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Rent Seeking and the Smoke and Mirrors Game in the Creation of Forest Sector Carbon Credits: An Example from British Columbia

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Rent Seeking and the Smoke and Mirrors Game in the Creation of Forest Sector Carbon Credits: An Example from British Columbia

ABSTRACT

From a cost standpoint and as demonstrated in this paper, it is beneficial to permit forest-sector carbon offsets in lieu of carbon dioxide emissions reduction. Such offsets play a role in voluntary markets and Europe's Emission Trading System. However, problems related to additionality, leakages, duration and impermanence, high transaction costs, and governance raise important questions about the validity of most carbon offset credits from forestry. Using data for a forest estate in south-eastern British Columbia owned by the Natural Conservancy of Canada (NCC), we construct a forest management model to demonstrate that the planned NCC management program yields questionable forest carbon offsets. NCC management results in slightly less annual carbon sequestration than leaving the forest as wilderness, but sustainable commercial management of the site sequesters between 8 and 270 thousand tonnes of CO_2 more per year than NCC management. Because commercial exploitation was the counterfactual used to justify the NCC carbon offsets, offsets were subsequently sold to non-arms-length buyers, and numbers of carbon offsets are highly sensitive to assumptions, one can only conclude that the carbon offsets generated by this (and probably many other) forest conservation projects are simply spurious.

Key words: climate change and forestry; forest carbon offsets; forest conservation; REDD

JEL categories: Q54, Q23, P28

0. INTRODUCTION

It makes intuitive sense as a strategy for mitigating climate change to take account of carbon offsets generated by projects that promote tree growth or otherwise cause more carbon to be stored in biological ecosystems, including those that enhance soil organic carbon (IPCC 2000). The European Union originally opposed the use of biological 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). However, after the United States withdrew from the Kyoto negotiations following COP6 in The Hague, partly as a result of Europe's stance on carbon sinks, the Kyoto signatories (minus the U.S.) 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).

The November 2001 Marrakech Accord specifically 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, it left open the possibility for including other components, such as wood product carbon sinks, wetlands and soil carbon sinks (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. There have been strict guidelines regarding projects to establish or re-establish plantation forests in developing countries under CDM, but a more troublesome aspect relates to the role of activities that prevent or delay deforestation.

Although forest conservation activities are currently not eligible for emission reduction offsets, concerns about tropical deforestation have led many to commend the use of forest conservation in developing countries as a tool for addressing global warming. In international negotiations, activities that Reduce Emissions from Deforestation and forest Degradation (REDD) are seen as an alternative means for earning certified emission reduction (CER) credits. Indeed, as a result of negotiations at Cancun in December 2010, the narrow role of REDD has been expanded to include sustainable management of forests, forest conservation and the enhancement of forest carbon stocks, collectively known as REDD+. In this way, the UN FCCC and the Convention on Biological Diversity (CBD), an agreement also signed at the 1992 Earth Summit in Rio de Janeiro, have become intertwined (Secretariat of CBD 2009). Increasingly, therefore, climate negotiators appear willing to accept REDD+ activities for potential emission offset credits to the extent that these activities also enhance biodiversity. As such, the idea is that REDD+ generates co-benefits of forest conservation that include ecological and social outcomes such as preservation of biodiversity and improved living standards of indigenous peoples. Since deforestation and biodiversity are a problem in developing countries, including REDD+ activities in the CDM can be viewed as an indirect form of development aid. Might it nonetheless be possible for REDD+ projects in developed countries to earn emission offset credits for sale on international markets in the same way as REDD+ credits from developing countries? If REDD+ (or just REDD) carbon offset credits can be created in developed countries as well as developing ones, what are the implications for reducing atmospheric CO_2?

In this paper, we examine the role of REDD+ carbon offset credits in emission trading markets, focusing in particular on the consequences of trading off emissions reduction for forest conservation. One important aspect that we investigate relates to REDD+ offsets created in rich countries versus those in poor countries. Our main argument is that rent-seeking behavior by economic agents on both sides of the emissions trading market has distorted global markets, depressed prices and market signals, increased the potential for corruption, and lessened incentives to address climate change.

We begin in the next section with a description of the rent-seeking opportunities that exist given the possibility of trade in carbon offsets across the voluntary and the mandatory markets, followed by a discussion of the mechanism by which emissions trading is distorted in favor of the large industrial emitters, environmental groups and government to the detriment of rich-country taxpayers, citizens in developing countries and the future climate. In section 3, we illustrate our arguments using the example of a forest conservation activity in British Columbia that generated REDD+ offset credits. We use a forest management model to determine that the credits created are questionable in terms of their contribution to the reduction of atmospheric CO_2. Our analysis concludes with support for the initial European position against carbon offset trading.

1. RENT-SEEKING TO CIRCUMVENT EMISSION REDUCTIONS

The international community is currently engaged in deliberations concerning whether the UN FCCC's Kyoto process ought to certify REDD+ greenhouse gas emission offset credits under the CDM and, if so, the requirements for including such credits as certified emission reductions (Bosetti and Rose 2011). Sathaye et al. (2011) indicate that the co-benefits of REDD+, namely the non-carbon sequestration benefits, amount to between 57.5 and 76.5 percent of the total REDD+ 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 net costs of achieving a global target of 550 parts CO_2 per million by volume in the atmosphere by upwards of $\$2\times10^{12}$. These results are based on output from computer models, that a new climate agreement will be struck, and ideal global governance (an ideal questioned in the current study).

In the meantime, REDD+ and other forestry activities play a large role in the voluntary emission reductions (VERs) market (Figure 1). The market for VERs amounted to $424 million in 2010, with trades averaging $3.24 per tCO_2 in 2010, down from a high of $5.81/$tCO_2$ in 2008 (Figure 2). This compared to a total global carbon market estimated to be worth €92 billion (approximately $125 billion) in 2011, an increase of 10% over 2010.[1] There is the suggestion, however, that VERs are sold not only in the voluntary market but also in the mandatory market, most notably the EU's Emission Trading System (EU ETS) (e.g., Peters-Stanley et al. 2011). Thus, while CER credits created by REDD+ activities are not currently available for sale in international markets, VER REDD+ credits are marketed in global carbon markets.

[1] This is according to a press release from Bloomberg New Energy Finance dated January 11, 2012.

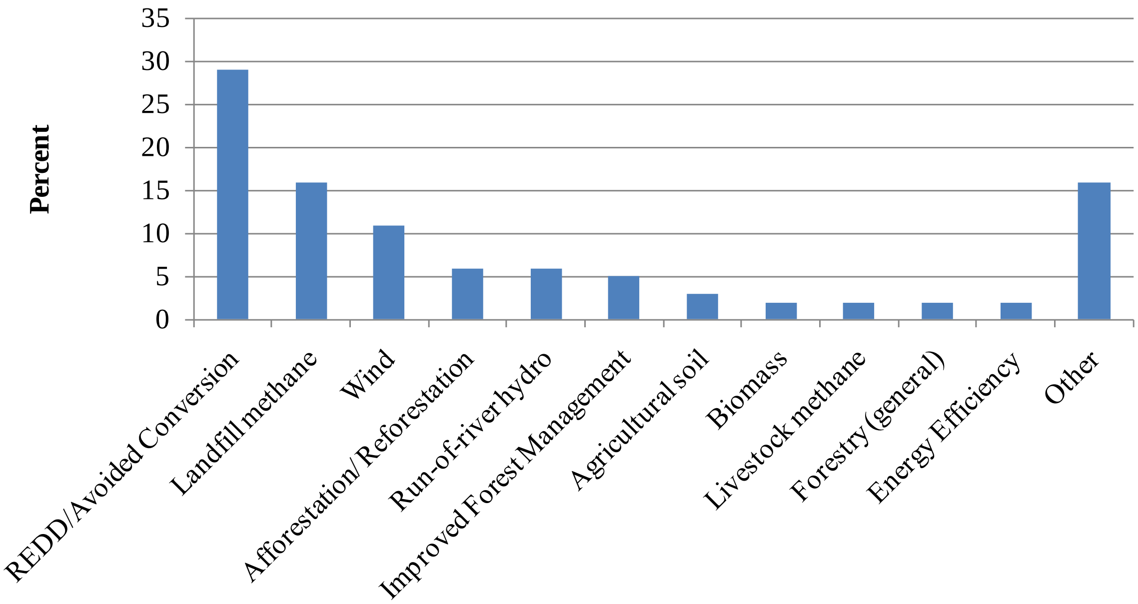

Figure 1: Over the Counter (OTC) Sales of Voluntary Carbon Offsets by Origin, 2010

