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forest management

Forest Carbon Offsets Revisited: Shedding Light on Darkwoods

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This paper investigates the viability of carbon offset credits created through forest conservation and preservation. A detailed forest management model based on a case study of a forest estate in southeastern British Columbia, owned by The Nature Conservancy of Canada (NCC) is used to demonstrate the challenging nature of estimating forest carbon offsets. For example, the NCC management plan creates substantial carbon offset credits because the counterfactual is that of a private forest liquidator, but when sustainable management of the site is assumed, the commercial operator would sequester much more carbon than under the NCC plan. The broader message is that the creation of carbon offsets is highly sensitive to ex ante assumptions and whether physical carbon is discounted. We demonstrate that more carbon gets stored in wood products as the discount rate on carbon rises (addressing climate change is more urgent). A high discount rate on carbon favors greater harvests and processing of biomass into products, while a low rate favors reduced harvest intensity. Further, since carbon credits earned by protecting forests may find their way onto world carbon markets, they lower the costs of emitting CO_2 while contributing little to mitigating climate change.

Keywords: forest management, carbon flux, discounting physical carbon, climate change

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 United States 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

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This article uses metric units; the applicable conversion factors are: meters (m): 1 m = 3.3 ft; cubic meters (m^3): 1 m^3 = 35.3 ft^3; kilometers (km): 1 km = 0.6 mi; hectares (ha): 1 ha = 2.47 ac.

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).

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. Overall, 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 such dynamic complications (see Wilman and Mahendrarajah 2004).

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" (Malmsheimer et al. 2011, Oliver 2013). 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, on 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% (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 cobenefits of such projects—the noncarbon benefits—amount to between 57.5 and 76.5% of the total protection benefits, while Rose and Sohngen (2011) argue that Kyoto's current focus on afforestation 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^{-1} in 2010, down from a high of \$5.81 tCO_2^{-1} 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 cobenefits can be financed from the sale of such offsets, thereby creating enhanced incentives for landowners to increase other services from the land, such as biodiversity. We show that this multimarket 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, to demonstrate that the carbon offsets created are questionable in terms of their contribution to climate change mitigation, we use an example of a forest preservation activity in British Columbia (BC), which generated forest offset credits for the voluntary market but imposed real costs on the province's citizens.

Using a detailed forest management model, our study finds that forest carbon sequestration is highly sensitive to assumptions about the postharvest 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 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 BC that generated important voluntary offset credits. We then develop a Geographic Information Systems (GIS)-based forest management model of the study area, using publicly available data, which we subsequently use to compare carbon fluxes under different management regimes. The data are then described, followed by the results comparing carbon sequestration under various management regimes. We end with a summary and conclusions.

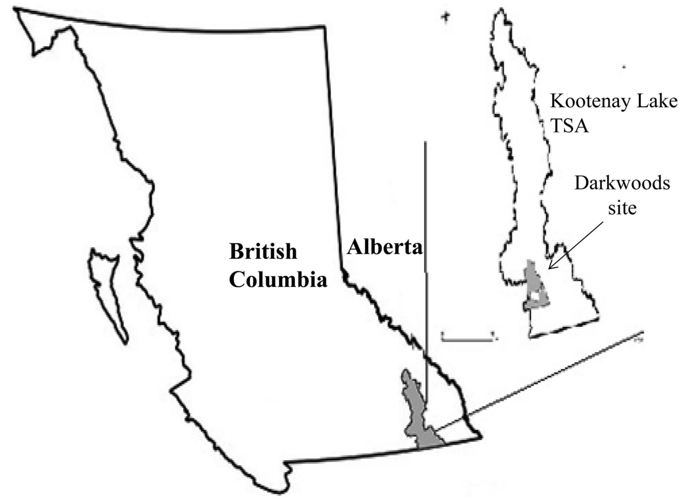

Figure 1. Location of the Darkwoods site in southeastern BC.

