Forest Carbon Offsets Revisited: Shedding Light on Darkwoods

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Abstract

This paper investigates the viability of carbon offset credits created through forest conservation activities and the corresponding impact on carbon flux. A detailed forest management model based on a case study of a forest estate in south-eastern British Columbia, owned by the Nature Conservancy of Canada (NCC), is used to demonstrate the questionable nature of forest carbon offsets. We find that NCC management results in slightly less annual carbon sequestration than leaving the forest as wilderness, while sustainable commercial management of the site sequesters between 34 and 260 thousand tonnes of CO_2 more per year than NCC management. As a result, ex ante claims of carbon offset creation by the NCC might be overstated. In terms of the number of offsets created, the broader message is that the large variation in carbon flux, which is highly sensitive to underlying modeling assumptions, has severe implications for the efficient functioning of carbon offset markets. Probably the only way to determine the carbon sequestered is ex post and not ex ante.

Keywords: Forest management; carbon flux; discounting physical carbon; climate change

JEL classification: P28, Q23, Q54

Acknowledgements: The authors wish to thank Canada's Social Sciences and Humanities Research Council for research support.

In the face of global warming, climate mitigation strategies that enhance carbon sequestration in ecosystems are becoming increasingly important. It makes intuitive sense to take account of carbon offsets generated by projects that promote tree growth or otherwise cause more carbon to be stored in ecosystems, including those that enhance soil organic carbon (IPCC 2000). Five categories of forest offset projects can be identified (Malmsheimer et al. 2011): (1) afforestation (planting trees where none existed previously); (2) reforestation (regenerating previously forested sites); (3) forest management (management of existing forests to achieve specific carbon uptake objectives while maintaining forest productivity); (4) forest conservation (managing existing forests to prevent their conversion to other uses); and (5) forest preservation (managing forests to prevent their deterioration or degradation). Although forest conservation and preservation are currently not eligible for emission reduction (or carbon) offsets, concerns about tropical deforestation have led many to commend their use in developing countries as a tool for addressing global warming (Kaimowitz 2008; Buttoud 2012). Indeed, forest conservation and preservation projects are increasingly considered alternative means for earning certified emission reduction (CER) credits under the rubric of Reducing Emissions from Deforestation and forest Degradation, or REDD (Law et al. 2012).

In this paper, we contribute to the emerging literature on these forms of forest offset credits by addressing the following question: What are the implications for reducing atmospheric CO_2 if carbon offsets from forest protection projects are used in lieu of emissions reduction? To answer this question, we examine the role of a particular forest preservation project in creating carbon offset credits, focusing on the procedures used to determine the extent of carbon offset creation (including identification of counterfactuals) and, more generally, the challenges of measuring the corresponding impact on carbon sequestration in forests.

Background

It may be helpful to recall that the European Union originally opposed the use of carbon sequestration as a means for countries to meet their greenhouse gas emission reduction targets under the Kyoto Protocol of the United Nations' Framework Convention on Climate Change (UN FCCC). Yet, after the U.S. withdrew from the Kyoto negotiations following the Sixth Conference of the Parties (COP6) to the UN FCCC in The Hague, the Kyoto signatories agreed at COP7 in Marrakech to permit carbon uptake from land use, land-use change and forestry (LULUCF) activities in lieu of greenhouse gas emissions in meeting targets, but only for the first Kyoto commitment period (2008-2012). More specifically, the November 2001 Marrakech Accord permitted carbon sequestration in trees planted as a result of an afforestation or reforestation program to be counted as a credit, but also required carbon lost by deforestation to be debited (article 3.3). The problem is that a wider array of options for trading alternative sequestration services typically increases the complexity of the market, primarily as a consequence of monitoring and dynamic complications (Wilman and Mahendrarajah 2004).

While only carbon sequestered in wood biomass was counted under Marrakech, it still left open the possibility for including such components as soil and wood product carbon sinks and wetlands that store methane (article 3.4). CO_2 offset credits could also be obtained for activities in developing countries under Kyoto's Clean Development Mechanism (CDM), which enables private companies and industrialized nations to purchase (certified) offsets from developing countries by sponsoring projects that reduce CO_2 emissions below business-as-usual levels in those countries. As a result, there are strict guidelines regarding projects to establish or re-establish plantation forests in developing countries under CDM, which has made it difficult for such projects to overcome the hurdles for acceptance (van Kooten et al. 2009). A more troublesome aspect relates to the role of forest conservation and preservation activities.

An emerging number of studies have assessed the economic functioning of carbon offset policies. A key issue relates to the extent to which projects would have been undertaken anyway, something known as 'additionality'. Mason and Plantinga (2013) argue that the problem of additionality is inherently downplayed or ignored as a result of asymmetric information; sellers of carbon offsets possess information about the opportunity costs of offset projects that is not available to buyers. This results in the sale of offsets, particularly in voluntary markets, at prices that do not reflect true opportunity costs of mitigating CO_2 emissions. For example, Millard-Ball (2013) finds that in the transportation sector many offsets are not additional, primarily due to uncertainty surrounding estimates of business-as-usual emissions.

In a systematic account of offset policies, Hahn and Richards (2013) argue that offset programs have the potential to reduce the costs of achieving environmental targets, but that in practice this is difficult to establish due to the complex nature of market design. In addition to the difficulty of setting appropriate baselines (counterfactuals), Hahn and Richards (2013) also highlight problems related to units of measurement, monitoring requirements, and the process of certifying offset credits.

A special task force of the United States' organization of professional foresters (Society of Foresters) charged with investigating forest carbon offsets takes a similar view: "Offset projects are highly variable and depend on numerous assumptions, most of which are susceptible to bias and 'virtually insurmountable' measurement errors" (Oliver 2013; also Malmsheimer et al. 2011). It points out that one of the main problems with forest carbon offset credits appears to be the misguided belief that an unmanaged forest will accumulate and retain an amount of carbon greater than what the offset buyer is emitting over time – a false sense that, upon purchasing offsets, a buyer's activity is carbon neutral. Further, it concludes that the global benefits of forest offsets are overstated due to additionality. Finally, there is a general failure to account for leakage – that harvest takes place elsewhere when a forest is protected; indeed, the task force points to econometric evidence suggesting that leakage is often close to 100 percent (Malmsheimer et al. 2011).

The international community is currently engaged in deliberations concerning whether the UN FCCC's Kyoto process ought to certify forest conservation and preservation projects under the CDM (Bosetti and Rose 2011). Sathaye et al. (2011) indicate that the co-benefits of such projects – the non-carbon benefits – amount to between 57.5 and 76.5 percent of the total protection benefits, while Rose and Sohngen (2011) argue that Kyoto's current focus on afforestation actually leads to a decline in the global carbon stored in ecosystems. However, they suggest that, although not ideal compared to immediate implementation of a tax/subsidy scheme for emissions/uptake of CO_2, the initial loss can be overcome by crediting avoidance of deforestation in the future. Bosetti et al. (2011) report that greater reliance on reduced deforestation and other land-use activities could reduce the net costs of achieving a global target of 550 parts CO_2 per million by volume in the atmosphere by upwards of $2 trillion. These results are based on output from climate models, and assume that a new climate agreement will be struck and administered under ideal global governance, which is an ideal that the current study disputes.

In the meantime, forest conservation and preservation projects play a large role in the voluntary emission reductions (VERs) market, a market that amounted to $424 million in 2010, with trades averaging $3.24/tCO_2$ in 2010, down from a high of $5.81/tCO_2$ in 2008 (Peters-Stanley et al. 2011). This compares to a total global carbon market estimated to be worth €92 billion (approximately $125 billion) in 2011, an increase of 10% over 2010. There is the suggestion, however, that VERs affect not only the voluntary market but also compliance markets, most notably the EU's Emission Trading System (EU ETS) (e.g., see Peters-Stanley et al. 2011).[1] Thus, while CER credits created by forest conservation and preservation activities are currently not available for sale in international markets, VER offsets created in this way are marketed in global carbon markets.

When carbon offsets can be created by changing land management practices, the supply of ecosystem services or other co-benefits can be financed from the sale of such offsets, thereby creating enhanced incentives for landowners to increase other services from the land, presumably environmental ones such as biodiversity. We show that this multi-market interaction creates incentives for rent-seeking, thereby highlighting the difficulty of establishing claims related to forest offset credits. Rent seeking occurs because economic agents are able to lobby for opportunities to sell carbon offsets even though there is no associated reduction in the atmospheric concentration of CO_2. In particular, we use an example of a forest preservation activity in British Columbia, which generated forest offset credits for the voluntary market but imposed real costs on the province's citizens, to demonstrate that the carbon offsets created are questionable in terms of their contribution to climate change mitigation.

