The Economic Challenge of Mitigating Climate Change through Forestry Activities

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Abstract

In this study, 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 CO_2 through forestry activities. A forest management model representative of the southern interior of British Columbia is described. The objective is to maximize net discounted returns to commercial timber operations plus the benefits of managing carbon fluxes. The model tracks carbon in living trees, organic matter, and post-harvest carbon pools. The decision about which forestry activities generate carbon offset credits and how many is essentially a political and not a scientific one.

Keywords: **carbon offsets; bioenergy; forest economics**

1. Introduction

To mitigate the effects of climate change, carbon reducing strategies are increasingly important, including the role of forests in sequestering carbon. One debate about forest management concerns whether to leave forests growing as carbon sinks or 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 retains but does not add to total carbon. Upon harvesting and processing trees, carbon can be stored in long-lived wood products that substitute for steel and cement in construction. Long-lived wood products constitute only a proportion of the timber that is harvested, with logging and sawmill residues used to produce short-lived products, such as pulp and oriented strand board (OSB), that release stored carbon more quickly. Logging and sawmill residues can also be burned to produce electricity, thereby reducing CO_2 emissions from fossil-fuel generating assets.

One controversy concerns whether to count reduced CO_2 emissions 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, 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, 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. We develop a forest management model based on the Quesnel Timber Supply Area (TSA) in the interior of British Columbia. The model maximizes net discounted returns to commercial timber operations plus the benefits of managing carbon fluxes, using a carbon price to incentivize carbon management. We can then identify strategies that sequester the most carbon and associated costs of reducing CO_2 emissions via the different forestry activities.

We employ the existing forest inventory for the Quesnel TSA and the 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. The Carbon Budget

Model CBM-CFS3 is applied to investigate how carbon fluxes vary by ecosystem types, tree species and rates of growth. It is expected that more carbon will be stored in standing forests if the substitution rate of wood products for concrete and cement is low, but more carbon will be stored and saved through harvesting if the substitution rate is high. 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. Nonetheless, 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.

2. Economics 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? To answer this in practice requires that forestry activities be incentivized to mitigate climate change as much as 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).

Scientists favor the use of radiative forcing as the appropriate method for measuring the climate impacts of bioenergy, because "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: 481, emphasis added). The concept of radiative forcing is not useful from a policy perspective, however: "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" (Lemprière et al., 2013: 298, 301).

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 life-cycle analysis (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. Therefore, forests should be managed and harvested for their carbon benefits.

It is not surprising that the CFS scientists find commercial harvesting of trees followed by the processing of timber into various wood products that store carbon, and replanting the harvested areas, is preferred to leaving carbon in unmanaged forests. Indeed, Lemprière et al. (2017) find that

[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.

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 nearly 15% of Canada's annual CO_2-emissions reduction target of 112 Mt CO_2 between 2014 and 2020 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 trees), 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 studies are the economic incentives that landowners, logging companies and wood processors need to bring this about. In particular, economic agents need to know the carbon accounting rules, especially the substitution rates for emissions avoided and weights on future carbon fluxes.

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 (including logging residuals left on site), transportation (roadside waste left behind), processing of fiber into products, 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 also 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 that establish the carbon fluxes associated with various forestry activities.

The length of time that carbon is stored in forest ecosystems, product pools or the atmosphere may be on the order of decades. While the release of CO_2 to the atmosphere contributes to climate forcing, removals do the opposite. Thus, if there is some urgency to remove CO_2 from the atmosphere, the timing of emissions and removals of carbon are important, with current emissions and removals from the atmosphere more important than later ones. 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 global warming is an urgent problem, however, 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 describe the study region and forest management model. A key component of the model is how we apply the concept of urgency to various carbon sinks.

