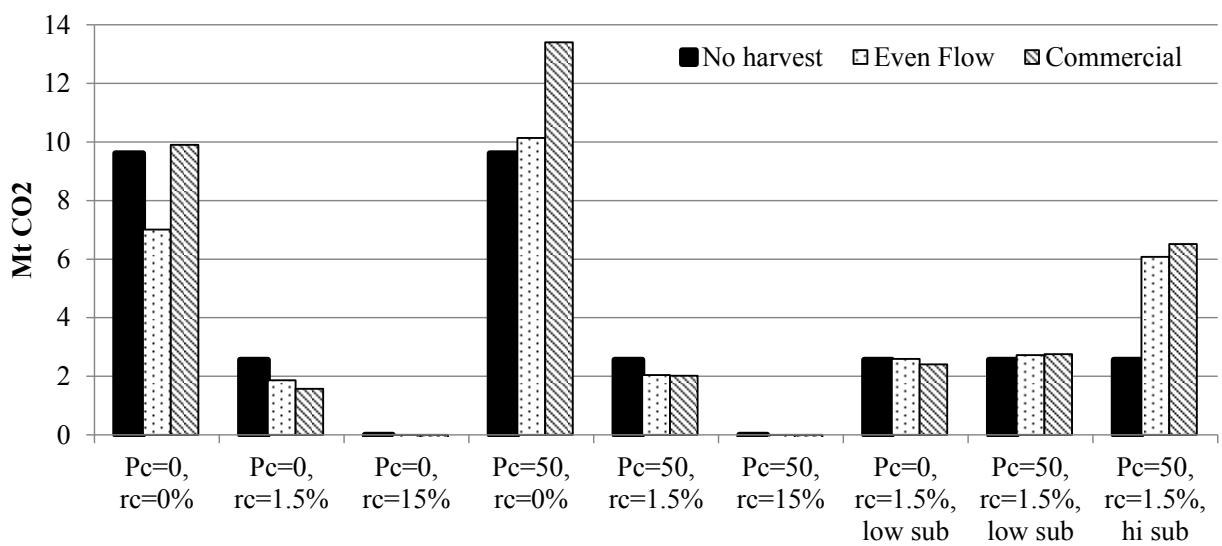

Figure 1: Number of carbon offsets created under various scenarios (Mt CO_2)

At low carbon discount rates, the benefit of one management regime over another depends on

[10] Xu et al. (2017) and Lemprière et al. (2017) refer to substitution as displacement, measuring it as tC saved per tC in wood products; they use values of 2.1 for sawnwood and 2.2 for wood panels. Assuming 0.32 tC per m^3 of sawnwood (=0.2 tC/m^3 green timber × 1.6 m^3 green timber/m^3 lumber), this implies that these authors use rates of 2.46-2.58 tCO_2/m^3.

carbon prices and the degree to which one counts carbon emissions avoided because wood substitutes for carbon-intensive products in construction or bioenergy for fossil fuels in production of electricity. To determine the carbon offset credits that might be awarded will depend on the baseline management regime that is chosen since offsets are counted against the baseline. It is clear from Figure 1 that the choice of a baseline scenario is crucial to the determination of the carbon offsets. The most carbon credits that might be generated by the forest strategies in this study are unlikely to exceed 4 Mt CO_2, and this would entail a switch from NH to CM (last scenario in Figure 1). This translates into a net discounted overall carbon benefit of less than 200 tCO_2 per hectare. What might be the associated cost of sequestering carbon?

If future carbon fluxes are not discounted then commercial exploitation is always preferred to forest conservation (NH) and EF management (Table 4), although NH is preferred to EF if carbon is unpriced. Because the value \$43.36/tCO_2 in Table 4 is in parentheses, it represents the implicit cost of sequestering carbon in going from EF to NH, with a management shift in the opposite direction (NH to EF) leading to an increase in atmospheric CO_2, *ceteris paribus*. When future carbon fluxes are discounted, conservation is always preferred to EF and CM, with EF also preferred to CM, regardless of the carbon price. The reason is that early emissions of CO_2 associated with logging, transportation and processing under CM exceed the discounted future carbon storage benefits.