Using a detailed forest management model, our study finds that forest carbon sequestration is highly sensitive to assumptions about the post-harvest use of wood products, substitution of wood for concrete and steel in construction, and the ability to regenerate harvested sites with improved genetic stock. We demonstrate that the carbon offsets claimed to have been generated by a relatively small-scale forest protection project in the BC interior are overstated. In particular, we show that credits created by activities that enhance preservation of

[1] While some VERs may indeed be sold in a compliance market, it is more likely that they are sold to various private and public entities that might otherwise make purchases in the ETS.

biodiversity enter the global carbon market without really contributing to net carbon reduction. Rather, by lowering the costs of emitting CO_2, such offsets signal that the future damages to society from climate change are lower than warranted so that more emissions can be tolerated. Overall, we illuminate how the institutional complexity of offset markets interacting with forest protection leads to rent-seeking (Helm 2010), which undermines the notion that society can accept cost-effective, wide-scale and more complex offset programs that are deemed economically efficient. In essence, we argue that there are many ways ex ante to create forest carbon offset credits, but, unfortunately, their soundness can only be established ex post.

The remainder of the paper is structured as follows. We begin in the next section by describing a forest preservation activity in British Columbia that generated important voluntary offset credits. We then develop a GIS-based forest management model of the study area that we subsequently use to compare carbon fluxes under different management regimes. To our knowledge, the original evaluation of carbon flux on this site neither employed GIS to organize the data nor a forest management model to evaluate it. The data are then described, followed by the results comparing carbon sequestration under various management regimes. We end with a summary and conclusions.

Carbon Offset Credits from Forest Protection: Darkwoods as an Example

Some 14.8 percent of British Columbia's land base is officially protected, while 42 percent of forestland (22.6 million ha) has trees that are 140 years or older (BC Ministry of Forests, Mines and Lands 2010). There are vast areas of forestland that are protected or inaccessible, unaffected by commercial timber operations. These forestlands have been impacted by wind throw (mainly on the Coast) and by wildfire and the mountain pine beetle (mainly in the Interior), but are left to regenerate naturally because of their inaccessibility. One might make the case that artificial regeneration that leads to higher and faster rates of growth – greater overall carbon uptake – should be eligible for VER credits. However, it would seem logical, in these cases, to count the CO_2 emitted as a result of wildfire and/or decay of biomass as a debit. Therefore, it makes sense neither to count CO_2 emissions from natural disturbance nor its removal from the atmosphere as a result of activities to mitigate the impact of the disturbance.

What about the biodiversity benefits of investing in forest preservation? Given the vast amount of forestland officially and unofficially protected in British Columbia, the marginal benefits of protecting another hectare of forestland are essentially zero (see van Kooten and Bulte 1999; Bulte et al. 2002).[2] Thus, in British Columbia, offset credits from forest protection need to be justified solely on the basis of the CO_2 removed from the atmosphere by the forest conservation activity.

In 2008, The Nature Conservancy of Canada (2010; hereafter NCC) purchased the 54,800 ha Darkwoods property on the west side of the south arm of Kootenay Lake near the U.S. border (Figure 1) for $125 million from the German logging company Pluto Darkwoods, having received financial support for this purchase from the federal government.[3] Although nearly half of the Darkwoods site had previously been logged and regenerated, there remains a significant tract of natural forest with some trees as old as 500 years. Because the site also suffers from mountain pine beetle damage, logging of pine-beetle killed timber has continued under NCC ownership, although such harvests have recently fallen from over 50,000 cubic meters to 10,000 m^3 per year.

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[2] Given so much forestland is in its natural state, studies found that citizens' marginal willingness to pay for more forest protection is insignificant; see van Kooten (1995) for a review.

[3] Information is available from stories appearing June 10 and 11, 2011, in local newspapers, the *Vancouver Sun* (June 10) and national *Globe and Mail*.

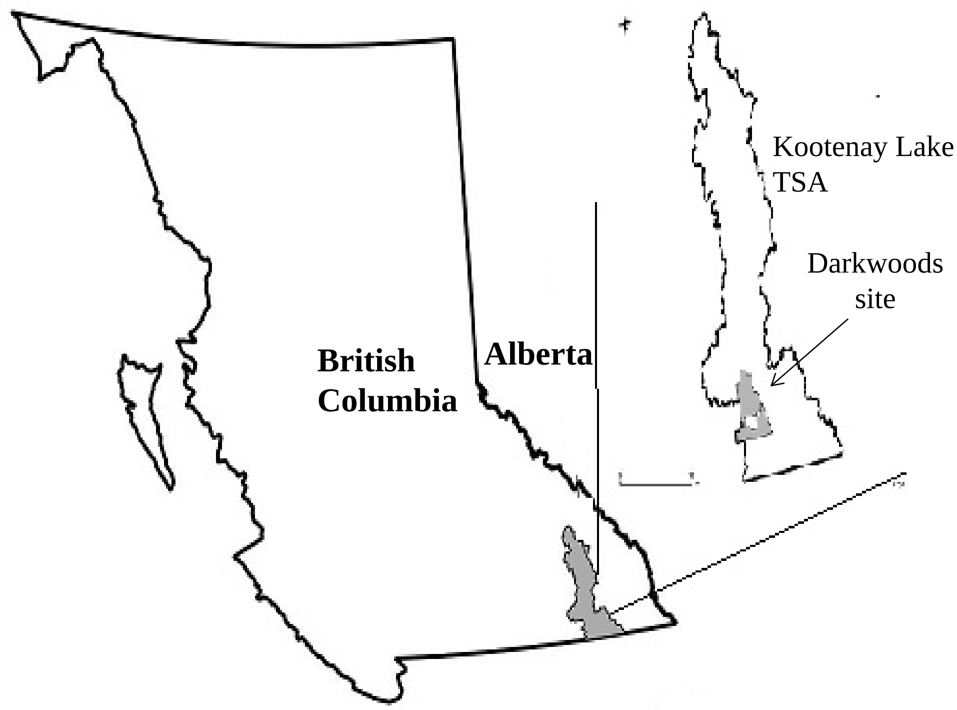

Figure 1: Location of the Darkwoods Site in Southeastern British Columbia

In June 2011, NCC announced that it had completed a sale of 700,000 metric tons of CO_2 (tCO_2) offset credits to Pacific Carbon Trust, a BC government-owned corporation, and to Ecosystem Restoration Associates (ERA), a North Vancouver-based company. The latter subsequently sold the credits in Europe through its German affiliate, the Forest Carbon Group – a German certifier of CERs under the CDM. NCC received more than \$4 million for the sale, or nearly C\$5.75/tCO_2, at a time when offset credits were trading for more than C\$15.00/tCO_2 on the European carbon exchange (ETS). An international environmental non-governmental organization (ENGO), the Rainforest Alliance (2011), certified the carbon offsets under the Voluntary Carbon Standard (VCS) label.[4]

[4] On-the-ground certifiers appear to be local rather than international, because the assessment was conducted by the local office in Nelson BC, although the Rainforest Alliance has its head office in Virginia.

The number of carbon offsets generated was determined as the difference in the carbon flux between the proposed NCC management regime (10,000 m^3 harvested annually) and the operation of the Darkwoods site by the hypothetical commercial operator.[5] The comparison between these management alternatives raises an issue regarding the counterfactual scenario. In making the case for certifying carbon offsets under the VCS label, the auditors note that: "Private land regulations in BC are quite strong compared to many other jurisdictions and the land is expected to be managed in compliance with all laws, under the direction of experienced land managers and Registered Forest Professionals" (Rainforest Alliance 2011, pp.34-35). However, when it comes to the counterfactual, the "proponent assumes that in the absence of the project, the most plausible baseline scenario is a market driven acquirer who implements a 15 year depletion of current mature timber stocks to provide a reasonable rate of return on investment, and a 100 year harvest schedule implemented with the typical regional practice of clearcut logging with minimum legal requirements for private forestlands in BC and comparable regional practices … [This is possible because] liquidation logging with little regard for basic environmental protections or sustainable timber production is legal and not uncommon in BC" (Ibid., p.32). Not only does the latter statement contradict the earlier one, but the private forest landowners would take offense at being told that their actions fail to take 'basic environmental protections' into account.[6] Nor would it be possible for a timber liquidator to sell timber into a market that requires forest management standards to be certified by the Forest Stewardship Council or another international certifier of forest practices.