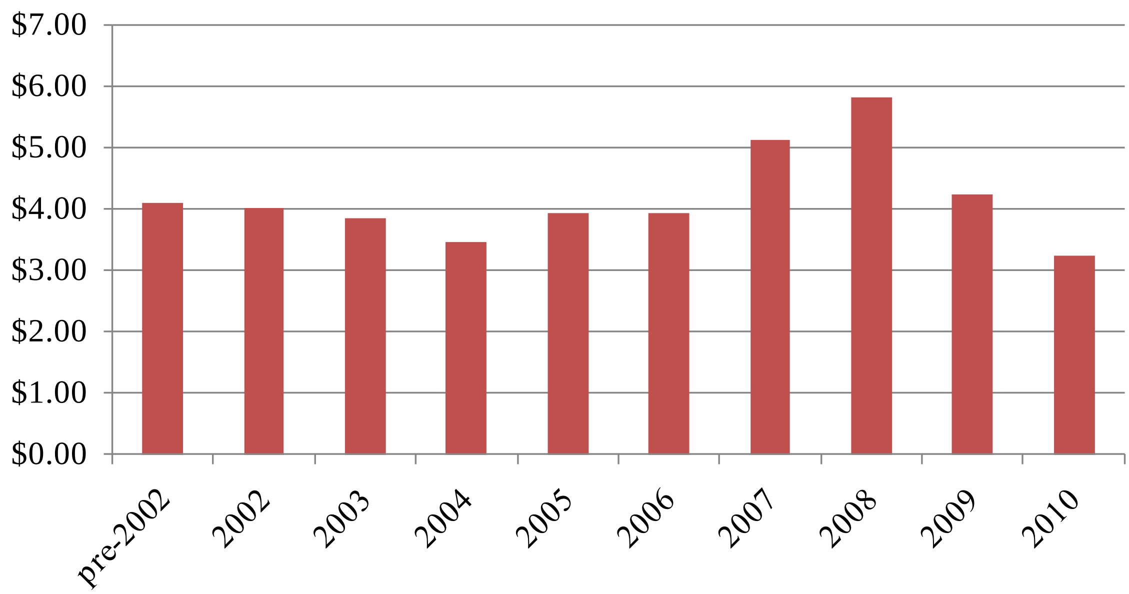

Figure 2: Average Prices of Voluntary Carbon Offsets, Pre-2002 through 2010

The situation is similar to the sale of contraband wildlife products in legitimate markets. Wildlife biologists and economists have examined the role of legal markets in facilitating the laundering of poached wildlife products, such as ivory, tiger parts and rhino horn (e.g., Kremer and Morcom 2000; Fischer 2004, 2010; Abbott and van Kooten 2011). Even if trade in wildlife products is banned, there will always be buyers of the product; however, if legal markets for the product exist, illegal trade is facilitated with a greater number of participants purchasing contraband product unless the legal suppliers can drive the illegal ones out of the market.

In the case of carbon markets, rent seeking on both sides of the market has created vibrant trade in carbon offsets that has little to do with the problem of global warming, but everything to do with the pursuit of (short-run) profits and objectives unrelated to climate change. In particular, large industrial emitters, companies wishing to appear 'green' and governments and their agencies wishing to demonstrate a commitment to climate change mitigation look to purchase emission offset credits at lowest cost (where cost might include the costs of meeting other objectives). Sellers of emission reduction credits constitute various private companies and nongovernmental organizations (NGOs) that are willing to supply emission offset credits even if their legitimacy is questionable, because they can thereby earn funds to finance objectives that are often unrelated to climate change. Finally, there are the financial intermediaries that earn money from each transaction. Given that the global carbon market is projected to be in the range of $1-$2 trillion in the future, the revenue accruing to financial intermediaries, which earn a percentage on every transaction, is enormous.

Given that taxes are unpopular, many politicians favor carbon trading schemes. In addition to the EU ETS, many U.S. states and Canadian provinces have indicated a willingness to participate in the proposed Western Climate Initiative that would employ emissions trading (Olewiler 2008). In 2009, the U.S. House of Representatives passed the *American Clean Energy and Security Act*, but the Senate failed to pass similar legislation despite several efforts to do so, and the Act did not become law. The Act required large emitters of greenhouse gases to reduce their aggregate CO_2 and equivalent (hereafter just CO_2) emissions by 3% below 2005 levels in 2012, 17% below 2005 levels in 2020, 42% in 2030, and 83% in 2050. One aspect of the Act was a cap-and-trade mechanism that would require firms to submit permits that allow them to emit CO_2. Only large industrial emitters (with emissions exceeding 25,000 tons of CO_{2e} per year) were affected, of which there were some 7,400. The program included all electrical utilities and producers or importers of liquid fossil fuels beginning in 2012; all industrial facilities that manufacture products or burn fossil fuels were to be included beginning in 2014. Covered firms would receive 4.627 billion (10^9) allowances in 2012 and as few as 1.035 billion in 2050, with each allowance permitting one metric ton of CO_2 emissions. Interestingly, 29.6% of allowances would be auctioned off in the first two years, 2012-2013, thereby raising a forecasted $846 billion in revenue. The proportion of allowances auctioned off would actually fall to less than 18% over the period to 2020, rising to 18.4% by 2022 and then gradually to about 70% by 2031, where it would remain.[2] In the first few decades, therefore, significant allowances would be grandfathered.

Grandfathering of allowances ensures industry support, although there is the notion that, by freely giving allowances to large emitters such as power companies, there will be little immediate impact on output prices. This is misleading because allowances will have a market value. Thus, a company will consider its 'freely-allocated' allowances to be an asset whose cost must be covered by revenues, i.e., there is an opportunity cost associated with allowances (Burtraw et al. 2002). The large industrial emitter could take the 'free' asset, sell it, and invest the proceeds in a technology that reduces CO_2 emissions (which is the idea behind allowances to begin with) or invest it elsewhere.[3] The cost of reducing CO_2 emissions will certainly need to be covered. The upshot is this: whether allowances are auctioned or given away (grandfathered), their cost will be reflected in final output prices. Thus, all citizens will face higher energy costs and higher costs for anything that involves the use of energy in its production and marketing.

While carbon trading systems are supposedly characterized by a limit on emissions, in practice politicians will look for a relief valve that keeps the price of emission allowances sufficiently low so that the scheme does not undermine the economy. This is particularly true since not all countries will participate in a cap-and-trade scheme. As a result, the system is highly influenced by rent seeking. Thus, large emitters favor a trading scheme that grandfathers allowances over a carbon tax because the trading scheme provides them with rents.

The price distortion through rent seeking by individual parties is primarily driven by how the market is organized. The carbon market has become so complex that parties exploit the market where possible, and the scope of rent seeking is usually proportional to the degree of market

[2] This information is based on a report by the Congressional Budget Office and Congressional Joint Committee on Taxation, as reported by Amanda DeBard in the *Washington Post*, Monday, June 8, 2009. See also Congressional Budget Office (2009).

[3] Some coal-fired power plants will prefer to go out of business, sell their allocated allowances to other emitters, and, if they also own coal deposits, export the coal abroad.

complexity (Helm 2010). It is this complexity that fundamentally impacts the carbon price mechanism. That is, by supplying the market with REDD+ carbon offsets, the price mechanism that ensures demand for credits equals supply becomes distorted because sale of credits from other than emissions reduction takes place. Instead of dealing only with the sale and purchase of permits to emit CO_2, the market has to deal with emission reduction credits from sources that have nothing to do with CO_2 emissions from fossil fuel burning. REDD+ credits derive from protection of biodiversity on private forestland and do not contribute explicitly to reductions in CO_2 emissions. By allowing these 'illegitimate' offsets, the carbon market gets distorted, with the price of carbon below what it would otherwise be. This results in inefficiency and reduces the incentive to invest in R&D that leads to reduced efficiency in the use of fossil fuels, conserves energy and/or fails to provide adequate incentives to spur development of alternative energy sources. Thus, credits created by activities that enhance preservation of biodiversity enter the global carbon market without really contributing to a net carbon reduction; rather, such credits signal that the shadow damage caused by an increasing concentration of CO_2 in the atmosphere is lower than warranted.

There are several adverse impacts when states allow the sale of REDD+ credits on the European market, for example. First, there is the distorting effect on prices (e.g., Bosetti et al. 2011);[4] falling prices of CERs (and with them prices of European allowances) are one indication of this, as shown in Figure 3. Because European firms can purchase lower cost emission permits, they can avoid other, more expensive efforts to do something about their carbon dioxide emissions. Second, although this situation enables states and private firms to meet their targets, it fails to address emission reduction obligations. Given that credits earned via carbon sequestration in terrestrial ecosystems were only meant to be a bridge to provide time for an economy or firm to develop and invest in emission-reducing technologies, the sale of such credits has turned out to be an impediment to the implementation of new technology because carbon prices are lower than

[4] Bosetti et al. (2011) deal with only legitimate (internationally approved) carbon offsets, which also have this same impact. They point out that, if carbon offset credits can be banked from one year to the next, prices in carbon markets will not fall by as much, thereby mitigating some of the negative incentives (discussed earlier) from substituting carbon offsets for emissions reductions.

necessary. This is true of all carbon offset credits, whose price has been declining (Figure 3).[5] Carbon offsets result in a wider gap between actual emissions, which remain high because they are covered by offsets, and emission targets in the future (van Kooten 2009). Carbon offsets from forestry activities simply contribute to this problem.