Carbon Offset Credits from Forest Protection: The Case of Darkwoods

Some 14.8% of BC's land base is officially protected, while 42% 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 and, thus, 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, but then it would seem logical to also count the CO_2 emitted as a result of wildfire and/or decay of biomass as a debit. However, since natural processes have always contributed to atmospheric CO_2, it might make more 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.

In 2008, The NCC purchased the 54,800 ha Darkwoods property on the west side of the south arm of Kootenay Lake near the US border (Figure 1) for $125 million from the German logging company Pluto Darkwoods, having received financial support for this purchase from the federal government.[2] 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 annual harvests have fallen from over 50,000 m^3 under the private owner to 10,000 m^3 under NCC ownership.

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^{-1}, at a time when offset credits were trading for more than C$15.00 tCO_2^{-1} on the European carbon exchange (ETS). An international environmental nongovernment organization (ENGO), the Rainforest Alliance (2011), certified the carbon offsets under the Voluntary Carbon Standard (VCS) label.[3]

The number of carbon offsets generated was determined as the difference in the carbon flux between the proposed NCC management regime (harvests of 10,000 $m^3\ yr^{-1}$) and the operation of the Darkwoods site by the hypothetical commercial operator.[4] 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, p. 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" (Rainforest Alliance 2011, p. 32). Not only does the latter statement contradict the earlier one, but private forest landowners would take offense at being told that their actions fail to take "basic environmental protections" into account.[5] Nor would it be possible for a timber liquidator to sell logs into a market that requires forest management standards to be certified by the Forest Stewardship Council (FSC) or another international certifier of forest practices. The counterfactual used to determine the carbon offsets generated on the Darkwoods site is not likely to be plausible.

In calculating the carbon offset benefits, the carbon sequestered annually in living biomass and long-term carbon stored in wood products constituted a credit, while CO_2 emissions associated with harvesting, hauling, processing, and silviculture constituted a source.[6] 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.

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 since the below market price received by the 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 reassessment of the Darkwoods project and the claim that forest conservation can 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

In this section, we outline the forest management model as applied to the Darkwoods property, with a particular focus on carbon accounting. As the basis of our 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 is employed.

Let $x_{s,a,z,m,t}$ denote the ha 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 postharvest silviculture (natural or artificial regeneration). Also, let $v_{s,a,z,m,t}$ be the associated total merchantable volume ($m^3\ ha^{-1}$) of the stand at time *t* that is to be converted to lumber, wood chips (used in pulp mills or the manufacture of oriented-strandboard, 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

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

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 subzones and two slope classes. Sites are further classified by seven primary and 10 secondary species.

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

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

where

$$C_t^r = \sum_{s=1}^{S} \sum_{a=1}^{A} \sum_{z=1}^{Z} \sum_{m=1}^{M} c^r_{s,a,z,m,t} v_{s,a,z,m,t} x_{s,a,z,m,t},$$

$$\forall t,\ r \in \{\text{log, haul, silv, admin, process}\}. \qquad (3)$$

In Equation 3, costs are much more coarsely defined than indicated. Thus, at time *t*, $c^{\log}_{s,a,z,m,t}$ are logging costs per cubic meter, 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 ha 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 and 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 logging site or as a result of processing. The price of chips is the same regardless of how chips are used. Let p_{lum}, p_{chip}, and p_{waste} be the fixed prices, respectively, of lumber, chips, and residual/waste wood fiber used for other purposes, including as fuel for heating or generation of electricity.