In calculating the carbon offset benefits, the carbon sequestered annually in living

[5] The documentation of the methods used to calculate carbon offsets is somewhat opaque. Therefore, we may not correctly characterize the procedure used to determine the carbon flux associated with the NCC scenario, both here and in the results section below.

[6] In this regard, see http://www.pfla.bc.ca/.

biomass and long-term carbon stored in wood products constituted a credit, while CO_2 emissions associated with harvesting, hauling and processing constituted a source.[7] From the carbon stored in wood at the time of harvest, the analysts then subtracted the carbon released from decay during the period from the time of harvest to the end of the time horizon. Since physical carbon flows were not discounted, the release due to decay was substantial. As indicated in the next sections, these assumptions would have reduced the carbon benefits attributable to the commercial operator relative to a less exploitive management regime.

Given that 700,000 tonnes of CO_2 offsets were sold from the Darkwoods site, one might ask why NCC sold the credits at a lower price (about \$5.75/tCO_2) than the German company Forest Carbon Group could sell them (the ETS price was \$15/tCO_2 or more at the time) and the \$25/tCO_2 that Pacific Carbon Trust charged BC provincial government agencies (schools, hospitals, etc.) to be carbon neutral. Selling below market price implied a loss in revenue for NCC of perhaps \$9 million. This income could have been used to finance biodiversity preservation on the site, which is NCC's prime objective.

As to the purchasers in the Darkwoods case, Pacific Carbon Trust and the Forest Carbon Group engaged in rent seeking so as to acquire carbon offsets and resell them in a way that maximized their net returns. Such rent seeking by the buyers adversely impacts the efficient functioning of the carbon market at the forest level as the below market price received by NCC for offsets results in too little forest preservation. Ideally, the buying and selling of carbon credits should take place in one market without the resellers, and it should not include project certifiers as eventual purchasers.

In a re-assessment of the Darkwoods project and the claim that forest conservation can

[7] See 3GreenTree Ecosystem Services & Ecosystem Restoration Associates (2011, pp.19-20). The above-ground, non-tree living biomass, litter, and soil carbon pools were not included.

generate more carbon offsets than under private management, we examine a situation where the Darkwoods site is sustainably managed for commercial timber production while maintaining or increasing carbon stocks. If harvested fiber is stored in wood products, substituted for other material in construction or used to produce energy, this "will generate the largest sustained mitigation benefit" (IPCC 2007, p.543). We demonstrate this in the following sections.

Forest Management Model of Darkwoods

As the basis of the work in this study, we have adapted a forest model and accounting approach developed by Krcmar and her colleagues (Krcmar et al. 1998, 2001, 2003; van Kooten et al. 1999; Krcmar and van Kooten 2008). Besides modifications required for application to the current study site, major changes related to carbon accounting have been made – in particular, carbon data come from the Carbon Budget Model (as discussed in the data section) and an updated accounting approach are employed. In this section, we outline the forest management model as applied to the Darkwoods property, with a particular focus on carbon accounting.

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 (natural or artificial regeneration). Also, 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 oriented strand board, medium-density fiberboard, 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:

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

where *S* is the total number of tree species, *A* the number of age classes, *Z* the number of zones and M the management regimes. Zones constitute a combination of 12 biogeoclimatic sub-zones and two slope classes. Sites are further classified by seven primary and ten secondary species.

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

$$C_t = C_t^{\log} + C_t^{\text{haul}} + C_t^{\text{silv}} + C_t^{\text{admin}} + C_t^{\text{process}}, \tag{2}$$

where

$$C_t^r = \sum_{s=1}^{S}\sum_{a=1}^{A}\sum_{z=1}^{Z}\sum_{m=1}^{M} c^r_{s,a,z,m,t} v_{s,a,z,m,t} x_{s,a,z,m,t}, \forall t, r \in \{\text{log}, \text{haul}, \text{silv}, \text{admin}, \text{process}\}. \tag{3}$$

In equation (3), costs are much more coarsely defined than indicated. Thus, $c^{\log}_{s,a,z,m,t}$ are logging costs per m^3, but they only vary by slope; $c^{\text{silv}}_{s,a,z,m,t}$ are regeneration costs per ha and vary only according to whether regeneration is natural or by replanting; and $c^{\text{admin}}_{s,a,z,r,.t}$ are administrative and development costs that are assumed to be constant on a per hectare basis. Processing or manufacturing costs are embodied in the net value of logs, except as these relate to greenhouse gas emissions (see below). Finally, because the study region is small, trucking costs from a harvest site to the mill are nearly constant across the region, which are given by $C_t^{\text{haul}} = c^{\text{truck}} \times H_t$.

Because the timber on the Darkwoods site is relatively homogenous, we assume that a 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 produce heat or generate electricity, while the remaining proportion, $\varepsilon_4 = 1 - (\varepsilon_1+\varepsilon_2+\varepsilon_3)$, is left to decay at the harvest site or from processing. The price of chips is the same regardless of how chips are used. Let p_{lum}, p_{chip} and p_{fuel} be the fixed prices of lumber, chips and wood fiber used to produce fuel, respectively.

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:

$$E_t = e_1\ c^{\text{log}}_{s,a,z,r,.t} + e_2\ c^{\text{haul}}_{s,a,z,r,.t} + e_3\ c^{\text{silv}}_{s,a,z,r,.t} + e_4\ c^{\text{process}}_{s,a,z,r,.t}\ ,\ \forall\, t\ , \tag{4}$$

where e_1, e_2, e_3 and e_4 are parameters that convert 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 $CO2_t^{eco}$. The ecosystem carbon fluxes are calculated using the Canadian Forest Service's Carbon Budget Model (Kull et al. 2011) as discussed below.

We also consider the carbon stored in three product pools – the carbon stored in lumber, in products made from wood chips (including pulp), and in residuals and waste used to produce medium density fiber board, wood pellets for exports, heat or electricity, et cetera.[8] 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). Let the rate of decay for each of the three product pools and the dead organic matter pool be denoted d_1, d_2, d_3 and d_4, respectively, and that decay begins in period t+1 following harvest in period t. Then, assuming physical carbon is discounted at rate r_c, the amount of carbon stored in the three pools as a result of harvest H_t is given as follows:

$$CO2_t^{product} = \varphi \sum_i \frac{1+r_c}{r_c+d_i} \varepsilon_i H_t\ ,\ i \in \{\text{lumber, chips, residuals/waste}\}. \tag{5}$$

[8] Residuals and waste are often burned on site (at a mill) to reduce energy costs. We do not count avoided emissions from fossils when wood is burned to generate electricity, partly because we lack information on the exact disposition of residuals and waste wood.

where parameter φ (= 44/12) converts carbon to CO_2.

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):

$$CO2_t^{ff} = \varphi \xi H_t, \tag{6}$$

where ξ is a parameter denoting the emissions avoided when wood substitutes for other products. Total carbon stored at any time is then given by the sum of (5), (6) and (7):

$$CO2_t = CO2_t^{eco} + CO2_t^{product} + CO2_t^{ff} . \tag{7}$$

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

$$\text{NPV} = \sum_{t=1}^{T} \beta^t \left[(p_{lum}\varepsilon_1 + p_{chip}\varepsilon_2 + p_{fuel}\varepsilon_3) H_t - C_t - p_C E_t + p_C \gamma \; CO2_t + S_t^{C\&S} \right], \tag{8}$$

where p_C refers to the (shadow) price of carbon dioxide ($/t$CO_2$), γ is the duration factor, and β = 1/(1+r) is the discount factor with r being the discount rate on monetary values. Notice that $CO2_t$ is the carbon stored in sinks and is multiplied by the duration factor γ, which could be set equal to the discount rate r as a limiting value. In essence, the duration factor (relative to the discount rate) accounts for the amount of time that climate mitigation practices prevent CO_2 from entering the atmosphere (van Kooten 2009). In our case it reflects the difference between actual emissions reduction and the VERs credited to forest conservation practices as the climate mitigation strategy, and is implemented in this application by specifying a separate discount rate for physical carbon (as discussed further below).[9] Further, for simplicity and given fixed product

[9] The importance of 'discounting' physical flows of resources as to when they take place is well established (see van Kooten 2009; van Kooten 2013, pp.332-334). This is discussed further below.

prices and proportions ε_i, we assume that the price of logs ($/m^3) (= $p_{lum}\varepsilon_1 + p_{chip}\varepsilon_2 + p_{fuel}\varepsilon_3$) is the value of interest in the objective function (8). Finally, $S_t^{C\&S}$ refers to the CO_2 emissions that are avoided because of the (reduced) production of cement and steel if wood substitutes for these materials in construction.

