Biological Carbon Sequestration and Carbon Trading Re-Visited

van Kooten G. C.[1]

[1] University of Victoria, Departments of Economics and Geography, Victoria, Canada
and
Wageningen University, Department of Social Science, Wageningen, The Netherlands

Abstract — **Under Kyoto, biological activities that sequester carbon can be used to create CO_2 offset credits that could obviate the need for lifestyle-changing reductions in fossil fuel use. Credits are earned by storing carbon in terrestrial ecosystems and wood products, although CO_2 emissions are also mitigated by delaying deforestation, which accounts for one-quarter of anthropogenic CO_2 emissions. However, non-permanent carbon offsets from biological activities are difficult to compare with each other and with emissions reduction because they differ in how long they prevent CO_2 from entering the atmosphere. This is the duration problem; it results in uncertainty and makes it difficult to determine the legitimacy of biological activities in mitigating climate change. While there is not doubt that biological sink activities help mitigate climate change and should not be neglected, in this paper we demonstrate that these activities cannot be included in carbon trading schemes.**

Keywords — **carbon offset credits, climate change, duration of carbon sinks**.

I. INTRODUCTION

Policy makers are particularly enthusiastic about sequestering carbon in terrestrial ecosystems or storing it in geological reservoirs, thereby creating CO_2 offsets that could obviate the need for lifestyle-changing reductions in fossil fuel use. Some scientists claim that, by converting marginal croplands to permanent grasslands or forests, the accompanying increase in biomass and soil organic carbon can offset 20% or more of countries' fossil fuel emissions [1, 2, 3]. The Government of Canada [4] had planned to rely on tree planting and improved forest management for meeting some one-third of its Kyoto commitment, although subsequent losses of large swaths of timber to Mountain Pine Beetle and wildfire greatly reduced the contribution that can be expected from forests.

Proponents of CO_2 capture and storage in deep underground aquifers and abandoned oil/gas fields indicate that there is enough available storage to trap decades of CO_2 emissions [5]. The costs of this option are unknown as there is a risk of a sudden release of deadly concentrations of CO_2 in the future – a cost to be evaluated by the willingness of people to pay to avoid such a risk and not unlike that associated with long-term storage of nuclear waste, which could be substantial (see [6]).

There is no lack of schemes to generate carbon credits through terrestrial activities. Even a cursory investigation finds there are many 'sellers' of carbon offset credits. Examples include:

- Greenfleet (http://www.greenfleet.com.au/greenfleet/objectives.asp, viewed 19 Oct 2007). "For $40 (tax deductible), Greenfleet will plant 17 native trees on your behalf. These trees will help to create a forest, and as they grow will absorb the greenhouse gases that your car produces in one year (based on 4.36 tonnes of CO2 for the average car)". This project is designed to increase planting of native species in Australia. Sale of carbon credits would help pay for tree planting, at a presumed cost of approximately US$0.82 per tCO_2, although, there is insufficient information about the timing of carbon uptake and release to determine the true cost.
- Trees for Life (http://www.treesforlife.org.uk/tfl.global_warming.html, viewed 19 Oct 2007). This is a conservation charity dedicated to the regeneration and restoration of the Caledonian Forest in the Highlands of Scotland. It uses the idea of a carbon footprint to solicit donations: "Rather than claiming to help you become 'carbon neutral,' we offer you the chance to make a real difference and become Carbon Conscious". Donations of £60 ($120), £140 ($280) and £280 ($360) are solicited depending on whether your

'carbon footprint' is rated as low, intermediate or high (a guide is provided). For each £5 ($10) donation, Trees for Life claims to plant one tree. No other details are available.

- Haida Gwaii Climate Forest Pilot Project (http://www.haidaclimate.com/, viewed 3 Nov 2006): The Haida-Gwaii First Nation needs to restore some 5,000 to 10,000 ha of degraded riparian habitat; starting with some 1,000-1,500 ha, they hope to fund the project by selling carbon credits. The idea is to remove alder that is "growing in an un-natural manner" and replace it with the preferred mixed-conifer climax rainforest that existed before clear-cutting some 50 years ago. The eventual old-growth forest will sequester 1928-2454 tCO_2 per ha; labour cost is estimated to be $15.92 million, or $6.49-$8.26 per tCO_2. No other cost is provided and there is no indication about the timing of carbon uptake or potential for future release, or loss of carbon from removing alder.