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

$$\text{NPV} = \sum_{t=1}^{T} \beta^t \left[(p_{lum}\varepsilon_1 + p_{chip}\varepsilon_2 + p_{waste}\varepsilon_3) H_t - C_t - p_C(E_t + CO2_t^{eco} + CO2_t^{product} + S_t^{C\&S}) \right], \qquad (4)$$

where p_C refers to the (shadow) price of carbon dioxide (\$ tCO_2^{-1}), and $\beta = 1/(1+r)$ is the discount factor with *r* the discount rate on monetary values. For simplicity and given fixed product prices and proportions ε_i, we assume that the price of logs (\$$m^{-3}$) ($= p_{lum}\varepsilon_1 + p_{chip}\varepsilon_2 + p_{waste}\varepsilon_3$) is the value of interest in the objective function (Equation 4). On the other hand, the price of CO_2 is used to incentivize the decisionmaker to manage the forest not only to harvest trees for commercial purposes but also to produce CO_2 sequestration services.

In the current implementation, the carbon price consists of a per unit tax on emissions, regardless of their source, and a subsidy for any removal of CO_2 from the atmosphere and subsequent storage in a variety of carbon pools. Notice that $CO2_t^{eco}$ and $CO2_t^{product}$ are the carbon stored in ecosystem and product sinks at time *t*. Because carbon is stored and released slowly over time, the associated carbon fluxes need to be aggregated to a single point in time, which is unnecessary for emissions that occur at a point in time. That is, it is necessary to account for the length of time that the carbon remains in a sink, preventing CO_2 from returning to the atmosphere—it is important to weight carbon flux as to when it occurs.[7] This issue is discussed further below. Finally, $S_t^{C\&S}$ refers to the CO_2 emissions from fossil fuels that are avoided in the production of cement and steel, say, if wood substitutes for nonwood products in construction.

Objective function 4 is maximized subject to Equations 1–3, a variety of technical constraints (see Krcmar et al. 1998, 2001, 2003), and the carbon dynamics. The technical constraints 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 be on the stand before harvest can occur; sustainability constraints; nonnegativity constraints; and other constraints relating to the specific scenarios that are investigated. We also 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 degradation of the Darkwoods site, although the government might impose more stringent sustainability requirements.

Model parameters are provided in the data description 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.

Carbon Pools and CO_2 Emissions

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. Discounting can be avoided, for example, by counting only the carbon fluxes that occur over some (arbitrary) time period.[8] 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, failure to weight carbon flows occurring at different times would encourage delay of mitigating action and, in the limit where there is no discounting of physical carbon, delay it indefinitely.

In the current model we take into account four categories of carbon flux: (1) CO_2 emissions from harvesting, hauling, and processing of logs into products and from silvicultural activities; (2) carbon that is sequestered in each period in the aboveground (leaves, branches, litter) and belowground (soil, roots) biomass; (3) carbon stored in wood products that decay over time; and (4) the avoided fossil fuel emissions when wood products substitute for nonwood products in construction. Since the price of fuel is fixed in the analysis as is the efficiency of equipment, CO_2 emissions, denoted E_t in Equation 4, are assumed to be fixed proportions of the logging, hauling, silvicultural, and manufacturing/processing costs. This is discussed further in the data description section.

To address ecosystem carbon flux ($CO2_t^{eco}$), we follow the approach employed by Malmsheimer et al. (2011). This is implemented in the current application using a forest growth-and-yield model that keeps track of carbon fluxes in the ecosystem. In particular, the carbon component of the model, which is described in greater detail in the data section, keeps track of living and dead biomass and whether it is above or below ground. The aboveground live component includes the wood, bark, branches, and leaves, while the belowground component constitutes the roots. The dead biomass stock includes litter and soil organic matter and roadside wastes, if any.

We consider the carbon stored in three product pools: in lumber, in products made from wood chips (including pulp), and in residuals and waste used to produce medium density fiberboard, wood pellets for exports, heat, or electricity.[9] The carbon stored in dead organic matter and material left at roadside are treated separately as

Table 1. Model parameters.