Objective function (8) is maximized subject to equations (1) through (7) and a variety of technical constraints (see Krcmar et al. 1998, 2001, 2003). The latter relate to the limits on harvest imposed by the available inventory in any period as determined by tree species, biogeoclimatic zones, slope and age characteristics; a total area constraint (55,000 ha); 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; non-negativity constraints; and other constraints relating to the specific scenarios that are investigated. We require that the harvest in any future period is within 5% of the first period harvest. This ensures a sustainable harvest rate and adequate investment in the future state of the forest to prevent clear cutting and degradation of the Darkwoods site, although the government might impose more stringent sustainability requirements.

Model parameters are provided in the next section, while the constrained optimization model was constructed using the General Algebraic Modeling System (GAMS) (Rosenthal 2008). All mathematical programming models are solved in GAMS using the CPLEX solver on an IBM System X 3755-M3 terminal server.

Data Description

A GIS model of the Darkwoods site was initially constructed. Since we were unable to obtain the inventory data used by the assessors, and given that one of the current authors had previously been a senior timber supply analyst for the province, we employed information on biogeoclimatic zones, existing data on inventory and timber supply in the adjacent Kootenay Lake Timber Supply Area (TSA; Figure 1), and forest cover from satellite data to develop a timber inventory for the Darkwoods site. This made it possible to identify the age and type of tree species growing on the site by biogeoclimatic zones, slope categories and other spatial characteristics – the timber inventory on the site. We then employed the BC Ministry of Forests and Range's growth and yield prediction model, TIPSY, to predict yield of managed and natural stands.[10] TIPSY is used in timber supply analyses, but can also be used to evaluate silvicultural treatments and address other stand-level planning options. The Darkwoods property consists of 10,332 stands of potential timber, with an average merchantable timber volume of 247.3 m^3 and 97.2 tC (=365.5 tCO_2) in living biomass. In the current application, TIPSY is used to determine the evolution of the forest for each of the various sites in the GIS model, whether the site was harvested or not.

Data on prices, costs and discount rates used in the model are also reported in Table 1. For convenience and because it has little effect on the results, we employ a constant rate of 4% for discounting monetary values, but employ rates of 0%, 2% and 4% for discounting physical units of carbon.

Silviculture

As noted earlier, a commercial operator needs to ensure that its management practices are sustainable, and is therefore required to regenerate a site once it is harvested. In that case, the site is replanted with genetic stock from tree nurseries (which results in faster growing trees than the

[10] TIPSY refers to the Table Interpolation Program for Stand Yields, but there is also a Variable Density Yield Prediction system for natural stands. Further information can be found at http://www.for.gov.bc.ca/hre/gymodels/tipsy/assets/intro.htm. The data files from TIPSY as well as the GAMS files are available from the authors upon request.

native ones that have been harvested) rather than being left to regenerate on its own with natural stock. Artificial regeneration could lead to a substantial increase in the amount of carbon sequestered; not only does it lead to earlier establishment of a growing forest, but, because higher-quality trees are planted, the total amount of biomass grown on the site could be significantly enhanced. Indeed, by planting nursery stock, the site index for the same tree species can be increased from, say, 20 m on a 50-year basis to perhaps 28 m, or by 40%.[11] This might translate into an increase in the amount of carbon stored on a site by perhaps 30% compared to allowing natural regeneration with 'non-improved' trees. This then is a clear benefit of permitting harvest activities and is included in the TIPSY output. Silvicultural costs are provided in Table 1 for artificially generated stands.

Carbon Pools and CO_2 Emissions

In the current application, ecosystem carbon ($CO2_t^{eco}$) is calculated by TIPSY's Tree and Stand Simulator (TASS), and is based on the Carbon Budget Model of the Canadian Forest Sector (Kull et al. 2011; Kurz et al. 1996). TIPSY tracks living and dead biomass, and whether it is above or below ground. The above-ground live component includes the wood, bark, branches and leaves, while the below-ground component constitutes the roots. The dead biomass stock includes litter and soil organic matter. TIPSY provides the addition to dead biomass in each period, and the cumulative live biomass as the stand grows, so that decay of dead matter is not explicitly taken into account. Hence, it is straightforward to calculate the 'periodic recruitment' of carbon, which can then be translated into a CO_2 equivalent measured in metric tons. In addition to ecosystem carbon, we track carbon entering product pools and the decay rate of various products, which determines release of CO_2 from the product pool over time.

[11] The site index is defined as the expected height of trees at a particular age.

We also consider the potential impact of avoided emissions when wood is substituted for non-wood products, such as steel and concrete, in construction. Information on these factors is available from several sources and is reported in Table 1. However, we do not account for the fossil fuel savings from burning wood, because electricity is BC is generated almost exclusively from hydro sources. Finally, we include CO_2 emissions associated with the activities of harvesting, trucking and manufacturing of wood products, and provide this in Table 2.

Table 1: Model Parameters

Parameter	Assigned value	Description
T	200 years	Length of the planning horizon
t	10 years	Time step
P_{logs}	\$75/m³	Net price of logs (determined from all product prices)
p_{C}	\$10/tCO_2	Shadow price of carbon dioxide
c^{truck}	\$4.50/m³	Trucking cost per m³ of logs fixed for each time period[a]
c^{log}	{\$22, \$42}	Logging cost per m³ varies by slope category (<40°, >40°)
c_1^{admin}	\$8/ha	Fixed administration & site development cost per harvested ha[b]
c_2^{admin}	\$14/ha	Overhead & road maintenance cost[b]
c_z^{silv}	{\$1522, \$1605}	Fixed silvicultural cost per harvested ha by 2 major BEC zones
r	4%	Discount rate for monetary values; β=1/(1+r)
r_c	{0%, 2%, 4%}	Discount rate for physical carbon; used to find duration factor γ
ε_1	0.54	Proportion of merchantable volume converted to lumber
ε_2	0.25	Proportion of merchantable volume converted to chips
ε_3	0.21	Proportion of merchantable volume as residuals and waste
d_1	0.02	Decay rate for softwood lumber (proportion on annual basis)
d_2	0.03	Decay rate for chips and pulpwood (proportion on annual basis)
d_3	0.60	Decay rate of waste wood (proportion on annual basis)
d_4	0.00841	Decay rate of dead organic matter (proportion on annual basis)
ξ	{0.0, 0.25, 0.75} tC/m³	Emissions avoided when wood substitutes for other products[c]
	150 m³ ha⁻¹	Minimum volume before site can be harvested

Notes:
[a] Assumes a cycle time of 1 to 2 hours.
[b] Two types of fixed administrative costs are identified – one associated with site maintenance, the other with road maintenance. With regard to the second, Thomae (2005) uses an overhead cost of \$11.24/ha and road maintenance cost of \$2.56/ha.
[c] Avoided emissions vary from 0.5 to 0.9 tC per m^3 (1.8 to 3.3 tCO2/m^3) for steel and 0.1-0.3 tC/m^3 (0.37-1.1 tCO_2/m^3) for concrete (Hennigar et al. 2008). We employ 0.0, 0.25 and 0.75 tC/m^3 as a sensitivity checks.
Source: Adapted from 3GreenTree Ecosystem Services & Ecosystem Restoration Associates (2011, pp.133, 137), Thomae (2005), Niquidet et al. (2012), Hennigar et al. (2008) and Ingerson (2011).

Table 2: Carbon Emissions (e_i) by Activity

Activity	Emissions (tC per tC raw material)
Harvesting	0.016
Manufacturing	
Sawnwood	0.040
Veneer, plywood, panels	0.060
Non-structural panels	0.120
Mechanical pulping	0.480
Chemical pulping	0.130
Trucking (50 km)	0.00007 per km

Notes:
We assume only mechanical pulping.
Source: 3GreenTree Ecosystem Services & Ecosystem Restoration Associates (2011, p.137)

Given that CO_2 fluxes (emissions, carbon capture and carbon release from decaying biomass or wood products) vary over time according to the forest management regime, a method is needed to compare different carbon profiles. One approach is to use a discount rate on physical carbon to aggregate CO_2 fluxes over time; discounting physical carbon assumes that CO_2 removed from, or released to, the atmosphere today is more important than removal of that CO_2 at some distant date. Alternatively, discounting can be avoided by counting only the carbon fluxes occurring over some (arbitrary) time period.[12] The alternative of not discounting physical carbon leads to problems related to duration (van Kooten 2009); unless current reductions in CO_2 emissions or removals from the atmosphere are considered more important than future ones, it would encourage delay of mitigating action and, in the limit where there is no discounting of physical carbon, delay it indefinitely.