Whether or not these planting programs are or will be certified, current information on projects is incomplete: it is not possible to determine how much carbon is sequestered for how long. Unless the timing of carbon uptake and release is known, it is impossible to know how many credits are created for sale in carbon markets. This we refer to as the duration problem.

Given that the Haida Gwaii are committed to restoring ancient forests because they are part of their cultural heritage, and that Trees for Life is committed to restoring the Caledonian Forest, the sale of carbon credits is no more than a marketing technique to solicit funds for a project that would proceed in any event.[1] Such projects would be additional only if they would not proceed in the absence of CO_2 offset payments, and that is difficult to demonstrate.

The forgoing are not the only questionable projects that aim to remove CO_2 from the atmosphere rather than prevent it from being released to begin with. Many CDM-initiated forestry activities also seek to create (tradable) carbon credits, as do forestry projects in developed nations. Some projects are simply funded by international agencies, or 'picked up' by companies seeking to improve their corporate image. Yet, projects fail to identify all of the carbon sequestration costs, the future path of carbon uptake and harvests, the risks of forest denudation, and so forth. Are they really contributing to climate mitigation?

In a review of terrestrial carbon sequestration, the FAO [7] examined 49 projects that were underway or proposed to create offset credits. Forty-three were in developing countries and eligible for CDM credits – 38 were forestry projects, of which 17 involved forest conservation. While all projects had local or offshore sponsors and/or investors (a country and/or company), only 33 of the 49 projects managed to provide some information on the amount of carbon to be sequestered. Data on the amount of carbon sequestered could be considered 'good' for only 24 projects, although none provided an indication of the timing of carbon benefits. Information on costs was provided for only 11 projects.

Determining the duration that CO_2 is removed from the atmosphere is a problem for terrestrial projects. Carbon offset credits from agricultural activities are particularly ephemeral, while CO_2 capture and storage might almost be considered permanent; forestry activities lead to carbon sinks that have a more intermediary duration. Most commentators believe that the carbon embodied in forests and, especially, agricultural ecosystems (grass and soils) is always at risk of accidental or deliberate release, but that avoided emissions are permanent, despite the fact that 'saved' fossil fuels might release stored CO_2 at some future date [8].

There is no denying that terrestrial activities create non-permanent carbon offsets, but they create problems for policy makers who wish to compare mitigation strategies that differ in the length of time they withhold CO_2 from entering the atmosphere. But how should markets for emissions trading value

[1] There are many efforts to gain carbon credits for ongoing or planned forestry activities. Two groups approached the author for advice on obtaining carbon credits. The Little Red River Cree Nation located in northern Alberta, Canada, sought tradable carbon permits for delaying the harvest of forests under their management. The delay was the result of a poor price outlook, and the request was subsequently turned down by the Canadian government. A community group in Powell River, British Columbia, hopes to obtain carbon credits to fund activities to prevent the harvest of coastal rainforest. Neither project provides additional carbon uptake services, but they do illustrate the potential for rent seeking via dubious carbon sink projects.

permanence? More specifically, how have producers of carbon offsets from forestry activities determined the value of these credits? And what guarantees are there that forest-generated credits are cheaper than emission reduction offsets?

In the remainder of this paper we investigate the role of duration in greater detail. This is done by expanding in comprehensive fashion on earlier work by Marland et al. [9], Sedjo and Marland [10], and Herzog et al. [8]. In particular, we compare carbon mitigation activities according to how long they are able to lower CO_2 levels in the atmosphere. This is important because storage times differ even among terrestrial activities, with some being more permanent than others.

In the next section, we consider economic issues regarding the role of terrestrial carbon sinks. We then investigate the implications of non-permanence of biological sinks in a formal fashion to determine whether the stop-gap nature of forestry activities makes it more burdensome for producers and buyers of temporary carbon offsets to value such credits, thereby adding to transaction costs and inhibiting trades. This is not the same as asking whether forestry activities can make a reasonable and useful contribution to a country's overall mitigation strategy, although it does shed light on this issue. The formal analysis is followed by a discussion of its policy implications. We end with some concluding observations.