The balance sheet changes dramatically, however, when carbon is priced and one attributes saved CO_2 emissions in other sectors to forestry. In particular, CM is the preferred management regime followed by EF if one credits emissions avoided in the production of concrete and steel when wood substitutes for non-wood in construction (0.25 to 2.5 tCO_2/m^3) plus emissions avoided when wood substitutes for fossil fuels in electricity production (1.365 tCO_2/m^3). Indeed, the costs of mitigating climate change in BC's interior quite reasonable for a carbon price of \$50/tCO_2 and carbon discount rates of 0% (fourth row in Table 4) and 1.5% in the 'hi sub' scenario (last row in Table 4). The costs could be even lower if the higher substitution values (>3.0 tCO_2/m^3) are employed. These findings support those of Xu et al. (2017) and Lemprière et al. (2017). Of course, they assume wood burning is carbon neutral and that saved greenhouse gas emissions from not producing steel and concrete in construction are attributable only to forestry.

Table 4: Opportunity Cost of Creating Carbon Offset Credits per tCO_2

Scenario[a]	No harvest to even flow NH→EF[b]	No harvest to commercial NH→CM[b]	Even flow to commercial EF→CM[b]
P_c=0, r_c=0%	($43.36)	$531.75	$14.13
P_c=0, r_c=1.5%	($161.07)	($154.47)	($138.76)
P_c=0, r_c=15%	($1,223.56)	($440.81)	($159.33)
P_c=50, r_c=0%	$217.43	$40.71	$12.55
P_c=50, r_c=1.5%	($216.07)	($280.24)	($1,557.60)
P_c=50, r_c=15%	($1,237.75)	($441.91)	($159.22)
P_c=0, r_c=1.5%, lo sub	$4,490.76	($964.39)	($221.47)
P_c=50, r_c=1.5%, lo sub	$732.90	$829.33	$1,302.62
P_c=50, r_c=1.5%, hi sub	$32.27	$39.01	$92.25

[a] Scenarios are described in the text. A 2.5% rate of discount is applied to monetary values.
[b] Values not in parentheses indicate net removal of carbon from the atmosphere in shifting management regimes in the direction indicated, with the value indicating the average cost of doing so; values in parentheses indicate that net removal of carbon from the atmosphere occurs by shifting management regimes in a direction opposite of that indicated, with the value providing the cost of mitigating climate change.

Decision makers are generally not interested in total discounted net carbon due to forestry activities because carbon uptake occurs far in the future. Rather, they are likely more interested in carbon fluxes at various times, particularly in the next decade or two. This is provided for selected scenarios (with r_c = 1.5% and p_c = \$50/tCO_2) in Figure 2. Commercial forestry results in negative carbon uptake in the first decade as a result of high rates of harvest as the forest owner seeks to liquidate some of the timber and convert the forestland to fast growing trees (using enhanced silviculture). Only when the substitution of wood for non-wood in construction is credited at 2.5 tCO_2/m^3 does CM lead to a high rate of carbon flux in the first decade, only to decline substantially as harvest levels in subsequent decades decline. Indeed, with the exception of the CM and EF scenarios where wood for non-wood substitution receives a high credit, NH leads to higher carbon uptake in the first four decades. It is not surprising, therefore, that the decision maker might well favor forest conservation, despite recommendations to the contrary (Xu et al. 2017; Lemprière et al. 2017).