Because the rate at which carbon in post-harvest product pools returns to the atmosphere

[12] The FCC process has developed a variety of methods to compare streams of carbon flux from alternative forest activities (e.g., see van Kooten 2013, pp.355-358), but none is as efficient as the use of a carbon discount rate.

varies considerably in our model (see Table 1), the release of CO_2 from post-harvest products is charged to a common date, namely time of harvest, using a discount rate on physical carbon. Consider perhaps the most important carbon pool, namely, wood products. It is easy to demonstrate that, if 0.27273 tC (= 1.0 tCO_2) is stored in wood products, the amount of CO_2 released as a result of future decay of wood products is equivalent at the time of harvest to:

$$\theta = \sum_{i=1}^{D} \left(\frac{d_i}{d_i + r_c} \right) \varepsilon_i \ , \tag{9}$$

where θ is measured in tCO_2 per m^3 of harvested wood, d_i is the decay rate (rate of CO_2 release), r_c is the rate used to discount physical carbon, and ε_i is the proportion of harvesting going into product pool i (= 1, …, D) (see Table 1). Clearly, if CO_2 flux is not weighted according to when it occurs, CO_2 released today is treated the same as CO_2 released 50 years from now or 200 years from now – it does not matter. Thus, if r_c=0%, all CO_2 stored in timber is treated as if it is released immediately upon harvest.

The implication of equation (9) is clear. As the rate used to discount physical carbon increases, future CO_2 emissions from the decay of wood products or biomass more generally matter less. Thus, it appears that more carbon gets stored in wood products, say, as the discount rate on physical carbon rises. From a carbon perspective, this favors harvest activities that result in increased processing of biomass into products. On the other hand, low discount rates on carbon favor lower harvest intensity. This insight is crucial to the results provided below.

A Comparison of Carbon Sequestration across Scenarios: Results

Our forest management model of the Darkwoods site employs a 200-year time horizon with a 10-year time step; the long time horizon is required to eliminate problems related to the determination of the site's salvage value, while a 10-year step is required to facilitate achieving a numerical solution to the model. Because commercial decision makers in our model are observed to adjust harvests in anticipation of the end of the time horizon as early as two decades prior, we present results only for 150 years. The long time horizon implies that the discounting of physical carbon plays a crucial role in what one can say about the importance of forest carbon offsets.

We first establish a baseline level of carbon sequestration by assuming that the Darkwoods site is designated a wilderness area with no harvesting or other management.[13] To determine the carbon flux for a natural forest, we maximize the growing stock subject to the biophysical inventory and growth constraints and a constraint limiting harvest to zero. Next we examine the levels of carbon uptake under NCC management by maximizing net revenues from timber harvest subject to the growth, inventory and other constraints imposed by the NCC.[14] Lastly, we find the carbon flux under commercial management by maximizing (8) subject to constraints (1)–(7) and other technical constraints required in the model (as discussed above), plus constraints required by government or a certifier of sustainable forest management practices (as opposed to a certifier of carbon offsets). The baseline includes carbon stored in products, but not the avoided fossil-fuel CO_2 emissions from substituting wood for non-wood materials in construction. The baseline carbon fluxes are provided in Figure 2.

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[13] Except perhaps fire suppression, as we do not take into account possible wildfires (see, e.g., Couture and Reynaud 2011). Including wildfire risk, however, would reinforce the overall conclusions reached below.

[14] As in the case of the natural forest where we maximize growing stock, maximizing net revenue is simply a device used in the model to implement the NCC's management strategy (annual harvest of 10,000 m^3) and is not meant to imply that the NCC acts to maximize profit from timber harvesting.

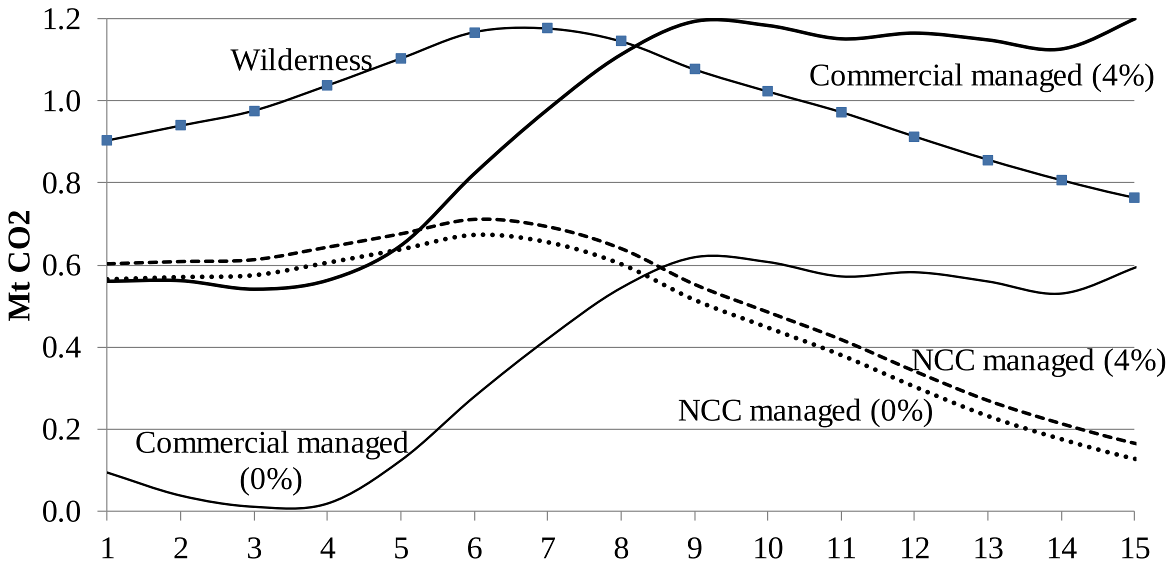


Figure 2: Carbon Flux on Darkwoods Site, Wilderness, NCC Management and Commercial Management, Biological and Product Carbon Pools Only, Carbon Discount Rates of 0% and 4%

When physical carbon is not discounted, leaving the Darkwoods site as wilderness leads to the greatest carbon benefit. In this case, there are no product pools to consider because there is no harvest. Thus, assuming no wildfire or further pest and/or disease outbreaks, carbon sequestration continues as long as forest growth exceeds decay, which is the situation here because the starting inventory had been affected by the mountain pine beetle, so a significant part of the forest constitutes young stands. In our model, the decline in net carbon uptake begins after about 70 years when tree growth slows. Much the same is true for NCC management, except that CO_2 emissions from harvesting and processing activities are counted against those from growing trees.

With r_c=0%, emissions from commercial harvesting and processing wood initially offset the gains from planting new trees, although the latter gains dominate after about 50 years with CO_2 flux leveling off after about 90 years. Since no effective carbon is stored in product pools (see equation 9), the only gains in carbon come from regeneration of stands. Whether the property is managed by the NCC or a commercial operator, the CO_2 removed from the atmosphere from growing trees minus that emitted from harvesting and processing activities is not sufficient to overtake the CO_2 removed by simply leaving the forest as wilderness (at least over the 150-year time horizon). Further, the net carbon flux on the property with a commercial operator will after 80 years exceed that under the NCC management, simply because the commercial operator will have more fast-growing immature forests on the site at that time.

When carbon fluxes are discounted, the story changes significantly: CO_2 released from future decay of wood products is weighted less than CO_2 released closer to the time of harvest. The higher the discount rate on physical carbon, the less important are future fluxes in carbon. This is seen in Figure 2. The commercial operator would end up storing much more carbon in post-harvest product pools, which, along with regeneration of harvested sites with younger, faster growing trees, leads to much greater potential for carbon offsets than under a NCC management regime. Although carbon flux also increases under the NCC management plan, the harvests are too small to result in significant carbon storage in wood products.

The story changes even more when the commercial manager is incentivized to reduce CO_2 emissions and increase sequestration of carbon in growing trees and wood products. It is further impacted when fossil fuel savings from reduced use of cement/concrete and steel/aluminum in construction because wood materials are used as substitutes (Hennigar et al. 2008). Summary results for these situations are provided in Table 3 and illustrated in Figure 3.