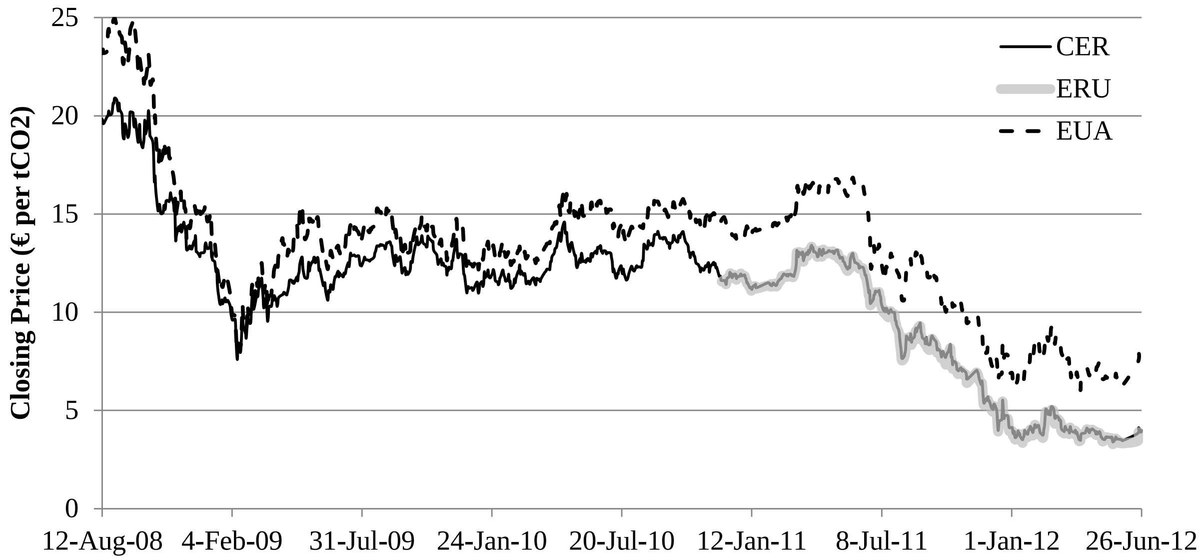

Figure 3: Daily Settlement Prices for European Union Allowances (EUA), Certified Emission Reductions (CER) and Emission Reduction Units (ERU) Traded on the European Emissions Trading System (ETS), August 2008 to June 2012

2. REDD+ CARBON OFFSET CREDITS IN BRITISH COLUMBIA: A CASE STUDY

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 or 'naturalness.' One might make the case that artificial regeneration that leads to higher and faster rates of growth – maybe even 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.

[5] Figure 3 provides closing prices for European allowances (EUA) that are part of the European cap-and-trade system, plus carbon offsets generated through Joint Implementation and referred to as emission reduction units (ERU) and the CDM's CERs. Notice that prices of EUAs and ERUs are almost identical.

That is, it makes sense neither to count emissions of greenhouse gases from natural disturbance nor the removal of CO_2 from the atmosphere as a result of activities to mitigate the impact of the disturbance.

What about the biodiversity benefits of investing in forest conservation? Given the vast amount of forestland officially and unofficially protected in British Columbia, the marginal benefits of protecting another hectare of forestland is essentially zero (see Bulte et al. 2001; van Kooten and Bulte 1999; van Kooten 1999). Thus, in British Columbia, REDD+ credits need to be justified solely on the basis of the CO_2 removed from the atmosphere by the forest conservation, biodiversity activity.

In 2008, The Nature Conservancy of Canada (NCC) purchased the 55,200 ha Darkwoods property on the west side of the south arm of Kootenay Lake near the U.S. border for $125 million from the German logging company Pluto Darkwoods (Figure 4).[6] NCC received financial support for this purchase from the federal government. Nearly half of the Darkwoods site had been logged previously although there remains a significant tract of natural forest with some trees as old as 500 years. Because the site also suffers from extensive mountain pine beetle damage, logging of pine-beetle killed timber has continued under NCC ownership, although annual harvests have recently fallen from 50,000 cubic meters to 10,000 m^3 as a result of logging of pine-beetle killed on the property.

In June 2011, NCC announced that it had completed a sale of 700,000 metric tons of CO_2 offset credits to Pacific Carbon Trust, a BC government-owned corporation, and Ecosystem Restoration Associates (ERA), a North Vancouver-based company. The latter subsequently sold the credits in Europe market through its German affiliate, the Forest Carbon Group.[7] NCC received more than $4 million for the sale, or nearly $5.75/t$CO_2$, at a time when offset credits were trading for much more on the European exchange (Figure 3).

The Nature Conservancy of Canada bases its sale of carbon credits on conservation grounds – that more intensive logging would have continued under private ownership (Nature

[6] Information is available from stories appearing June 10 and 11, 2011, in local newspapers, the *Vancouver Sun* (June 10) and national *Globe and Mail*.
[7] It is not clear whether the German certifier, which also certifies CERs under the CDM, sold any credits on the ETS, but speculation to that effect is clearly not unfounded.

Conservancy of Canada 2010). The carbon sequestered under NCC ownership versus that under private ownership – the counterfactual – constitutes a measure of the emission reduction units available for sale. Experts determined the amount and value of carbon absorbed by the southeastern BC forest site compared to the counterfactual, with details available in documents prepared for the assessors (3GreenTree Ecosystem Services, Ltd. and ERA Ecosystem Restoration Associates Inc. 2011). Finally, an international environmental non-governmental organization (ENGO), the Rainforest Alliance (2011), certified the carbon offset credits under the Voluntary Carbon Standard (VCS) label.[8]

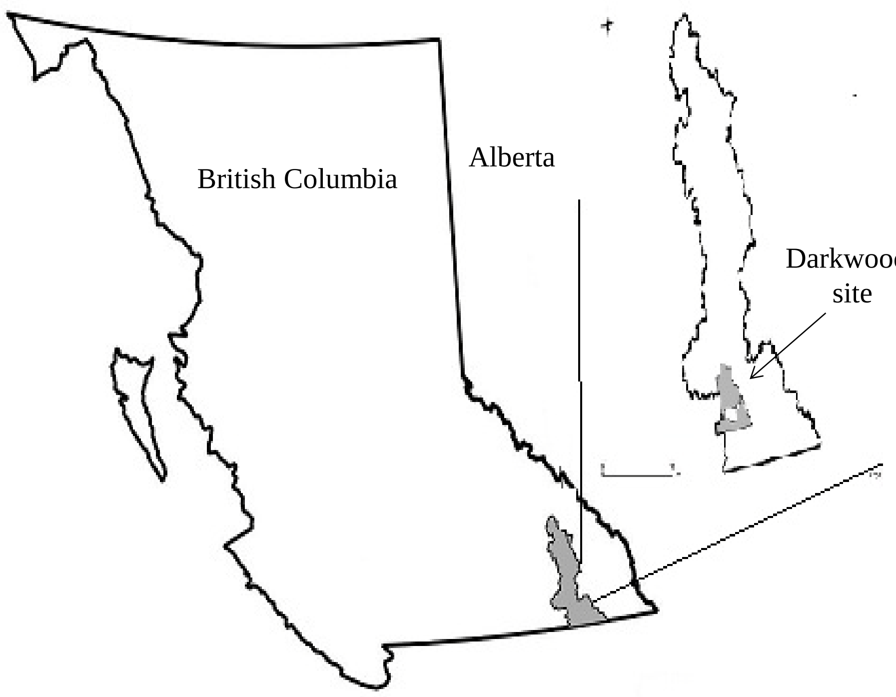

Figure 4: Location of the Darkwoods Site in Southeastern British Columbia

Given the 700,000 tons of CO_2 offset credits that constituted the Darkwoods site, one may 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 (say, on the ETS at about \$13/tCO_2 at the time) and that Pacific Carbon Trust charges government agencies (schools, hospitals, etc.) to be carbon neutral

[8] See previous two footnotes. It appears that the on-the-ground certifiers were local rather than international, because, although Rainforest Alliance has its head office in Virginia, the assessment was conducted by the local office.

($\$25/tCO_2$). Selling below market price implied a loss in revenue of perhaps \$9 million.[9] This income could have been used to finance biodiversity preservation on the site, which is NCC's prime objective. An ENGO such as NCC should maximize net revenue so it can attain its objectives, just like any other private entity. On the buyer side of the market in the Darkwoods case, the buyers (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 maximizes their net returns. However, rent seeking on the buyer side of the forest conservation market adversely impacts the efficient functioning of the carbon market at the forest level as too little forest conservation takes place. Ideally, the buying and selling of carbon credits should take place in one market without the resellers.