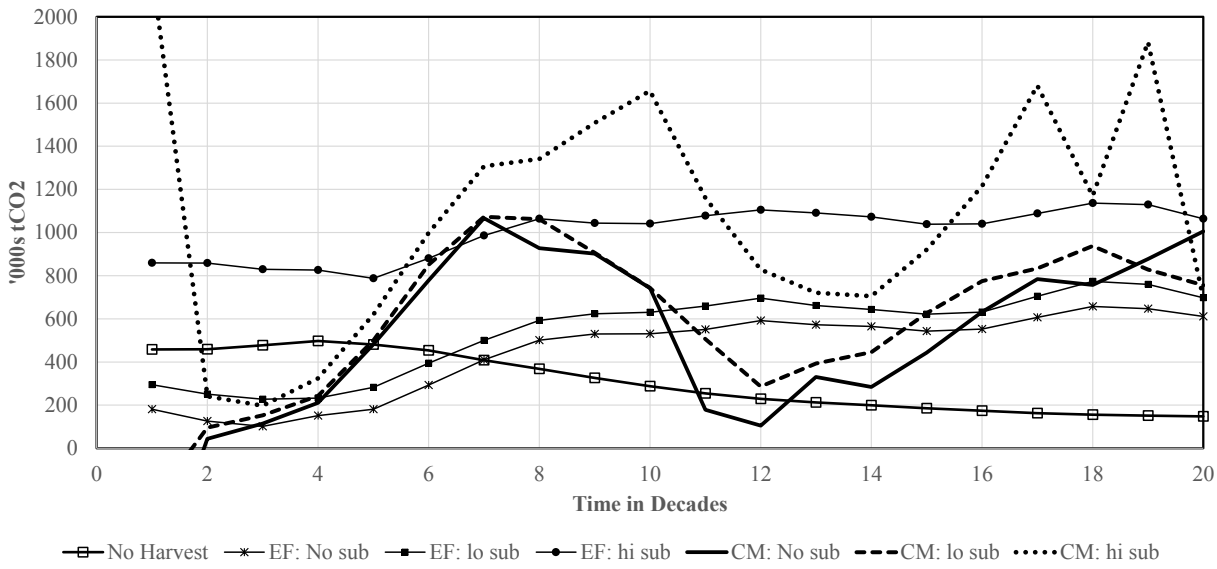

Figure 2: Discounted CO_2 uptake per decade for non-harvested, even-flow and commercially managed forests; 1.5% carbon discount rate; 2.5% monetary discount rate; carbon price = \$50/tCO_2; 1.37 tCO_2/m^3 credit for bioenergy-for-coal substitution; and credits of 0.25 tCO_2/m^3 (lo) and 2.5 tCO_2/m^3 (hi) for reduced emissions elsewhere when wood substitutes for non-wood in construction

There is no reason, however, that a forest of today might not have the characteristics exhibited by our forest in decade seven, say. That is, if the decision maker is faced with a forest structure identical to that which our forest would have in seven decades had EF or CM been employed today, forest conservation is much less attractive than currently. Indeed, with some minor exceptions, NH would be less attractive than both EF and CM. The reason is that, although harvesting today would result in significant current carbon emissions, the regenerated forest would in 70 years sequester substantially more carbon than the original forest because the quality of trees is enhanced and carbon continues to enter carbon pools as a result of harvest.

Accreditation of carbon offsets for the substitution of wood for non-wood in construction and power generation is important for climate change mitigation policy. It causes a commercial operator to create carbon offset credits (i.e., reduce carbon flux), especially early in the time horizon (due to discounting), thereby lowering atmospheric CO_2 to a greater extent than the conservationist. The commercial operator manages the forest to maximize income not only from the commercial sale of forest products but also the revenue from storing carbon in the ecosystem through sequestration and silvicultural management, and from producing long-lived products

such as CLT with the lowest possible rates of decay. If the substitution parameter is sufficiently high, CM will be the preferred strategy for mitigating climate change in all circumstances.

When a forest reaches maturity (after about 15 decades), it sequesters little carbon because biomass decay offsets much or all carbon uptake in new growth (Figure 2). In drier regions, mature forests are susceptible to wildfire, pests and disease that could release large amounts of carbon, as illustrated by the devastation caused by the mountain pine beetle in the BC interior. If the risk of natural denudation is high, and if the carbon released as a result is charged to the forest owner, the decision maker may be much more prone to harvest trees to avoid risk of loss. Therefore, if carbon is priced, the decision maker will harvest a mature forest and store carbon in products while regenerating the site so new growth sequesters carbon at a faster rate than leaving the forest unharvested.