II. DURATION: NON-PERMANENCE OF GREENHOUSE GAS MITIGATION

Land use, land-use change and forestry (LULUCF) activities remove carbon from the atmosphere and store it in biomass, and, under Kyoto, are eligible activities for creating carbon offset credits. Tree planting and activities that enhance tree growth are among the most important, although tree plantations release a substantial amount of their stored carbon once harvested, which could happen as soon as five years after establishment for some fast-growing species. Sequestered carbon might also be released as a result of wildfire, disease or pests (e.g., mountain pine beetle infestation in British Columbia).

Based on a meta-regression analysis of 68 studies, van Kooten and Sohngen [11] estimated the potential marginal costs of creating carbon offset credits via different forestry activities. These are provided in Table 1, but they ignore transaction costs In many of the studies included in the analysis, and particularly for a large number of studies not included in the analysis because of lack of information, the actual number of offset credits (as opposed to total carbon) that could be counted as part of the project was not available. Less than 10% of studies provided information on the duration that carbon was retained in sinks. Even so, given that utility companies are banking on carbon credits costing no more than $20 per metric ton of CO_2 (see [12]), many forest activities are not competitive with emissions reduction because the opportunity cost of land is generally too high. This holds even when account is taken of carbon stored in wood products. Not surprisingly, because of lower land costs, tree planting in the tropics and some activities in the boreal region might be worth undertaking, as well as some U.S. projects. The only other exception occurs when trees are harvested and burned in place of fossil fuels to generate electricity, and then not in all locations. Of course, none of these estimates include transaction costs which could easily double the costs in Table 1.

Table 1 Marginal Costs of Creating Carbon Offset Credits through Forestry Activities, Various Forestry Activities and Regions, $/t$CO_2$; Source: Adapted from [11]

	Region			
Activity	Global	Europe	Boreal	Tropics
Planting	$22-33	$158-185	$5-128	$0-7
Planting & fuel substitution	$0-49	$115-187	$1-90	$0-23
Forest management	$60-118	$198-274	$46-210	$34-63
Forest management & fuel substitution	$48-77	$203-219	$44-108	$0-50
Forest conservation	$47-195	n.a.	n.a.	$26-136

Agricultural activities that enhance soil organic carbon and store carbon in biomass are also eligible means to create offset credits. Included under Kyoto are re-vegetation (establishment of vegetation that does not meet the definitions of afforestation and reforestation), cropland management (greater use of conservation tillage, more set asides) and grazing management (manipulation of the amount and type of vegetation and livestock produced). Most of these activities provide temporary offsets only. One study reported, for example, that all of the soil organic carbon stored as a result of 20 years of conservation tillage was released in a single year of conventional tillage [13].

During the 1990s, farmers increasingly adopted conservation tillage practices, particularly zero tillage cropping. There is concern that these soil conservation practices could be reversed at any time as a consequence of changes in prices and technologies. Farmers who adopt no-till agriculture balance costs (lower yields, higher chemical outlays) against benefits (labour and machinery savings due to reduced field operations, and carbon payments if any).[2] If output prices (or chemical costs) rise because of greater demand for energy crops, say, no-till is a less attractive option. An increase in the opportunity cost of zero tillage could tip the farmer back to using conventional tillage, thus releasing carbon stored in soils. Given that costs of conservation tillage have declined dramatically in the past several decades, it is questionable whether increases in soil carbon that result from conservation tillage can even be counted towards Kyoto targets, simply because they cannot be considered additional as farmers undertake them to reduce costs and conserve soil, and not to sequester carbon per se.

It is not uniformly true that zero tillage sequesters more carbon than conventional tillage, since less residue is available for conversion to soil organic carbon in arid regions [15], which affects the costs of creating carbon credits. Some cost estimates based on meta-analyses of 52 studies of soil carbon flux and 51 studies of cost differences between conventional and zero tillage are provided in Table 2. The estimates omit the increased emissions related to greater chemical use and the transaction costs associated with measurement and monitoring. With the exception, perhaps, of the U.S. South, the cost of generating carbon credits by changing agronomic practices is not very competitive with emissions reduction if it costs \$20 per tCO_2.