3. FOREST MANAGEMENT MODEL OF DARKWOODS

In this section, we develop a forest management model of the Darkwoods property. The objective is to determine the net benefits of operating the property for commercial timber purposes versus that of forest conservation for biodiversity and REDD+ carbon offsets. The model will be used to determine the number of VERs that might reasonably be credited to forest conservation by specifying a counterfactual that better represents how a private forest company would operate the site (e.g., conforming to Forest Stewardship Council certification of forest management practices) and tracking carbon in the forest products pool.[10] The difference in carbon uptake and release between the forest conservation case and the counterfactual constitutes a measure of the available carbon credits. We also use the model to estimate the opportunity cost of creating REDD+ carbon credits.

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

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[9] The price received by the NCC approximately equaled or exceeded the price of offset credits sold in voluntary market (see Figures 1 and 2 above).

[10] In section 3.5.12 (Observation of local laws and regulations) of the Validation Report Template for obtaining certification under the VCS (Voluntary Carbon Standard 2007), the auditors note that: "Private land regulations in B.C. 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). This is inconsistent with the counterfactual used to determine the carbon offsets generated on the site – that a private company would log the site in unsustainable fashion.

silviculture (natural or artificial regeneration with improved genetic stock). 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 or other non-lumber products), or for production of energy; and assume the stand's initial volume is given by $v_{s,a,z,m,0}$. Finally, let $p_{s,a,z,m,t}$ be the proportion of the stand's volume $v_{s,a,z,m,t}$ that is merchantable in period t, and define total harvest in period t as follows:

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

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 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:

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

where

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

In equations (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 are assumed 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, and are given by $C_t^{\text{haul}} = c^{\text{truck}} \times H_t$.

Given that 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 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_{fuel} be the fixed price 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, emissions of carbon dioxide are derived as follows:

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

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.

Next, it is important to take into account carbon sequestered in the ecosystem and stored in wood products. We assume that the amount of carbon stored in the forest ecosystem – the above-ground biomass (leaves, branches, litter) and soil organic matter – is related to the volume of timber on the site. This can be done by inflating volume by a fixed factor or using a function that converts volume into ecosystem carbon. Here we employ a fixed factor that varies by species, age of the stand, and biogeoclimatic zone. Total carbon stored in the ecosystem at any given time, as measured in terms of CO_2, is given by:

$$CO2^{eco}_t = \varphi\ b_{s,a,z}\ v_{s,a,z,t}\ X_z\ , \qquad (5)$$

where $b_{s,a,z}$ is a parameter that converts timber volume into ecosystem carbon for species s of age a in biogeoclimatic zone z, parameter ratio φ (=44/12) converts carbon to CO_2, and X_z is the total area in zone z.

It is also necessary to consider the carbon stored in products. There are three product pools to consider – the carbon stored in lumber, in products made from wood chips (including pulp), and in residuals and waste used to produce heat and/or power. 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 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 θ, the amount of carbon stored in the three pools as a result of harvest H_t is given as follows:

$$CO2_t^{product} = \varphi \sum_i \frac{1+\theta}{\theta + d_i} \varepsilon_i H_t \text{, } i = \text{lumber, chips, residuals/waste for fuel.} \tag{6}$$

Lastly, we consider the reduction in fossil fuel emissions when wood products substitute for cement and concrete, as is increasingly the case in building construction (Hennigar et al. 2008).

$$CO2_t^{ff} = \varphi \xi H_t, \tag{7}$$

where ξ is a parameter denoting the emissions avoided when wood substitutes for other products.

Total carbon stored at any time is given by the sum of (5), (6) and (7):

$$CO2_t = CO2_t^{eco} + CO2_t^{product} + CO2_t^{ff}. \tag{8}$$

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

$$\text{NPV} = \sum_{t=1}^{T} \beta^t \left[(p_{lum}\varepsilon_1 + p_{chip}\varepsilon_2 + p_{fuel}\varepsilon_3) H_t - C_t - p_C \left(E_t + \gamma\, CO2_t \right) \right], \tag{9}$$

where p_C refers to the (shadow) price of carbon dioxide ($/t$CO_2$), γ is the duration factor, and β = 1/(1+δ) is the discount factor with δ being the discount rate. 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 δ as a limiting value. In essence, the duration factor (relative to the discount rate) accounts for the amount of time that climate mitigation practices withhold 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. Further, for simplicity and given fixed product prices and proportions ε_i, we also assume the price of logs ($/$m^3$) represents the value of interest in the objective function (9).

The objective function (9) is maximized subject to equations (1) through (8) and a variety of technical constraints. The latter relate to the limits on harvest imposed by the available inventory in any period as determined by tree species, 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 (that also address certification of forest practices); non-negativity constraints; and other constraints relating to the specific scenarios that are investigated. The sustainability constraint, for example, prevents harvests in any decade from deviating more than 5% in either direction from what they are in the first decade. Model parameters are provided in the next section, while the constrained optimization model is constructed in GAMS.

4. DATA DESCRIPTION AND RESULTS

A GIS model of the Darkwoods site was initially constructed. 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. 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.[11] TIPSY is used in timber supply analyses, but can also be used to evaluate silvicultural treatments and address other stand-level planning options. In the current application, it was 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.

Silviculture

As noted earlier, a commercial operator needs to certify its management practices and, therefore, is required to regenerate a site once it is harvested. In that case, the site is generally replanted using improved genetic stock as opposed 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 would be planted, the total amount of biomass grown on the site could be significantly enhanced.

[11] 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.

Indeed, by planting improved 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%.[12] This might translate into an increase in the amount of carbon stored on a site of 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 is calculated by TIPSY's Tree and Stand Simulator (TASS), and is based on the Carbon Budget Model of the Canadian Forest Sector (Kurz et al. 1996). TIPSY tracks live-tree 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 the same components. 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 carbon dioxide 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. We also consider the potential impact of reduced emissions from the substitution of wood for steel and concrete in construction. Information on these factors is available from several sources and is reported in Table 1. Finally, we include CO_2 emissions associated with the activities of harvesting, trucking and manufacturing of wood products. This information is provided in Table 2.

Other Economic Data

Data on prices, costs and discount rates used in the model are 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 2% and 4% for discounting physical units of carbon. The alternative of not discounting physical carbon leads to problems related to duration

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

(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.

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/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^o, >40^o)
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
δ	4%	Discount rate for monetary values; β=1/(1+δ)
γ*	{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 converted to fuel use
d_1	0.02	Decay rate for softwood lumber
d_2	0.03	Decay rate for chips and pulpwood
d_3	0.60	Decay rate of biomass for fuel
d_4	0.00841	Decay rate of dead organic matter
ξ	{0.25, 1.5} tC/m^3	Emissions avoided when wood substitutes for other products[c]
	150 m^3 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 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 0.25 tC/m^3 and 1.5 tC/m^3 as a sensitivity check.
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)

5. COMPARING CARBON SEQUESTRATION ACROSS PROJECTS: RESULTS

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, except perhaps fire suppression as we do not take into account the possibility of wildfire (see, e.g., Couture and Reynaud 2011). To determine 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 and inventory constraints and other constraints imposed by the Nature Conservancy. Lastly, we find the carbon flux under commercial management by maximizing (9) subject to constraints (1)–(8) plus other constraints required by the government or a certifier of sustainable forest management (SFM) practices.[13] In each case, we subtract the associated wilderness carbon profile. Of course, the carbon profiles will change depending on the rate used to weight carbon as to when it is released to or removed from the atmosphere.

[13] 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. The government usually imposes more stringent sustainability requirements. All mathematical programming models are solved using the CPLEX solver. The GAMS file is listed in the Appendix, but data files from TIPSY are not included because of their large size.

Net carbon sequestration results are provided in Table 3. With a 4% discount rate on monetary values and no carbon tax to incentivize forest managers to sequester carbon and reduce greenhouse gas emissions, the amount of carbon (measured in terms of undiscounted carbon dioxide[14]) sequestered by the NCC management plan averages more than 25 Mt CO_2 per annum below that which would be stored in biomass had the region been left solely to wilderness. NCC management results in higher sequestration early in the time horizon compared with wilderness, but less sequestration later in the time horizon (see Figure 5), and, as long as CO_2 remains undiscounted, NCC management results in a loss of carbon relative to the natural state. The reason is that, compared to leaving the site in wilderness, the small gains made in the early years of the time horizon by sequestering carbon in wood products are eventually offset by lower levels of carbon in the ecosystem relative to the wilderness case. Unless carbon taken out of the atmosphere today is preferred to carbon sequestered or released at a later date, the natural forest is preferred to the NCC forest from a carbon standpoint.

It is only when carbon is discounted and then only when the rate at which wood substitutes for steel and/or concrete in construction is high (ξ=0.75) does NCC management result in the potential generation of carbon offsets; even at the lower substitution rate (ξ=0.25) the natural forest leads to higher levels of carbon sequestration than what the Nature Conservancy of Canada could achieve by harvesting some trees and storing carbon in wood products. These effects are more clearly illustrated in Figure 5 where, in both panels, the 'NCC Management' scenario uses the higher substitution rate (ξ=0.75).[15] What is most striking is that commercial management of the forest leads to much higher levels of carbon uptake than would occur under NCC management despite claims to the contrary (Nature Conservancy Canada 2010; RainForest Alliance 2011).