5. CONCLUDING DISCUSSION

There are many ways in which forestry activities can mitigate climate change, but some are more effective than others, some preclude others, and some are less cost-effective than others. Perhaps not unexpectedly, some forestry activities actually contribute to global warming when compared to a baseline scenario. When two or more forest management options are compared to each other, assumptions regarding the accreditation of carbon fluxes, whether to count emissions saved when wood substitutes for non-wood in construction and/or power generation and to what extent, will determine which forest management strategy will make a contribution to climate mitigation efforts. The strategy that leads to the greatest climate benefit is also impacted by the perceived urgency of taking action to mitigate climate change, which affects the weighting of future carbon fluxes. The conclusion from this study is that the decision about which forestry activities generate carbon offset credits and how many is essentially a political one and not a scientific one. Although constrained by the biophysical realities of timber growth, forest ecosystem dynamics and processing technologies, the analyst has sufficient room to demonstrate that any forest management regime, whether forest conservation, even-flow management, commercial exploitation or some mix of strategies, is preferred to another for mitigating climate change.

Some more specific conclusions related to the role of forests in mitigating climate change also

follow from the research reported here. First, it is not clear that forests should ever be conserved in perpetuity, partly because of their eventual susceptibility to natural disturbance (e.g., wildfire) and partly because carbon gets stored in post-harvest products (Xu et al. 2017). For many of the scenarios considered in this study, commercial exploitation can bring about more carbon offsets than leaving forests unharvested, because of carbon benefits from substituting wood for non-wood in construction and bioenergy production that are over and above those related to carbon storage in products. Forest conservation might be a good strategy in the short run if the forests are not at full maturity, but is unlikely a long-run option because harvest activities store carbon in wood products while regenerated forests grow more rapidly than mature ones, and growth can even be enhanced by planting higher quality seedlings.

Second, wood burning is not carbon neutral if there is urgency to address climate change. Wood burning is carbon neutral if future carbon is not discounted (r_c=0%), but then so is coal burning (Johnston and van Kooten 2015). Third, counting CO_2 emissions avoided when wood burning substitutes for fossil fuels results in offsets ('lo sub' and 'hi sub' scenarios in Figure 1 and Table 4), but this leads to double counting because the electricity entity will count the emissions avoided from not burning coal or gas towards its targets. We find that not counting these emission savings reduces offset credits by 8.3%. Likewise, CO_2 emissions avoided when wood substitutes for non-wood in construction leads to more carbon offset credits, but results in double counting just as with wood burning. Therefore, although carbon stored in wood is properly credited to forestry activities, the carbon credits created because emissions are reduced in another sector should not be attributed to forestry.[11]

Finally, how many carbon offset credits do forestry activities create? Since we need a baseline and then weight credits as to when they occur, forestry activities generally create few offset credits. Indeed, the more urgent policy makers consider climate change to be, the fewer offset credits are realizable because future carbon uptake by forests is counted less today.

While forest ecosystems should be included in efforts to mitigate climate change, it is necessary to incentivize those engaged in forestry activities to take carbon fluxes into account in their decisions. The only viable instruments for doing so are a tax-subsidy scheme or accreditation of

[11] We do recognize that the IPCC has allowed economic entities to count these substitution credits, but this again is a political decision that can be reversed, and not a scientific one.

carbon offsets to be traded in established and mandatory carbon markets. In this regard, it is important to allow for post-harvest use of fiber, especially post-harvest wood product carbon sinks and emissions avoided when wood substitutes for non-wood construction materials. To implement such schemes might require contracts that include a simple forest inventory and yield model, the rate of decay of post-harvest fiber (based on age of harvest and anticipated use of logs by downstream processors), schedules pertaining to the crediting of avoided emissions (where wood is used in lieu of fossil fuels or less concrete and steel is produced), and satellite images of land use and land use changes. The authority or certifier need only confirm land use and how it changes to determine annual subsidies or taxes, or carbon credits for sale or purchase. More research into these types of contracts is required to determine the potential for carbon offsets in compliance and voluntary markets.