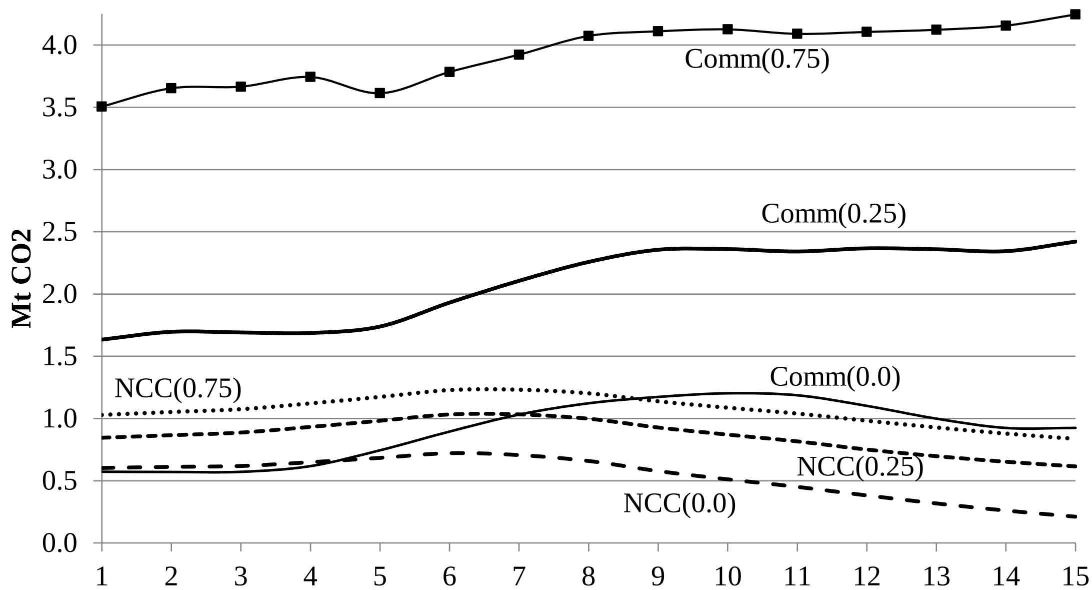
Net carbon sequestration results are provided in Table 3 for carbon discount rates of 0% and 4% and carbon prices of \$0/tCO_2 and \$10/tCO_2. As noted earlier, these represent extremes in terms of the carbon offsets that might be generated over the 150-year time horizon; the results for a 2% discount rate for carbon fall between those of 0% and 4%, while results for a \$50/tCO_2

price lead to the same levels of carbon as the \$10/tCO_2 price. With a 4% discount rate on monetary values and no carbon price to incentivize forest managers to sequester carbon and reduce greenhouse gas emissions, the amount of undiscounted CO_2 sequestered by the NCC management plan averages some 52,000 tCO_2 per annum below that which would be stored in biomass had the region been left solely to wilderness. While trees grow somewhat faster than in the case of wilderness, NCC management results in CO_2 emissions from some of the harvesting, hauling and processing that occurs, with any carbon stored in products effectively lost to the atmosphere upon harvest (as noted in conjunction with Figure 2). When physical carbon is discounted at 4%, however, the NCC plan leads to greater storage than wilderness, by some 97,000 tCO_2 annually.

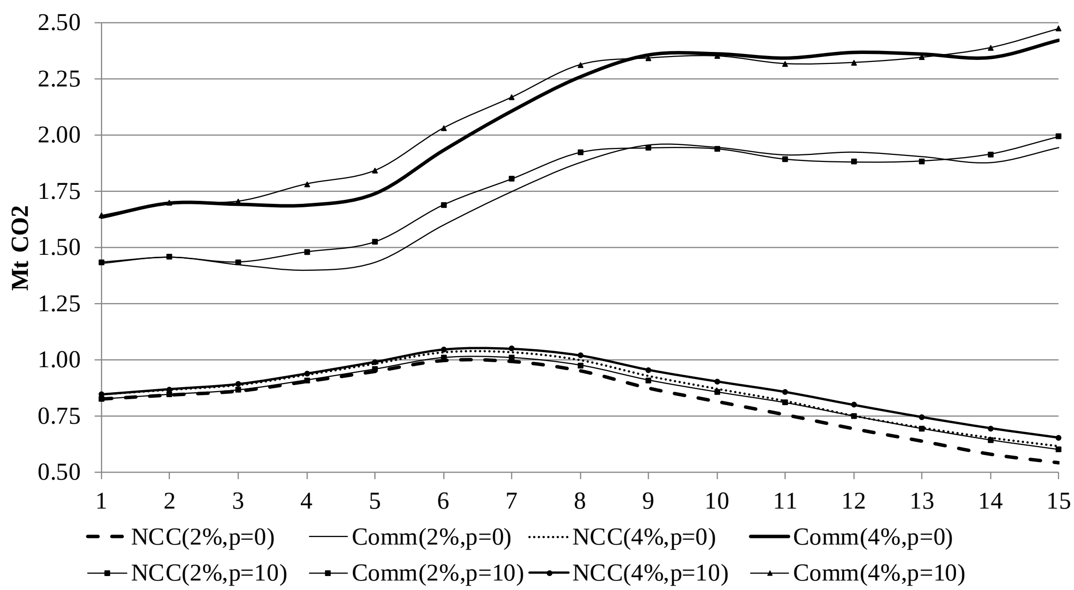
Table 3: Annualized Carbon Sequestered for Management Alternatives, Carbon Prices, with and without Carbon Discounting and Wood Product Substitution Rates,[a] Monetary Values Discounted at 4% (Mt CO_2)

Management type	Price of carbon = \$0/tCO_2		Price of carbon = \$10/tCO_2	
	0%[b]	4%	0%[b]	4%
Wilderness	0.099	0.064	0.099	0.064
No fossil fuel savings from substituting wood for concrete/steel (ξ=0.0)				
NCC managed	0.047	0.196	0.048	0.205
Commercially managed	0.037	0.351	0.040	0.356
Low fossil fuel savings from substituting wood for concrete/steel (ξ=0.25)				
NCC managed	0.075	0.332	0.077	0.341
Commercially managed	0.102	0.805	0.107	0.816
Medium fossil fuel savings from substituting wood for concrete/steel (ξ=0.75)				
NCC managed	0.093	0.403	0.095	0.412
Commercially managed	0.281	1.496	0.285	1.515

Notes:
[a] ξ is the rate wood substitutes for steel/concrete in construction and is measured in tC per m^3 of harvested commercial timber.
[b] This is not a pure annualized value but obtained by taking total carbon accumulated over 150 years divided by 150; for the 4% discount rate, a true annualized value is reported.



(a) Carbon Price of \$10 per tCO_2, 4% Discount Rate for Physical Carbon Fluxes, and Various Wood Substitution Parameters (in parentheses; tC per m^3)



(b) Carbon Flux, 2% and 4% Carbon Discount Rates, \$0 and \$10 per tCO_2 Carbon Prices

Figure 3: Net CO_2 Sequestered per Decade: NCC vs. Commercial Management, 4% Discount Rate for Monetary Values

The potential to create forest carbon offsets increases only slightly if the NCC manages Darkwoods to take into account the sales value of carbon offsets. This assumes that, while harvest levels do not change, lands are managed somewhat differently (e.g., different sites are chosen for harvest, tree planting occurs faster). In the absence of discounting, annual positive carbon flux is 51,000 tCO_2 below that associated with wilderness; at a carbon discount rate of 4% (so carbon stored in products is now taken into account), the NCC plan results in 106,000 tCO_2 more per year than wilderness. Of course, the NCC carbon flux is nearly equivalent to that of wilderness if carbon stored in products is not taken into account (0% carbon discount rate), while the NCC plan clearly leads to much greater overall carbon offsets (as much as 313,000 tCO_2 annually) if fossil fuel savings from substituting wood for non-wood construction materials are taken into account. It is only when carbon is discounted that NCC management results in positive carbon offsets relative to leaving the site as wilderness (Table 3); the reason is that carbon stored in wood products is counted when the carbon discount rate is not zero.