Further examination of Figure 5 reveals several important points. Upon comparing the upper and lower panels, we find that a higher discount rate leads to higher levels of carbon sequestration in almost all periods. But this is the result of its effect on management – more is harvested early on with the higher discount rate, although limited by the sustainability constraint.

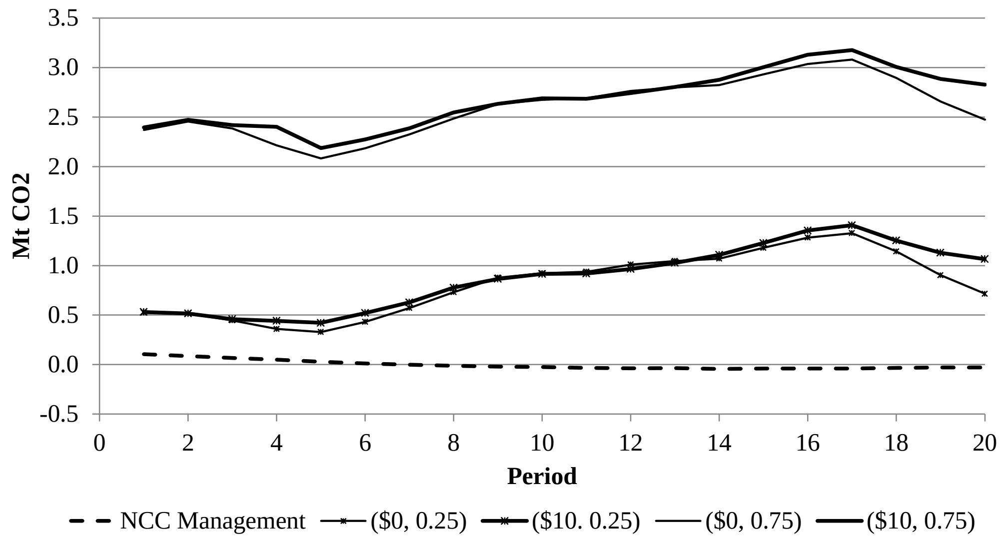
[14] When physical carbon is not discounted, total carbon sequestration is a function of the (arbitrary) time period employed.
[15] This is done solely so that the most optimistic NCC management scenario is presented.

Table 3: Annualized Carbon Sequestered (‘000s tCO_2) under Various Management Alternatives, Carbon Prices, Carbon Discount Rates and Wood Product Substitution Rates,[a] Monetary Values Discounted at 4%

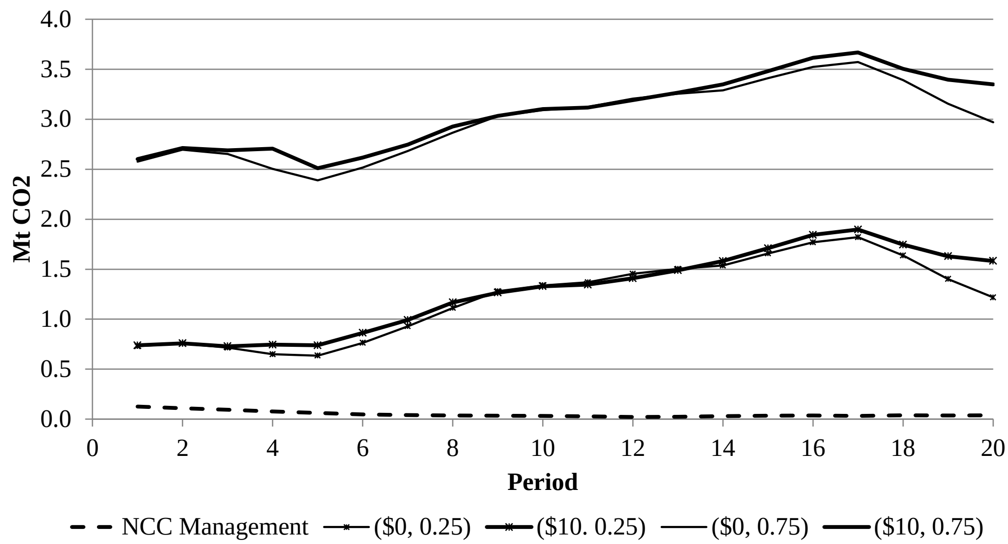
Item/Discount rate on physical carbon	0%[b]	2%	4%
Unmanaged wilderness	41.7	118.8	134.1
After subtracting CO_2 under unmanaged wilderness			
NCC Management			
$0/$tCO_2$ (ξ=0.25)	-25.5	-14.0	-8.8
$0/$tCO_2$ (ξ=0.75)	-7.2	4.2	9.7
$10/$tCO_2$ (ξ=0.25)	-23.0	-12.5	-8.3
$10/$tCO_2$ (ξ=0.75)	-4.7	5.7	10.3
Commercial Management			
$0/$tCO_2$ (ξ=0.25)	8.1	57.1	77.3
$0/$tCO_2$ (ξ=0.75)	186.3	238.1	265.8
$10/$tCO_2$($\xi$=0.25)	22.4	60.3	80.2
$10/$tCO_2$ (ξ=0.75)	193.3	243.9	271.4
Commercial management minus NCC management			
$0/$tCO_2$ (ξ=0.25)	33.6	71.1	86.1
$0/$tCO_2$ (ξ=0.75)	193.5	233.9	256.1
$10/$tCO_2$($\xi$=0.25)	45.4	72.8	88.5
$10/$tCO_2$ (ξ=0.75)	198.0	238.2	261.1

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 200 years divided by 200; for other discount rates, a true annualized value is employed.

Second, 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 reductions in fossil fuel emissions when wood products substitute for steel and concrete in construction. At higher carbon taxes, any operator wants to harvest as many trees as possible to benefit from carbon stored in products and associated savings in fossil fuel emissions in the steel and concrete sector, and wants to regenerate the forest quickly with improved genetic stock. Only two carbon prices are provided in Figure 5 because the harvest strategy does not change for positive carbon prices in the range considered ($5 to $50 per tCO_2); the reason pertains to both sustainability requirements and biophysical constraints on growth. Yet, the commercial operator has more flexibility to pursue opportunities to generate carbon offset credits than the Nature Conservancy of Canada.



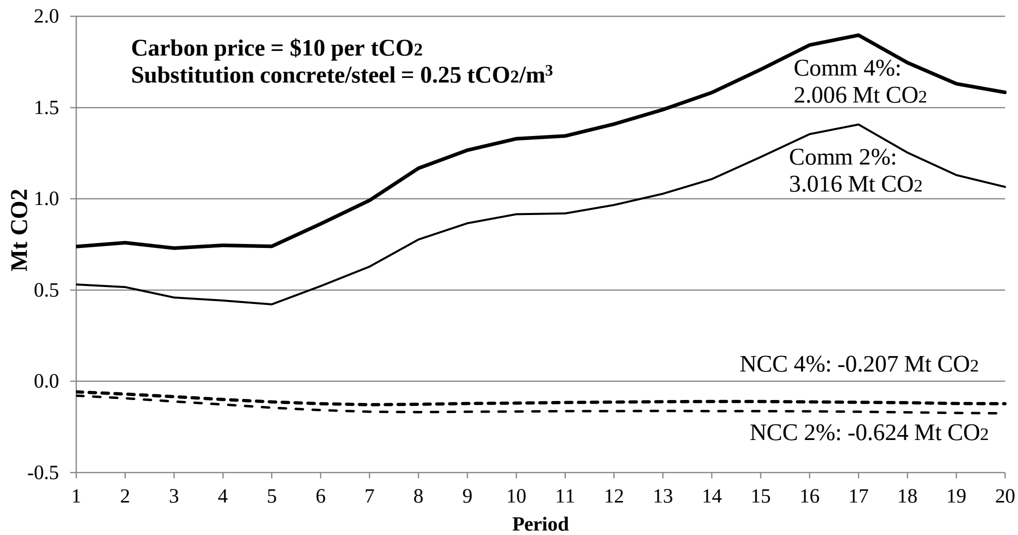
(a) *2% Discount Rate for Physical Carbon*



(b) 4% Discount Rate for Physical Carbon

Figure 5: Net Additional CO_2 Sequestered per Period: Nature Conservancy vs Commercial Management at CO_2 Prices of \$0 and \$10 per tCO_2 and Wood Substitution Parameters of 0.25 and 0.75 tC per m^3, and 4% Monetary Discount Rate

Sustainable commercial management of the site always leads to improved carbon sequestration compared to wilderness, regardless of the rate at which future carbon sequestration is discounted relative to current uptake. The additional net CO_2 removed from the atmosphere by commercial management compared to leaving Darkwoods as wilderness amounts to a low of 33.6 kt CO_2 to a high of 261.1 kt CO_2 annually depending on the carbon price, carbon discount rate and wood product substitution rate (Table 3). As indicated in Figure 6, the most important of these parameters that we consider is the ability to substitute wood products for steel and concrete. We examined substitutions of 0.25 and 0.75, but these could be as high as 1.5 (Hennigar et al. 2008). 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.