Parameter	Assigned value	Description
T	200 yr	Length of the planning horizon
T	10 yr	Time step
P_{logs}	\$75/m^3	Net price of logs (determined from all product prices)
p_C	{\$0, \$10} tCO$_2^{-1}$	Shadow price of carbon dioxide
c^{truck}	\$4.50 m^{-3}	Trucking cost per m^3 of logs fixed for each time period[a]
c^{log}	{\$22, \$42}	Logging cost per m^3 varies by slope category (<40°, >40°)
c_1^{admin}	\$8 ha^{-1}	Fixed administration & site development cost per harvested ha[b]
c_2^{admin}	\$14 ha^{-1}	Overhead and road maintenance cost[b]
c_z^{silv}	{\$1522, \$1605}	Fixed silvicultural cost per harvested ha by two major BEC zones
R	4%	Discount rate for monetary values; $\beta = 1/(1+r)$
r_c	{0%, 2%, 4%}	Discount rate for physical carbon; used to find duration factor g
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 m^{-3}	Emissions avoided when wood substitutes for other products[c]
	150 m^3 ha^{-1}	Minimum volume before site can be harvested

[a] Assumes a cycle time of 1 to 2 h.
[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^{-1} and road maintenance cost of \$2.56 ha^{-1}.
[c] Avoided emissions vary from 0.5–0.9 tC per m^3 (1.8–3.3 tCO$_2$ 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, p. 133, 137), Thomae (2005), Niquidet et al. (2012), Hennigar et al. (2008), and Ingerson (2011).

is the carbon in living matter (which does not decay). Let the rate of decay for each of the three product pools be denoted d_1, d_2, and d_3, 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 carbon stored at time t in the three product pools as a result of harvest H_t is given as[10]

$$CO2_t^{product} = \varphi \sum_{i=1}^{D} \frac{r_c}{r_c + d_i} \varepsilon_i H_t, \quad (D = \text{lumber, chips, residuals/waste}). \tag{5}$$

where d_i is the decay rate of carbon in product pool i (see Table 1 below), and parameter φ (= 44/12) converts carbon to CO_2. Notice that, when the discount rate on carbon is zero ($r_c = 0\%$), no carbon is effectively retained in carbon products as all carbon is eventually released to the atmosphere.

The corollary to Equation 5 relates to emissions of CO_2 from decaying wood products. Because the rate at which carbon in post-harvest product pools returns to the atmosphere varies considerably in our model (see Table 1), the release of CO_2 from postharvest products is charged to a common date, namely the time of harvest; this again requires the use of a discount rate on physical carbon. Consider perhaps the most important carbon pool, namely, wood products. As demonstrated with respect to Equation 5, 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 at the time of harvest is equivalent to

$$\theta = \sum_{i=1}^{D} \left(\frac{d_i}{d_i + r_c} \right) \varepsilon_i, \tag{6}$$

where θ is measured in tCO_2 per cubic meter of harvested wood and ε_i is the proportion of harvesting going into product pool i. Clearly, if the 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 or even 1,000 years from now. Thus, if $r_c = 0\%$, all CO_2 stored in timber is treated as if it is released immediately on harvest.

The implication of Equations 5 and 6 is clear. As the rate used to discount physical carbon increases, future CO_2 emissions from the decay of wood products or biomass 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, but it is also important because, by using a zero discount rate for carbon, the implication is that climate change is not an urgent matter. After all, $r_c = 0\%$, implies that the removal of CO_2 from the atmosphere can be delayed indefinitely.

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

$$S_t^{C\&S} = \varphi \xi H_t, \tag{7}$$

where ξ is a parameter denoting the emissions avoided when wood substitutes for other products. If $\xi = 0$, there is no benefit when wood substitutes for nonwood products in construction. In the scenarios, we consider various values of ξ, including zero.

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, 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 publicly available forest cover 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.