3. Study Area and Model 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 (43.4% of Canada's total), and exports of more than $10.8 billion (50.4% of total forest product exports). The study area is Quesnel TSA, which is located in the Southern Interior, covers 1.4 million ha, of which 70% is in the harvest land base, and consists of pine (85%), spruce (10%) and Douglas-fir (3%) with the remainder hemlock, balsam and deciduous species. Quesnel TSA consists of two bio-geoclimatic zones – Montane Spruce (MS) and Sub-Boreal Pine Spruce (SBPS), with costs of regeneration higher in MS, four subzones, 17 slope classes, seven major tree species, 10 secondary species, and 21 age classes. While this potentially gives 200,000 combinations of site possibilities, species other than pine and spruce rarely occur as major or secondary species; thus, hardwood species were classified together as were the remaining softwoods (mainly Douglas fir and Balsam). To keep the model 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 varied the percentages of major and secondary species based on information for the southern interior, and used the TIPSY model (BC Ministry of Forests, Lands & Natural Resource Operations, hereafter MFLNRO, 2016) to estimate growth and yield for 200 years (using a decadal time step) and for two treatments after harvest – stands planted with genetically-enhanced stems planted over a two-year period or stands planted with natural growing stock (basic silviculture) within six years of harvest. In this way, the 538 sites were expanded into 6,205 stands covering an area of 20,266.4 ha. The Canadian Forest Service's Carbon Budget Model CBM-CFS3 (Kull et al., 2011) was used to track carbon fluxes and stocks in living and dead biomass in the forest ecosystem over time.

The costs of converting standing trees into lumber, sawmill residues and chips are 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 silviculture). These were also available from the TIPSY and are summarized in Table 1. Sawmilling leads to the production of lumber and sawmilling residuals that can be used to produce chips or biomass fuel. Prices used in the study are also given in Table 1, as is information on transportation costs.

A typical distribution of lumber and residues in the lumber manufacturing process is available for the BC interior from the annual mill survey (MFLNRO, 2015). In 2014, the total 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 burned on site to generate heat or electricity or made into wood pellets. Chips are used to make pulp, produce OSB, MDF and other engineered wood products, or manufacture wood pellets to generate electricity.

As indicated in Table 2, lumber is the most valuable wood product, and sawmill residues are the most important source of residues 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 (m^3), and other residuals (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 mill survey (MFLNRO 2015). As a check, a comparison of the TIPSY data for Quesnel used here and the average observed conversion factors for the BC interior from the 2014 mill survey indicates they are almost identical.

We find that pulp mills in the BC interior consumed 20.038 million m^3 of wood fiber, while pellet plants consumed 4.366 million m^3. 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 engineered products (9.3%); engineered products and lumber are employed in construction, with lumber potentially used to produce CLT (longest-lived product).

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. If 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 and product pools used in this study are provided in Table 3.

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. With carbon markets, economic agents can be required to purchase carbon offsets for emissions to the atmosphere and receive carbon credits for sale for CO_2 sequestered in ecosystem sinks, growing vegetation or product pools.

To overcome issues related to measurement and monitoring, carbon offset credits/debits can be based on a forest management (growth and yield) model specified in advance and observed changes in land use. 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 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 to establish how much carbon enters post-harvest pools. Decay rates for each carbon pool can be established a priori and the carbon fluxes resulting over infinite time discounted to the present to determine the credits to be purchased to cover emissions at the time of harvest.

The weighted current carbon released from and stored in a post-harvest wood product pool, or dead wood fiber pool left to decay on site, is given by:

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

where d is the rate at which the wood in the pool decays, r_c is the rate used to discount carbon, C is the carbon going into a post-harvest pool, and ε is the proportion the fiber entering that pool. If d=0 (no decay) then the carbon released from the pool 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.

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). Importantly, inclusion of these avoided emissions is a political not scientific decision, but it influences the choice of forest strategy to mitigate climate change. Thus, economic agents must know the rules of the carbon game before making forestry decisions.

4. 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 a forest management model of the Quesnel TSA, adapted from van Kooten et al. (2015), 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,[2] 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 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

[2] 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).

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).[3]

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 shifted into long-lived products.

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

[3] 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.

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 land to faster growing trees (plant GE tree stock). 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 decades, 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).

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 generally 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 release), 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 disturbance 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. Conclusions

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 also follow: First, it is not clear that forests should ever be conserved in perpetuity, partly because of their eventual susceptibility to natural disturbance and partly because carbon gets stored in post-harvest products. Forest conservation might be a good strategy in the short run if the forests are not at full maturity, but is unlikely a good long-run option because with commercial forestry carbon is retained in wood products while regenerated forests grow more rapidly than mature ones with growth 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. Third, counting CO_2 emissions avoided when wood burning substitutes for fossil fuels results in offsets, 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 even though IPCC rules might permit this.