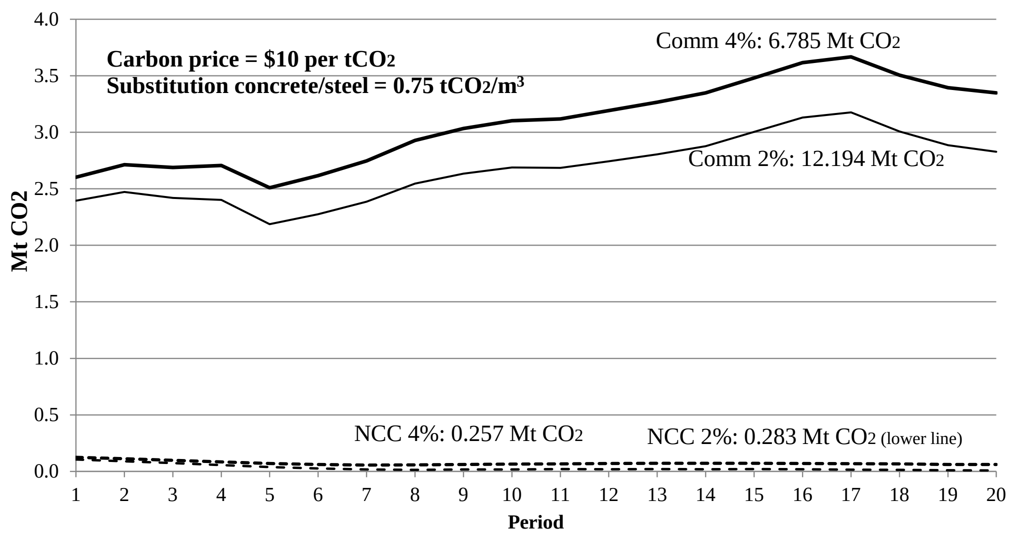


Figure 6: Net Additional CO_2 Sequestered per Period: NCC vs Commercial Management, 4% Monetary Discount Rate, 2% and 4% Refer to Discount Rates for Physical Carbon, Numbers Refer to Total Discounted Carbon Sequestered over 200 Years, Upper and Lower Panels Indicate Low and High Possibilities for Product Substitutions

6. DISCUSSION AND CONCLUSIONS

In their quest to be carbon neutral, private companies have purchased carbon offsets in voluntary markets, with many of these generated in the forestry sector (Figure 1). In their desire to lower carbon dioxide emissions, companies and nations have found carbon forest offsets to be a less expensive alternative to actual emissions reduction. International agreements have legitimized the use of forest sector carbon sequestration in lieu of emissions reduction for meeting targets. They are considered a stop-gap measure to enable countries and/or companies to meet targets while investing in technology and processes that reduce actual $CO_{2\text{-}e}$ emissions. However, few have questioned the validity of carbon offset credits, especially those generated through forest activities.

In this paper, we have shown from economic theory why carbon offsets are popular – they reduce the costs of meeting emissions reduction targets. However, we also demonstrated that, by lowering the price at which carbon credits trade, they reduce incentives to invest in R&D to become more energy efficient and to invest in manufacturing processes and equipment that actually lowers reliance on fossil fuels. Indeed, we suggest that carbon offsets help explain why prices in Europe's Emissions Trading System, the only carbon exchange in existence, have fallen to such a low level.

With respect to forestry activities that create carbon offsets, we pointed out problems related to additionality, leakages, impermanence (duration), and measuring, monitoring and other transaction costs. We also pointed out the potential for corruption. This is not to suggest that corruption is the result of covert action by economic agents. Although this cannot be ruled out in some perhaps important cases, in most instances the very nature of the attendant uncertainty related to forestry activities and what constitutes a carbon offset suggests that well-meaning agents, who are concerned with the protection of forests, tree planting and so forth, seek to sell carbon offset credits to help cover the costs of those actions – forest conservation, aforestation and protection of biodiversity. Whether activities to create forest carbon offsets are well intentioned or not, the evidence increasingly suggests that they have no impact on atmospheric carbon dioxide. Rather, they constitute a major distraction from the job of reducing CO_2 from fossil fuel emissions.

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 create and 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 this: the buyers were not only promoters of the sale, but facilitated (BC government) or certified (ENGOs such as Ecosystem Restoration Associates) the sale. Our analysis indicates that, given the assumptions used to create the offset credits, the forestry 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 upwards of 12 Mt CO_2, or more than ten times the amount claimed as a credit. While all parties might well have acted honestly, one cannot easily overlook the fact that the choice of scenarios and parameters by the NCC favored the creation and sale of carbon offset credits from the Darkwoods property. One cannot ignore the questionable validity of the carbon offsets that were claimed, simply because Canadian taxpayers are the ultimate losers.

Finally, it is worth noting that the costs of monitoring the creation of carbon offsets can be extremely high, which might explain why many ‘shady’ projects are accepted and granted the right to sell carbon offsets. In the Darkwoods case, it was necessary to construct a GIS model of the site, determine the current inventory, estimate growth and yield under various management alternatives, construct a forest management model that included a component that kept track of carbon pools over time, and so on. It is clearly the case that, unless an independent certifier with no stake in the outcome (unlike the case with Darkwoods where the certifier was an environmental NGO prone to favor REDD+ projects) is able to spend the time necessary to judge a project, many more debatable carbon offset credits will be forthcoming onto world markets. This not only distorts carbon markets but leads to an adverse impact on future warming (by promoting it) and wastes society’s resources needlessly.

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APPENDIX

According to NCC, only 60% of the biomass on the site goes to commercial use.

Table A1: Biomass Contained in Components of Mature Forests Typical of Western North America, metric tons (% of aboveground total)

			Biomass	
Location	Forest Type	Forest floor	Crown	Bole
British Columbia	Subboreal white spruce (*Picea glauca*, *Pinus contorta*)	65 (29%)	32 (14%)	126 (57%)
Colorado	Subalpine fir (*Abies lasiocarpa*)	103 (31%)	54 (16%)	173 (52%)
Idaho	Mixed conifer (*Abies*, *Picea*, *Pinus*)	70 (27%)	31 (12%)	160 (61%)
Washington	Douglas fir (*Pseudotsuga menziesii*)	14 (8%)	31 (17%)	134 (75%)
California	Mixed conifer (*Abies*, *Pinus*)	59 (11%)	221 (42%)	252 (47%)
Arizona	Pine (*Pinus ponderosa*)	47 (24%)	31 (16%)	121 (61%)

Source: Peterson et al. (2009)