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APPENDIX: PROOF OF THE CO_2 MEASURE OF INFINITE RELEASE OF CARBON FROM A POST-HARVEST WOOD CARBON POOL

Let r_c be the rate used to weight (discount) physical carbon, d be the rate at which carbon enters into atmosphere from the decay in the post-harvest carbon pool, and ε is the proportion of carbon that goes into the wood product sink at harvest time. At the time of harvest, how much carbon can we count going into a product sink? After one year, the amount of carbon going into the atmosphere is given by $d \times \varepsilon \times$C, where C is the carbon in harvested timber. In the second year, the amount of carbon going into the atmosphere is given by $d(1-d)\ \varepsilon$ C; in the third year, carbon escaping to the atmosphere because of decay equals $d\ (1-d)^2\ \varepsilon$ C. The stream of carbon entering the atmosphere is given by:

(1) $d\,\varepsilon\,\mathrm{C} + d\,(1-d)\,\varepsilon\,\mathrm{C} + d\,(1-d)^2\,\varepsilon\,\mathrm{C} + \ldots = [1 + (1-d) + (1-d)^2 + (1-d)^3 + \ldots]\ d\,\varepsilon\,\mathrm{C}.$

However, we need to weight the stream of carbon release. So let the stream of carbon release over n periods be:

$$(2)\quad V_n = \frac{d\varepsilon C}{1+r_c} + \frac{d(1-d)\varepsilon C}{(1+r_c)^2} + \frac{d(1-d)^2\varepsilon C}{(1+r_c)^3} + \frac{d(1-d)^3\varepsilon C}{(1+r_c)^4} + \ldots + \frac{d(1-d)^{n-1}\varepsilon C}{(1+r_c)^n}.$$

Multiply both sides by $(1-d)/(1+r_c)$:

$$(3)\quad \frac{1-d}{1+r_c}V_n = \frac{d(1-d)\varepsilon C}{(1+r_c)^2} + \frac{d(1-d)^2\varepsilon C}{(1+r_c)^3} + \frac{d(1-d)^3\varepsilon C}{(1+r_c)^4} + \ldots + \frac{d(1-d)^{n-1}\varepsilon C}{(1+r_c)^n} + \frac{d(1-d)^n\varepsilon C}{(1+r_c)^{n+1}}.$$

Subtract (7) from (6) gives:

$$(4)\quad \frac{r_c+d}{1+r_c}V_n = \frac{d\varepsilon C}{(1+r_c)} - \frac{d(1-d)^n\varepsilon C}{(1+r_c)^{n+1}} = \left(\frac{1}{1+r_c}\right)\left(1-\frac{(1-d)^n}{(1+r_c)^n}\right)d\,\varepsilon\,C.$$

Thus,

$$(5)\quad V_n = \left(\frac{1}{r_c+d}\right)\left(1-\frac{(1-d)^n}{(1+r_c)^n}\right)d\,\varepsilon\,C.$$

Finally, let $n \to \infty$ so that

(6) $V_{Crelease} = \lim_{n \to \infty} V_n = \left(\frac{d}{r_c + d} \right) \varepsilon C$.

Notice that if r_c=0, then all the stored carbon is released. That is, regardless of the decay rate (d), all of the carbon eventually is released from products through decay. Only if d=0, so there is no decay, is the amount of carbon released from products also zero.

Since V is the discounted release of carbon at the time of harvest, the amount stored at time of harvest is given by:

(7) $V_{Cstored} = \varepsilon C - V = \left(1 - \frac{d}{r_c + d} \right) \varepsilon C = \left(\frac{r_c}{r_c + d} \right) \varepsilon C$.

If r_c=0, then no carbon is stored because it is all released (see above). If d=0, then all the carbon is retained regardless of the rate used to weight carbon.