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

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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: Random Lengths (2016); Renzie and Han (2002, 2008); BC Ministry of Forests, Lands & Natural Resource Operations (2016).

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 (%)	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[b]	*0*	n.a.	
Total Harvest	**46,924.0**		

[a] Source: MFLNRO (2015); [b] Logging residuals and roadside wastes (from trimming logs to fit trucks optimally) are too costly to remove (Stennes et al. 2010).

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

Source: Healy et al. (2009)

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.

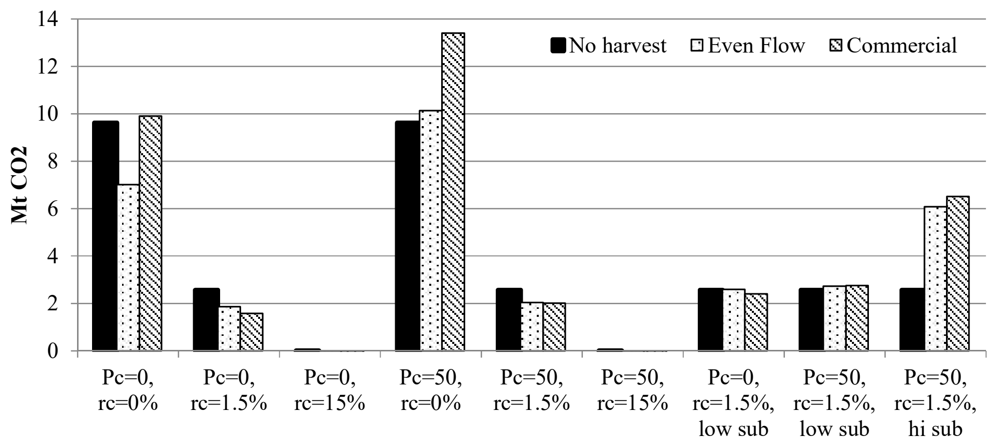

Figure 1: Number of carbon offsets created under various scenarios (Mt CO_2)

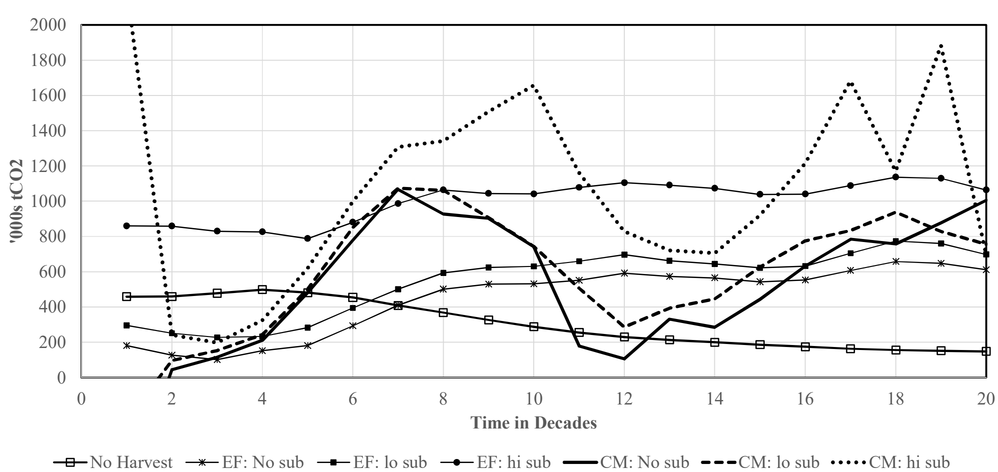

Figure 2: Discounted CO_2 uptake per decade for non-harvested, even-flow and commercially managed forests; 1.5% carbon discount rate; 2.5% monetary discount rate; carbon price = $50/tCO_2$; 1.37 tCO_2/m^3 credit for bioenergy-for-coal substitution; and credits of 0.25 tCO_2/m^3 (lo) and 2.5 tCO_2/m^3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