GAMS Program Listing

```
$Title Darkwoods Forest Management Model

$Oneolcom
Sets
 age     Age Class              / 0*20 /
 z       Biogeoclimatic Zone     / ESS, ICH /
 sz      Biogeoclimatic Subzone  / dm, dw, mw, wc, wm, xw /
 sl      Slope class            / 1, 2 /
 sp1     Species 1              / B, C, F, H, L, P, S /
 sp2     Species 2              / A, B, C, E, F, H, L, P, S, u /
 mgd     Management category     / 0, 1 /
*mgd=0 natural stand, 6 yrs regeneration delay (bare ground) before
*trees naturally germinate at a low stocking of 600 trees per hectare,
*mgd=1 managed stand 1200 stems per ha planted w genetic stock for higher volume
 info    Stand information       / pct1, pct2, MerchV, VPT, LogVol,
                                   LumRecov, CarbL, CarbD /
 t       Time                   / 1*20 /
;

alias(mgd, ncc) !! NNC management;
*ncc=0 if NNC placed this in a no-harvest zone, ncc=1 if low level of logging

SETS
   tinit(t)     first time period
   tfinal(t)    Last period
   regen(age)   regeneration ageclass
   oldage(age)  oldest ageclass
   Offlimits(ncc) Outside ncc planned management
   ;
   regen(age) = yes$(ord(age) eq 1);
   oldage(age) = yes$(ord(age) eq card(age));
   tinit(t) = yes$(ord(t) eq 1);
   tfinal(t) = yes$(ord(t) eq card(t));
   Offlimits(ncc) = yes$(ord(ncc) eq 0);

* Stand age broken into 10 yr classes. Class 20 represents stands > 200 yrs.
* Merchantable stands are stands ABOVE 150 cubic metres per ha
* Carbon is in oven dry tonnes (odt)/ha; Time is in 10 year steps
* Area wtd SI for THLB e.g. WHERE (si > 7 and more 40deg <> 1 and vph_200>150) is
* ESSF 14m and ICH 18m
* Trendline produces the following cost_factor multiplier when merch volume <
* 251 m3/ha = -0.005 VPH + 2.0363

$OFFlisting;
Parameter area(z,sz,sl,sp1,sp2,mgd,age,ncc) 'total inventory in ha'
```

```
/
$Include NCCForest.gms
/
;

Parameter NatCO2(t) 'Natural carbon saved each period under wilderness'
/
$Include NaturalCarbon.gms
/
;

Table standInfo(z,sz,sl,sp1,sp2,mgd,age,info) yield projections per ha
$Include NCCYield.gms
;

$ONlisting
SCALARS
 bdt       m3 per Bone Dry Tonne                          /2.44/
 drate     Discount rate on monetary values               /0.04/
 crate     Discount rate for carbon                       /0.02/
 resid     Part of stand's merchantable vol that is roadside residual /0.1/
 dev       development and adminstration cost $ per m3    /8.0/
 cycle     cost per m3 w cycle time 1-2 hrs Thomae$4.61 Niquidet$4.44 /4.50/
 overRoad  cost per m3 Overhead & road maintain Thomae $11.24+2.56   /14/
 minMerch  Minimum volume per ha (m3) for harvesting      /150/
 period    Period length in years to scale annual harvest /10/
 LogValue  Value of log $ per m3 (Could differ by species or bec?)   /75/
 pcarb     Price of carbon in $ per tCO2                  /0/
 ;

PARAMETERS
 i(t)        counting parameter for discounting
 dfactor(t)  discount fator for monetary values
 cfactor(t)  'discount rate for carbon (could equal monetary rate)'
;

 i(tinit)=5;
  loop (t, i(t+1) = i(t)+10);
 dfactor(t) = 1/((1+drate)**i(t));
 cfactor(t) = 1/((1+crate)**i(t));

*----------------------------------------------------------------------
*Carbon data
*----------------------------------------------------------------------
SCALARS
decay      Decay rate of dead organic matter              /0.00841/
```

```
declumber    Decay rate for softwood lumber                         /0.02/
decchip      Decay rate for chips and pulpwood                      /0.03/
decfuel      Decay rate of biomass for fuel                         /0.60/
prolumber    Proportion of commercial volume used in lumber         /0.54/
prochip      Proportion of commercial volume used in chips          /0.25/
profuel      Proportion of commercial volume used in fuel           /0.21/
eharv        Emissions as tC per tC in raw material when harvesting /0.016/
esaw         Emissions as tC per tC in raw material in sawnwood     /0.04/
eveneer      Emissions as tC per tC in raw material in veneer       /0.06/
epanel       Emissions as tC per tC in raw material in panels       /0.12/
epulp        Emissions as tC per tC in raw material in mech pulp    /0.48/
chemepulp    Emissions as tC per tC in raw material in chem pulp    /0.13/
km           Average truck distance to mill 1-2hr cycle time        /50/
etruck       trucking emissions per km per tC in raw material       /0.00007/
sub          'emissions saved by product substitution (tC per m3)'  /0.25/
;

PARAMETERS
discarb    'infinite discounted proportion CO2 from site, lumber, chips, waste'
product    tons of carbon released producing products per tC in raw material
emitharv   'tCO2 emitted at harves time, including discounted decay of product'
;

discarb = (declumber/(crate+declumber))*prolumber
          + (decchip/(crate+decchip))*prochip
          + (decfuel/(crate+decfuel))*profuel;
product = esaw*prolumber + (eveneer+epanel+epulp)*prochip/3;
emitharv = eharv + product + discarb + etruck*km;
*----------------------------------------------------------------------

PARAMETER yard(sl) 'Yarding cost per m3 by slope class (<40% & >40%) (Thomae)'
/ 1       22
  2       42/
;

TABLE silv(z, mgd) 'Silvicultural costs $ per hectare for no plant and planting'
        0    1
ESS     0    1605
ICH     0    1522
;

PARAMETERS
merch(z,sz,sl,sp1,sp2,mgd,age,t) 'Volume exceeding minMerch volume'
vph_factor(z,sz,sl,sp1,sp2,mgd,age,t) 'Impact of vol per ha on logging cost'
value(z,sz,sl,sp1,sp2,mgd,age,t) 'Value exceeding minMerch volume'
cost(z,sz,sl,sp1,sp2,mgd,age,t) 'Total harvest cost per ha volume>minMerch vol'
```

```
NetRev(z,sz,sl,sp1,sp2,mgd,age,t)  'Net return per ha for volume>minMerch vol'
ChgCO2biomass(z,sz,sl,sp1,sp2,mgd,age,t) Annual change in tCO2 in biomass
;

merch(z,sz,sl,sp1,sp2,mgd,age,t)$(standInfo(z,sz,sl,sp1,sp2,mgd,age,'MerchV')
  > minMerch) = standInfo(z,sz,sl,sp1,sp2,mgd,age,'MerchV');

vph_factor(z,sz,sl,sp1,sp2,mgd,age,t)$(merch(z,sz,sl,sp1,sp2,mgd,age,t) >
   minMerch) = (-0.005 * merch(z,sz,sl,sp1,sp2,mgd,age,t)
   + 2.0363)$(merch(z,sz,sl,sp1,sp2,mgd,age,t)<251)
   + 0.79$(merch(z,sz,sl,sp1,sp2,mgd,age,t) >= 251);

value(z,sz,sl,sp1,sp2,mgd,age,t)$(merch(z,sz,sl,sp1,sp2,mgd,age,t) >
   minMerch) = LogValue * merch(z,sz,sl,sp1,sp2,mgd,age,t);

cost(z,sz,sl,sp1,sp2,mgd,age,t)$(merch(z,sz,sl,sp1,sp2,mgd,age,t) >
   minMerch) = (silv(z,mgd)+(dev + overRoad + cycle + yard(sl))*
   merch(z,sz,sl,sp1,sp2,mgd,age,t)) * vph_factor(z,sz,sl,sp1,sp2,mgd,age,t);

NetRev(z,sz,sl,sp1,sp2,mgd,age,t)$(value(z,sz,sl,sp1,sp2,mgd,age,t) >
    cost(z,sz,sl,sp1,sp2,mgd,age,t)) = (value(z,sz,sl,sp1,sp2,mgd,age,t)
    - cost(z,sz,sl,sp1,sp2,mgd,age,t)) ;

ChgCO2biomass(z,sz,sl,sp1,sp2,mgd,age,t) = (44/12)*
        ((standInfo(z,sz,sl,sp1,sp2,mgd,age,'CarbL') - (1+crate)
        * standInfo(z,sz,sl,sp1,sp2,mgd,age-1,'CarbL'))$(not(regen(age)))
        + standInfo(z,sz,sl,sp1,sp2,mgd,age,'CarbD'));
*-----------------------------------------------------------------------
* MODEL SET UP
*-----------------------------------------------------------------------
POSITIVE VARIABLES
tharvest(t)      'total harvest in period t (m3)'
harvest(z,sz,sl,sp1,sp2,mgd,age,ncc,t)  'harvest activity (hectares)'
regenstock(z,sz,sl,sp1,sp2,mgd,ncc,t)   regeneration activity in hectares
stock(z,sz,sl,sp1,sp2,mgd,age,ncc,t)    inventory measured in hectares
gs(t)            periodic total growing stock summary measured in m3
agearea(age,t)   ageclass information by period measured in hectares
harvarea(t)      'harvest area within darkwoods'
darkarea(t)      'area within darkwoods'
CO2Rel(t)        'Total tCO2 released when site harvested incl in products'
CO2Str(t)        'tCO2 stored in biomass plus in products'
;

VARIABLES
NPV        'Objective value ($ 000s)'