To predict timber growth and yield of managed and natural stands, we then employed the TIPSY model, which is used by the BC Ministry of Forests, Lands and Natural Resource Operations, for example, for timber supply analysis. TIPSY refers to the Table Interpolation Program for Stand Yields; it includes the Tree and Stand Simulator (TASS) and a variable density yield prediction system for natural stands.[11] TASS employs the Carbon Budget Model of the Canadian Forest Sector (Kurz et al. 1996, Kull et al. 2011) to track all living and dead biomass and whether it is above or below ground. TIPSY can be used to evaluate silvicultural treatments and address other stand-level planning options; it also 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. Using TIPSY carbon fluxes and the decay rates in Table 1, it is straightforward to calculate the "periodic recruitment" of carbon, which can then be translated into a CO_2 equivalent measured in metric tons.

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. TIPSY output is then called directly into the forest management model written in GAMS.[12]

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.

Consider the effects of 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, and, because some selective breeding for growth characteristics, such as height or pest resistance, has occurred in the nurseries, these seedlings grow faster than the harvested or naturally regenerated trees (BC Ministry of Forests, Mines, and Lands 2010, p. 147–148). 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 than if the stand were left to regenerate on its own, 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 (expected height of trees at a particular age) for the same tree species can be increased from, say, 20 m on a 50-year basis to perhaps 28 m, or by 40%. This might translate into an increase in the amount of carbon stored on a site by perhaps 30% compared to allowing natural regeneration. This is a clear benefit of permitting harvest activities and is included in the TIPSY output. Silvicultural costs are provided in Table 1 for artificially regenerated stands.

We also consider the potential impact of avoided emissions when wood is substituted for nonwood products, such as steel and concrete in construction. Information on the extent of avoided emissions is reported in Table 1, with values of ξ ranging from 0.0 to 0.75, although Hennigar et al. (2008) report values as high as ξ = 1.5. Notice, however, that we do not account for the fossil fuel savings from burning wood because electricity in 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 (see Table 2).

Results: Comparison of Carbon Sequestration across Scenarios

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 the (commercial) decisionmaker in our model begins to increase harvests in anticipation of the end of the time horizon as early as 2 decades beforehand, we present results only for 150 years while still optimizing over 200 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 Equation 4 subject to constraints 1–3 and other technical constraints required in the model (as discussed above) plus constraints required by the 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 nonwood materials in construction. The baseline carbon fluxes are provided in Figure 2.

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. In the current situation, the forest is growing faster than it decays because the starting inventory includes significant young stands as a result of previous logging activities. In our model, the decline in net carbon uptake begins after about 70 years when tree growth slows down. 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.

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
Nonstructural panels	0.120
Mechanical pulping	0.480
Chemical pulping	0.130
Trucking (50 km)	0.00007 per km

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

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 Equations 5 and 6), 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 sequestered 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 follows from Equation 6 and is also shown in Figure 2. The commercial operator would end up storing much more carbon in postharvest product pools, which, along with regeneration of harvested sites with younger and 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 a 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^{-1} and $\$10$ tCO_2^{-1}. 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

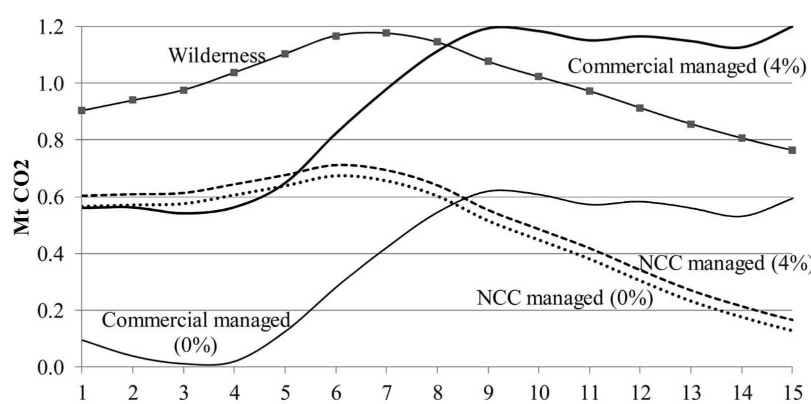

Figure 2. Carbon flux on Darkwoods site, wilderness, NCC management and commercial management; biological and product carbon pools only; carbon discount rates of 0 and 4%.