Leaving land in its natural state or adopting the NCC plan are preferred to commercial operation of the Darkwoods property only if the sole carbon fluxes to be considered are those related to timber growth (including carbon in all above- and below-ground pools) and CO_2 emissions from harvesting, hauling and processing wood – that is, post-harvest carbon pools are ignored. The potential of the commercial operator to create carbon offsets increases with the price of carbon, the discount rate on physical carbon (so future release of CO_2 from product pools is counted less today), and the savings from avoided fossil fuel emissions when wood substitutes for steel and concrete. The latter point is illustrated most clearly in Figure 3(a), where only the potential fossil fuel savings from substituting wood for non-wood products in construction are considered.

Although not shown diagrammatically, carbon prices have little impact on carbon flux. One expects a higher carbon tax/subsidy to lead to more sequestration because the commercial operator benefits not only from carbon stored in products, but also from credits related to the avoided fossil fuel emissions when wood substitutes for non-wood products in construction. At higher carbon prices, a commercial operator wants to harvest as many trees as possible to benefit from carbon offsets created by storing carbon in products and claiming these avoided fossil fuel emissions; likewise, the commercial forestland owner will regenerate the forest quickly to take advantage of carbon uptake credits, because the trees that are planted are a genetic improvement over the natural stock and grow much faster than mature trees. However, our results also indicate that the harvest strategy does not change for carbon prices ranging from \$10 to \$50 per tCO_2 (higher prices were not considered). The commercial operator does not harvest more trees because of the sustainability requirements and biophysical constraints on growth. Yet, the commercial operator does have somewhat more flexibility to pursue opportunities to generate carbon offset credits than under the stricter management regime imposed by the NCC.

If the avoided emissions from substituting wood for non-wood in construction are credited, sustainable commercial management of the Darkwoods site always leads to improved carbon sequestration compared to wilderness, as shown in Figure 3(a). If avoided emissions are not considered, a commercial operator will still create more carbon offsets as long as carbon in the product pool is counted; in our model, this implies that future carbon flux is discounted relative to current uptake. These same conclusions hold if commercial management of the property is compared to NCC management. It is most striking that commercial management of the forest could lead to much higher levels of carbon uptake than would occur under NCC management.

The results indicate that one of the most important parameters we consider is the ability to substitute wood for non-wood products, such as steel and concrete, in construction. We examined no substitution and substitution rates of 0.25 and 0.75, but these could be as high as 1.5 (Hennigar et al. 2008). NOTE THAT IF NOT INCLUDED COULD IMPLY LEAKAGE. Clearly, the number of carbon offsets that a forestry project might be able to claim is highly sensitive to a variety of assumptions about what might happen in the real world.

Discussion

International agreements have legitimized the use of forest sector carbon offset credits for meeting emissions reduction targets. They are considered a stop-gap measure to enable countries and/or companies to meet targets, while they invest in technology and processes that reduce actual CO_2 emissions. However, there are problems with the use of forest offset credits.

First, most analyses of the potential carbon offsets from forest conservation projects do not utilize optimization methods, presumably because they are difficult and expensive to carry out. That is, evaluation of forest carbon offset projects greatly increases transaction costs.

Second, to our knowledge, the original evaluation of the Darkwoods offsets failed to discount physical carbon, and did not consider regeneration of harvested sites (say by a private operator) with improved genetic stock or the fossil fuel emissions saved when lumber substitutes for steel or concrete in construction. If carbon is not discounted, CO_2 removed from the atmosphere 50 or 100 years from now is treated the same as CO_2 removed today. Thus, the carbon offsets created by a project where CO_2 uptake occurs later than sooner are overstated compared to a project that sequesters carbon early on. Further, if post-harvest carbon product sinks are taken into account, landowners seeking to create carbon offsets will harvest trees as soon as possible to be able to credit carbon entering product sinks; this also enables them to plant a new crop of trees that sequester carbon faster than those that were harvested, thereby generating more carbon offset credits. Indeed, if stands are regenerated using improved genetic stock, carbon is sequestered even faster, yielding more carbon offsets than if standard genetic stock were employed. Finally, more carbon offset credits could be earned if emission reductions resulting when wood products substitute for concrete and/or steel in construction are counted.

Nonetheless, this is not the main shortcoming. Rather, it is simply that, ex ante, it is possible to come up with various claims regarding the forest carbon offsets that a land management project generates – there is no clear way of determining how many carbon offsets are created and whether some other management regime would create more or less. It is difficult enough to determine the offset credits created by a tree planting project when account is taken of future harvests, but, when it comes to forest conservation or preservation, it is likely an impossible task. Unmanaged forests are not capable of sequestering as much carbon as forests that are managed sustainably, where harvested timber is used to produce energy and/or wood products that store carbon and substitute for other construction materials, and where harvested sites are artificially regenerated (IPCC 2007; Malmsheimer et al. 2011; Oliver 2013).

Third, the conclusions of most studies of forest carbon sequestration are only made worse if one takes into account problems related to additionality, carbon leakage, impermanence (duration), and transaction costs (measuring, monitoring, etc.), which lead to even larger variation in estimates of carbon sequestration and, thus, the carbon offsets that might be claimed. The complexity of all the carbon fluxes and the task of identifying them leads to an asymmetry (Mason and Plantinga 2013), which, in turn, opens the door to rent seeking opportunities.

These points were demonstrated using a case study of a forestry estate in southeastern British Columbia, Canada. The environmental organization that owns the site managed to sell 700,000 tCO_2 offset credits for which it received \$4 million, or about \$5.75/tCO_2. The buyers subsequently turned around and sold the credits for as much as \$25/tCO_2. The problem was that the buyers were not only promoters of the sale, but also helped facilitate the sale (BC government) or certified the number of carbon offsets the project created (Ecosystem Restoration Associates and its German subsidiary). Our analysis indicates that, given the assumptions used to create the offset credits, the forest estate would not generate the credits indicated. Indeed, we find that, compared to commercial operation of the site, managing the forest estate under the conditions proposed by the Nature Conservancy of Canada, would imply forgoing more than ten times the amount claimed as a credit (or some 12 Mt CO_2).[15] Further, the amounts of forest carbon offsets that could be justified ex ante depend on the method of analysis, the assumed baseline, land tenure, other assumptions relating to the length of time horizon, discount rates, post-harvest carbon storage and regeneration, and so on. As a result, a wide variety of forest offset values could be justified, which makes it difficult to accept any, particularly if one is serious about addressing climate change. This might have been a reason why Europe originally opposed the use of forest carbon offsets in lieu of actual CO_2 emissions reduction.

Finally, it is worth noting that the costs of monitoring the creation of carbon offsets can be extremely high, which might explain why many projects are accepted and granted the right to sell carbon offsets. In the Darkwoods case study considered here, it was necessary to construct a GIS model of the site, determine the current inventory, estimate growth and yield under various management alternatives, and develop a forest management model that included a component that kept track of carbon pools over time. It is clearly the case that, unless an independent certifier with no stake in the outcome is able to spend the time necessary to judge a project, many questionable offset credits will be forthcoming on (global) carbon markets (Helm 2010). This not only distorts the functioning of carbon markets but, by reducing the value of carbon, also creates

[15] The implication is that an additional 12 Mt CO_2 is released into the atmosphere in exchange for protection of a 55,000 ha forest estate, and the environmental benefits it might provide.

adverse incentives for investments in energy-savings technology and energy conservation and its subsequent adverse impact on future warming.

References

3GreenTree Ecosystem Services, Ltd. and ERA Ecosystem Restoration Associates Inc. 2011. Project Description Document, Voluntary Carbon Standard. Nature Conservancy of Canada. Darkwoods Carbon Forest Project. Version 1.8. Belcarra and Victoria, BC: 3GreenTree Ecosystem Services/Nature Conservancy of Canada. April 21. 158pp. Latest version available at: https://s3.amazonaws.com/CCBA/Projects/The_Darkwoods_Forest_Carbon_Project/Darkwoods+CCBA+PDD+v.1.6+-+Final.pdf (accessed 25 February 2014).

BC Ministry of Forests, Mines and Lands. 2010. The State of British Columbia's Forests. 3rd Edition. Victoria, BC: The Province of British Columbia. 308pp.

Bosetti, V. and S.K. Rose. 2011. Reducing Carbon Emissions from Deforestation and Forest Degradation: Issues for Policy Design and Implementation, *Environment and Development Economics* 16(4): 357-360.

Bosetti, V., R. Lubowski, A. Golub and A. Markandya. 2011. Linking Reduced Deforestation and a Global Carbon Market: Implications for Clean Energy Technology and Policy Flexibility, *Environment and Development Economics* 16(4): 479-505.