CO2(t)     Annual change in CO2
```

```
TotalCO2   Total tCO2
;

EQUATIONS
obj                Define objective function
totalharvest(t)     Total harvest in cubic metres
MaxHarvest(z,sz,sl,sp1,sp2,mgd,age,ncc,t) Cut no more than current inventory
InitialStock(z,sz,sl,sp1,sp2,mgd,age,ncc,t) Starting inventory constraint
Regeneration(z,sz,sl,sp1,sp2,mgd,ncc,t) Natural regeneration of harvest
MgdRegen(z,sz,sl,sp1,sp2,ncc,t)       Managed Regeneration of period harvest
Growth(z,sz,sl,sp1,sp2,mgd,age,ncc,t) Growth of forest accum area oldest age
NoHarv              No harvest outside of managed forest area
Darklimit(t)       'Limit of 100 000 m3 harvest off Darkwoods under NNC manage'
*-----------------------------------------
AreaSum(t)         Summarize the total area
AgeSum(age,t)       Summarize the ageclass
HarvSum(t)         Summarize the harvest area
GSsum(t)           Summarize the growing stock
AreaMgmt(t)        Maintain between period total area within darkwoods
*------------------------------------------
*Eflow(t)           'Evenflow requirement (more stringent than next two)'
Eflow1(t)          Lower sustainability condition
Eflow2(t)          Upper sustainability condition
*-------------------------------------------
CO2Release(t)       'tCO2 emitted upon harvest including in products'
CO2Store(t)        'Change inl tCO2 stored on site & in products at time t'
PeriodCO2(t)       'Calculate periodic (10-year) total tCO2'
AllDiscCO2         'Total discounted tCO2 over planning period'
;

obj..  NPV =E= 0.001*sum((z,sz,sl,sp1,sp2,mgd,age,ncc,t), dfactor(t)*
   (NetRev(z,sz,sl,sp1,sp2,mgd,age,t)* harvest(z,sz,sl,sp1,sp2,mgd,age,ncc,t)
      + pcarb*CO2(t)));

InitialStock(z,sz,sl,sp1,sp2,mgd,age,ncc,tinit)..
         stock(z,sz,sl,sp1,sp2,mgd,age,ncc,tinit) =E=
                 area(z,sz,sl,sp1,sp2,mgd,age,ncc);

MaxHarvest(z,sz,sl,sp1,sp2,mgd,age,ncc,t)..
       stock(z,sz,sl,sp1,sp2,mgd,age,ncc,t) =G=
     harvest(z,sz,sl,sp1,sp2,mgd,age,ncc,t)$merch(z,sz,sl,sp1,sp2,mgd,age,t);

totalharvest(t)..  tharvest(t) =E= sum((z,sz,sl,sp1,sp2,mgd,age,ncc),
  (merch(z,sz,sl,sp1,sp2,mgd,age,t)*
  harvest(z,sz,sl,sp1,sp2,mgd,age,ncc,t))$merch(z,sz,sl,sp1,sp2,mgd,age,t));
```

```
Regeneration(z,sz,sl,sp1,sp2,mgd,ncc,t)..
        regenstock(z,sz,sl,sp1,sp2,mgd,ncc,t) =E=
             sum(age, harvest(z,sz,sl,sp1,sp2,mgd,age,ncc,t)
               $merch(z,sz,sl,sp1,sp2,mgd,age,t));

MgdRegen(z,sz,sl,sp1,sp2,ncc,t).. regenstock(z,sz,sl,sp1,sp2,"0",ncc,t)
           + regenstock(z,sz,sl,sp1,sp2,"1",ncc,t) =E=
           sum((mgd,age), harvest(z,sz,sl,sp1,sp2,mgd,age,ncc,t)
           $merch(z,sz,sl,sp1,sp2,mgd,age,t));

Growth(z,sz,sl,sp1,sp2,mgd,age,ncc,t)$(not(tinit(t)))..
        stock(z,sz,sl,sp1,sp2,mgd,age,ncc,t) =E=
          regenstock(z,sz,sl,sp1,sp2,mgd,ncc,t-1)$(regen(age))
          + (stock(z,sz,sl,sp1,sp2,mgd,age-1,ncc,t-1)
          - harvest(z,sz,sl,sp1,sp2,mgd,age-1,ncc,t-1))$(NOT(regen(age)))
          + (stock(z,sz,sl,sp1,sp2,mgd,age,ncc,t-1)
          -  harvest(z,sz,sl,sp1,sp2,mgd,age,ncc,t-1))$(oldage(age));

NoHarv..  sum((z,sz,sl,sp1,sp2,mgd,age,t),
             harvest(z,sz,sl,sp1,sp2,mgd,age,"0",t)) =E= 0;

Darklimit(t).. tharvest(t) =L= 100000;  !!10 yrs at 10 000 per year

*----------------------------------------------------------------------
* Checks to ensure that area, age, harvest & management conditions met
*----------------------------------------------------------------------

AreaSum(t)..  darkarea(t) =E=
      sum((z,sz,sl,sp1,sp2,mgd,age,ncc),stock(z,sz,sl,sp1,sp2,mgd,age,ncc,t));

AgeSum(age,t)..     agearea(age,t) =E=
      sum((z,sz,sl,sp1,sp2,mgd,ncc), stock(z,sz,sl,sp1,sp2,mgd,age,ncc,t));

GSsum(t)..    gs(t) =E=
    sum((z,sz,sl,sp1,sp2,mgd,age,ncc), stock(z,sz,sl,sp1,sp2,mgd,age,ncc,t)
      * standInfo(z,sz,sl,sp1,sp2,mgd,age,'MerchV'));

HarvSum(t)..     harvarea(t) =E=
          sum((z,sz,sl,sp1,sp2,mgd,age,ncc),
               harvest(z,sz,sl,sp1,sp2,mgd,age,ncc,t));

AreaMgmt(t)$(NOT(tinit(t))).. darkarea(t) =E= darkarea(t-1);

*----------------------------------------------------------------------
* Sustainability Requirements
*----------------------------------------------------------------------
```

```
Eflow1(t)$(NOT(tinit(t)))..   tharvest(t) =G= 0.95*tharvest("1");
Eflow2(t)$(NOT(tinit(t)))..   tharvest(t) =L= 1.05*tharvest("1");

*------------------------------------------------------------------------
* Carbon Accounting
*------------------------------------------------------------------------

CO2Release(t).. CO2Rel(t) =E= sum((z,sz,sl,sp1,sp2,mgd,age,ncc),
    (0.2 * emitharv * 44/12 * merch(z,sz,sl,sp1,sp2,mgd,age,t)*
    harvest(z,sz,sl,sp1,sp2,mgd,age,ncc,t))$merch(z,sz,sl,sp1,sp2,mgd,age,t));
* Notice sub refers to emissions saving from fossil fuel used in cement, etc

CO2Store(t).. CO2Str(t) =E= sum((z,sz,sl,sp1,sp2,mgd,age,ncc),
    (0.2 * (1-discarb) + sub) * 44/12 * merch(z,sz,sl,sp1,sp2,mgd,age,t)
    * harvest(z,sz,sl,sp1,sp2,mgd,age,ncc,t)$merch(z,sz,sl,sp1,sp2,mgd,age,t)
       + stock(z,sz,sl,sp1,sp2,mgd,age,ncc,t)
       * ChgCO2biomass(z,sz,sl,sp1,sp2,mgd,age,t));

PeriodCO2(t)..  CO2(t) =E= CO2Str(t) - CO2Rel(t) - NatCO2(t);

AllDiscCO2..  TotalCO2 =E= sum(t, cfactor(t) * CO2(t));

*------------------------------------------------------------------------
*Two scenarios:
*#1: NNC manages forest naturally (nat regen with low stocking) & not
*  harvesting some areas. This comes from NNC Darkwoods management plan
*  where they identify no harvest areas which were identified spatially and
*  placed off limits. NOT assigned the harvest prescribed by NNC.
*#2: Commercial forestry potential of 2, e.g. assume genetic stock,
*  prompt replanting etc?

Model NNCManage /obj, InitialStock, totalharvest, MaxHarvest, Growth, Eflow1,
      Eflow2, AreaSum, AgeSum, GSsum, HarvSum, AreaMgmt, CO2Release, CO2Store,
      PeriodCO2, AllDiscCO2,  Regeneration, NoHarv, Darklimit /;

Model Commercial /obj, InitialStock, totalharvest, MaxHarvest, Growth, Eflow1,
      Eflow2, AreaSum, AgeSum, GSsum, HarvSum, AreaMgmt, CO2Release, CO2Store,
      PeriodCO2, AllDiscCO2,  MgdRegen /;

Option iterlim = 1000000;
Option reslim = 20000;

*---------------------------------------------------
Solve NNCManage using lp maximizing NPV;

file OutDark;
```

```
OutDark.nd=2;
put OutDark 'Run on ' system.date ' using source file ' system.ifile///;
put OutDark 'Model 1: NNC MANAGED WITH NO HARVEST AREAS'/;
put OutDark;
  put "Model status , " NNCManage.modelstat/;
  put "Solver status , " NNCManage.solvestat/;
  put "NPV of NNC management , " NPV.l /;
  put "Total discounted carbon (tCO2) ," TotalCO2.l/;
  put /;
  put "  , Growing, Harvest, Harvest, "/;
  put "Period, Stock, Volume, Area, "/;
  loop(t, put t.tl "," gs.l(t) "," tharvest.l(t) "," harvarea.l(t) /);
  put /;
  put "       Carbon Dioxide Uptake (Storage) & Release & Total (tCO2) "/;
  put "Period, Release, Uptake, TOTAL "/;
  loop(t, put t.tl "," CO2Rel.l(t) "," CO2Str.l(t) "," CO2.l(t)/);
  put //;
putclose OutDark;

OutDark.ap=1;

*--------------------------------------------------

Solve Commercial using lp maximizing NPV;
file OutDark;
OutDark.nd=2;
put OutDark 'Model 3: COMMERCIAL MANAGEMENT'/;
put OutDark;
  put "Model status , " Commercial.modelstat/;
  put "Solver status , " Commercial.solvestat/;
  put "NPV of commerical operation of property  , " NPV.l /;
  put "Total discounted carbon (tCO2) ," TotalCO2.l /;
  put /;
  put "  , Growing, Harvest, Harvest, "/;
  put "Period, Stock, Volume, Area, "/;
  loop(t, put t.tl "," gs.l(t) "," tharvest.l(t) "," harvarea.l(t) /);
  put /;
  put "       Carbon Dioxide Uptake (Storage) & Release & Total (tCO2) "/;
  put "Period, Release, Uptake, TOTAL "/;
  loop(t, put t.tl "," CO2Rel.l(t) "," CO2Str.l(t) "," CO2.l(t)/);
putclose OutDark;
```