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^{-1}		Price of carbon = \$10 tCO_2^{-1}	
	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

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

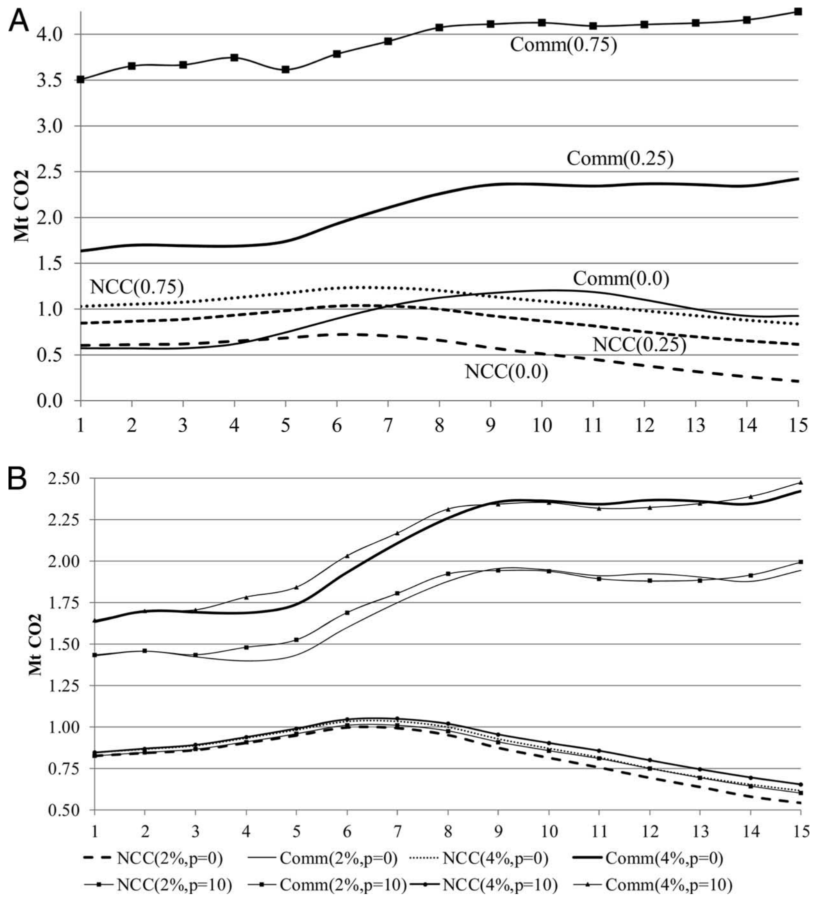

Figure 3. Net CO_2 sequestered per decade: NCC versus commercial management, 4% discount rate for monetary values. (A) Carbon price of \$10 per tCO_2, 4% discount rate for physical carbon fluxes, and various wood substitution parameters (in parentheses; tC m^{-3}). (B) Carbon flux, 2% and 4% carbon discount rates, \$0 and \$10 per tCO_2 carbon prices.

fall between those of 0% and 4%, while results for a \$50 tCO_2^{-1} price lead to the same levels of carbon as the \$10 tCO_2^{-1} price. With a 4% discount rate on monetary values and no carbon price to incentivize forest managers to sequester carbon and reduce CO_2 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 timber growth is somewhat faster than in the case of wilderness, NCC management results in CO_2 emissions from the little harvesting, hauling, processing, and silvicultural activity that occurs on the site, with any carbon stored in products effectively lost to the atmosphere on 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.