Bulte, E., D.P. van Soest, G.C. van Kooten and R.A. Schipper. 2002. Forest Conservation in Costa Rica: Optimal Forest Stocks under Uncertainty and Rising Nonuse Benefits, *American Journal of Agricultural Economics* 84(1): 150-60.

Buttoud, G. (editor). 2012. Emerging Economic Mechanisms for Global Forest Governance, *Forest Policy and Economics* (Special Issue) 18(1): 1-52.

Couture, S. and A. Reynaud. 2011. Forest Management under Fire Risk when Forest Carbon Sequestration has Value, *Ecological Economics* 70(11): 2002-2011.

Hahn, R. and K. Richards. 2013. Understanding the Effectiveness of Environmental Offset Policies, *Journal of Regulatory Economics*, forthcoming, DOI 10.1007/s11149-013-9211-1.

Helm, D., 2010. Government Failure, Rent-Seeking, and Capture: The Design of Climate Change Policy, *Oxford Review of Economic Policy* 26: 182-196.

Hennigar, C.R., D.A. MacLean and L.J. Amos-Binks. 2008. A Novel Approach to Optimize Management Strategies for Carbon Stored in Both Forest and Wood Products, *Forest Ecology and Management* 256(4): 786-797.

Ingerson, A. 2011. Carbon Storage Potential of Harvested Wood: Summary and Policy Implications, *Mitigation and Adaptation Strategies for Global Change* 16(3): 307-323.

IPCC, 2007. *Climate Change 2007: Mitigation of Climate Change*, edited by B. Metz, O.R. Davidson, P.R. Bosch, R. Dave and L.A. Meyer. Contribution of Working Group III to the Fourth Assessment Report of the IPCC. New York: Cambridge University Press.

IPCC, 2000. *Land Use, Land-Use Change, and Forestry*. New York, NY: Cambridge University Press.

Kaimowitz, D. 2008. The Prospects for Reduced Emissions from Deforestation and Degradation (REDD) in Mesoamerica, *International Forestry Review* 10: 485-495.

Kull, S.J., G.J. Rampley, S. Morken,J. Metsaranta, E.T. Neilson and W.A. Kurz, 2011. Operational Scale Carbon Budget Model of the Canadian Forest Sector (CBM – CFS3), Version 1.2: User’s Guide. Catalogue No. Fo134-5/2011E-PDF. Edmonton, AB: Northern Forestry Center, Canadian Forest Service, Natural Resources Canada.

Kurz, W.A., S.J. Beukema and M.J. Apps. 1996. Estimation of Root Biomass and Dynamics for the Carbon Budget Model of the Canadian Forest Sector, *Canadian Journal of Forest Research* 26(11): 1973-1979.

Law, E.A., S. Thomas, E. Meijaard, P.J. Dargusch and K.A. Wilson. 2012. A Modular Framework for Management of Complexity in International Forest-Carbon Policy, *Nature Climate Change* 2(March): 155-160.

Malmsheimer, R.W., J.L. Bowyer, J.S. Fried, E. Gee, R.L. Izlar, R.A. Miner, I.A. Munn, E. Oneil and W.C. Stewart, 2011. Managing Forests because Carbon Matters: Integrating Energy, Products, and Land Management Policy, *Journal of Forestry* 109(7S): S7–S50. http://www.safnet.org/documents/JOFSupplement.pdf. (accessed 31 October 2013).

Mason, C.F. and A.J. Plantinga. 2013. The Additionality Problem with Offsets: Optimal Contracts for Carbon Sequestration in Forests, *Journal of Environmental Economics and Management*, forthcoming.

Millard-Ball, A. 2013. The Trouble with Voluntary Emissions Trading: Uncertainty and Adverse Selection in Sectoral Crediting Programs, *Journal of Environmental Economics and Management* 65: 40-55.

Nature Conservancy Canada. 2010. Darkwoods Conservation Area. Property Management Plan Summary 2011-2016. September. Invermere, BC: NCC British Columbia Region. 20pp.

Niquidet, K., B. Stennes and G.C. van Kooten. 2012. Bio-energy from Mountain Pine Beetle Timber and Forest Residuals: The Economics Story, *Canadian Journal of Agricultural Economics* 60(2): 195-210.

Oliver, M., 2013. Do Carbon Offsets Work? The Role of Forest Management in Greenhouse Gas Mitigation, *Science Findings* Issue 155, August. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Peters-Stanley, M., K. Hamilton, T. Marcello and M. Sjardin. 2011. Back to the Future. State of the Voluntary Carbon Markets 2011. Report by Ecosystem Marketplace & Bloomberg New Energy Finance. June 2. Washington, DC & New York, NY: Ecosystem Marketplace and Bloomberg New Energy Finance. 93pp.

Rainforest Alliance. 2011. Validation Assessment Report for The Nature Conservancy Canada Darkwoods Carbon Forest Project in Nelson, BC. Doc. No. C-56 May 2010. Final Report, Smartwood Program Carbon Forestry Validation Audit for the Voluntary Carbon Standard (VCS), April 21. Richmond, VT: Rainforest Alliance. 73pp. Viewed 25 February 2014 at:

http://www.rainforest-alliance.org/sites/default/files/climate_project/Darkwoods_Audit_Report.doc

Rose, S.K. and B. Sohngen. 2011. Global Forest Carbon Sequestration and Climate Policy Design, *Environment and Development Economics* 16(4): 429-454.

Rosenthal, R.E., 2008. *GAMS – A User's Guide*. Washington, DC: GAMS Development Corporation.

Sathaye, J., K. Andrasko and P. Chan. 2011. Emissions Scenarios, Costs, and Implementation Considerations of REDD-plus Programs, *Environment and Development Economics* 16(4): 361-380.

Smith JE, Heath LE, Skog KE, Birdsey RA: Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States Newtown Square, PA: USDA Forest Service Northeastern Forest Experiment Station; 2006, Gen Tech Rep NE-343.

Thomae, O. 2005. Timber Merchantability Analysis. March. 24pp. Cranbrook, BC: ArbourTech Forest Management Services. Accessed 5 October 2011 from: www.for.gov.bc.ca/ftp/hcp/external/!publish/web/fia/MerchantabilityModel2003Revision.pdf

van Kooten, G.C. 1995. Economics of Protecting Wilderness Areas and Old-Growth Timber in British Columbia, *The Forestry Chronicle* 71(Feb/Mar): 52-58.

van Kooten, G.C. 2009. Biological Carbon Sequestration and Carbon Trading Re-visited, *Climatic Change* 95(3-4): 449-463.

van Kooten, G.C. 2013. *Climate Change, Climate Science and Economics: Prospects for an Alternative Energy Future*. Dordrecht, NL: Springer.

van Kooten, G.C. and E.H. Bulte. 1999. How Much Primary Coastal Temperate Rainforest Should Society Retain? Carbon Uptake, Recreation and Other Values, *Canadian Journal of Forest Research* 29(12): 1879-1890.

van Kooten, G.C., S. Laaksonen-Craig and Y. Wang. 2009. A Meta-Regression Analysis of Forest Carbon Offset Costs, *Canadian J of Forest Research* 39(11): 2153-2167.

Wilman, E.A. and M.S. Mahendrarajah. 2002. Carbon Offsets, *Land Economics* 78(3): 405-416.

Krcmar, E. and G.C. van Kooten, 2008. Economic Development Prospects of Forest-Dependent Communities: Analyzing Tradeoffs using a Compromise-Fuzzy Programming Framework, *American J of Agricultural Economics* 90(4):1103-1117.
Krcmar, E., I. Vertinsky and G.C. van Kooten, 2003. Modeling Alternative Zoning Strategies in Forest Management, *International Transactions of Operations Research* 10(5): 483-498.
Krcmar, E., B. Stennes, G.C. van Kooten and I. Vertinsky, 2001. Carbon Sequestration and Land Management under Uncertainty, *European J of Operational Research* 135(December): 616-629.
van Kooten, G.C., E. Krcmar-Nozic, B. Stennes and R. van Gorkom, 1999. Economics of Fossil Fuel Substitution and Wood Product Sinks when Trees are Planted to Sequester Carbon on Agricultural Lands in Western Canada, *Canadian J of Forest Research* 29(11): 1669-1678.
Krcmar-Nozic, E., G.C. van Kooten, I. Vertinsky and S. Brumelle, 1998. An Interactive Multiobjective Approach to Harvest Decisions in Forest Planning, *Scandinavian J of Forest Research* 13(3): 356-68.