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, land is managed somewhat differently (e.g., different sites are chosen for harvest, treeplanting 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 nonwood 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 is preferred to commercial operation of the Darkwoods property only if the only carbon fluxes to be considered are those related to timber growth (including carbon in all above- and belowground pools) and CO_2 emissions from harvesting, hauling, and processing wood—that is, postharvest 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 3a, where only the potential fossil fuel savings from substituting wood for nonwood 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 nonwood 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 seedlings that are planted grow faster than ones that regenerate naturally, while both 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). A 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 nonwood in construction are credited, sustainable commercial management of the Darkwoods site always leads to improved carbon sequestration compared to wilderness or NCC management (Figure 3). 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 carbon uptake or CO_2 emissions. 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.

We have not addressed leakage. If prices of wood products are unaffected by products from Darkwoods (a reasonable proposition given the property's small contribution to regional timber supply), then lumber from Darkwoods, for example, would simply substitute from lumber produced elsewhere. In that case, the carbon stored in forest products from Darkwoods and the associated CO_2 emissions from logging, hauling, processing, and silvicultural activities would be offset by reduced production elsewhere. The same would be true for the substitution of wood for nonwood products, as this only occurs if the prices of wood products fall relative to those of nonwood—the harvests from Darkwoods are likely insufficient to impact markets to such an extent. This makes it even more difficult to determine the extent to which carbon offset credits can be claimed. 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 use optimization methods, primarily 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 Darkwoods' carbon offsets failed to discount physical carbon and did not consider regeneration of harvested sites with improved genetic stock or the avoided fossil fuel emissions 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 postharvest 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 landowners 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 seedlings from tree nurseries (enhanced genetic stock), carbon is sequestered even faster, yielding more carbon offsets than if stands were allowed to regenerate on their own. Further, 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 treeplanting 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. This is a systemic problem in the market for voluntary carbon offset credits that needs to be avoided in true markets.

These points were demonstrated using a case study of a forestry estate in southeastern BC, 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^{-1}. The buyers subsequently turned around and sold the credits for as much as \$25 tCO_2^{-1}. 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 is capable of creating additional carbon offsets. Indeed, we find that, compared to commercial operation of the site, managing the forest estate under the conditions proposed by the NCC might imply forgoing nearly twice as much CO_2 sequestration as was claimed, or more than 1.1 Mount CO_2 (Table 3).[15] However, 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, and postharvest carbon storage and regeneration. 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 and verifying 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 distorts the functioning of carbon markets by reducing the value of carbon.

Endnotes

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.
2. Information is available from stories appearing June 10 and 11, 2011 in local newspapers, the *Vancouver Sun* and national *Globe and Mail*.
3. 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.
4. 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.
5. In this regard, see www.pfla.bc.ca/.
6. See 3GreenTree Ecosystem Services & Ecosystem Restoration Associates (2011, p. 19–20). The aboveground, nontree living biomass, litter, and soil carbon pools were not included.
7. The importance of discounting physical flows of resources as to when they take place is well established (see van Kooten 2009, van Kooten 2013, p. 332–334).
8. To avoid weighting carbon fluxes according to when they occur, the United Nations' Framework Convention on Climate Change (UN FCC) process has developed a variety of methods to compare carbon fluxes from alternative forest activities (e.g., van Kooten 2013, p. 355–358), but none is as efficient as the use of a carbon discount rate.
9. 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 but also because forest companies would otherwise purchase emissions-free hydropower for heating.
10. This follows because $\lim_{n\to\infty}\left\{C + \frac{(1-d)C}{1+r_c} + \frac{(1-d)^2C}{(1+r_c)^2} + \ldots + \frac{(1-d)^nC}{(1+r_c)^n}\right\} = \frac{r_c}{r_c+d}C$, where d is the rate of decay of carbon C.
11. Information can be found at www.for.gov.bc.ca/hre/gymodels/tipsy/assets/intro.htm.
12. The data files from TIPSY and the GAMS files are available from the authors upon request.
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.
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.

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