Table 2 Cost of Creating Carbon Credits via Zero Tillage Agriculture, \$ per metric ton of CO_2; Source: Adapted from [15]

Region	Wheat	Other Crops
U.S. South	\$3 to \$4	\$½ to \$1
Prairies	\$105 to >\$500	\$41 to \$57
U.S. Corn Belt	\$39 to \$51	\$23 to \$24

While the Kyoto Protocol permits various terrestrial options, particularly ones related to biological sinks, its main focus is on the avoidance of greenhouse gas emissions, especially CO_2 emissions associated with the burning of fossil fuels. What are the long-term consequences of reducing current fossil fuel use? Some argue that, by leaving fossil fuels in the ground, their eventual use is only delayed and, as with carbon sequestered in a terrestrial sink, results in the same obligation for the future [8]. The reasoning behind this is that the price path of fossil fuels will be lower in the future because, by reducing use today, more fossil fuels are available in the future. However, if society commits to de-carbonizing the economy, behaviour changes and technology evolves in ways that reduce future demand for fossil fuels, much as wood used by locomotives was replaced by coal and then by diesel. Carbon in terrestrial sinks, on the other hand, always has the potential to be released.

The appropriate way to deal with this problem is to count removals of CO_2 from the atmosphere and emissions reduction on the same footing. A credit is earned by removing CO_2 from the atmosphere and storing it in a terrestrial sink. The credit is the mirror image of an emissions reduction – one removes CO_2 from the atmosphere, the other avoids putting it there to begin with. However, if agricultural practices or land use change, or a forest is harvested, any carbon not stored in products but released to the atmosphere is debited (in the same way as emissions from fossil fuels). Likewise, any carbon released by decay of

[2] We focus on zero tillage because reduced tillage does not lower atmospheric CO_2 as the carbon stored in soils is offset by that released by increased production, transportation and application of chemicals [14]. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: Comparing tillage practices in the United States. Given the risk that carbon stored in soils is released when economic conditions change, reduced tillage may actually increase overall CO_2 emissions.

wood products, or any soil carbon released to the atmosphere, is counted as a debit at the time of release. If harvested fiber is burned in lieu of fossil fuels, a debit is also incurred but it is offset by the credit earned when growing biomass removes CO_2 from the atmosphere: The net benefit from biomass energy production is the reduction in CO_2 emissions from fossil fuel burning. The main difference between emissions reduction and carbon uptake and release from a terrestrial sink relates to measurement and monitoring, which greatly increase transaction costs.

What about forest conservation or avoidance of deforestation, which accounts for more than one-quarter of all anthropogenic emissions? In some ways this is similar to the emissions situation. Credits can only be earned through emissions avoidance if there is a target level of emissions and emissions are below the target. Without a target, emissions avoidance is nothing more than avoidance of debits. True credits can only be earned by removing CO_2 from the atmosphere. While it may be possible to mitigate CO_2 emissions by delaying (perhaps indefinitely) deforestation, there can be no credit for doing so unless there is some target level of deforestation so that, just as in the case of emissions avoidance, one gets credits by being below the target. Otherwise, the only benefit results from the avoidance of debits.

There are some problems with this solution to the duration problem. First, accounting for CO_2 uptake and release from terrestrial sinks requires measurement and monitoring, both of which are imprecise and expensive. This is the biggest strike against the use of terrestrial ecosystem sinks. Second, in the real world, countries have already agreed how they will address mitigation, and the existing Kyoto agreement permits carbon sequestration in ecosystems to count toward country targets. Kyoto also has a definitive time frame, the commitment period 2008-2012, so policy makers had to decide the fate of ephemeral sinks that could release large amounts of CO_2 after 2012. To the extent possible, they did this by holding countries responsible for carbon held in sinks at the end of the period. But this is simply the duration problem in another guise – terrestrial carbon storage is somehow less permanent than emissions reduction.

There exist several proposals for addressing the duration problem. Partial instead of full credits can be provided for storing carbon based on the perceived risk that carbon will be released from a sink at some future date. The buyer or seller may be required to take out an insurance policy, where the insurer will compensate for the losses associated with unexpected carbon release [16]. Alternatively, the buyer or seller can assure that the temporary activity will be followed by one that results in permanent emission reductions.

The ton-years approach specifies that emissions can be compensated for by removing CO_2 from the atmosphere and storing it for a period before releasing it back to the atmosphere. The conversion rate between ton-years of (temporary) carbon sequestration and permanent tons of emissions reduction is specified in advance [17, 18]. The rate ranges from 42 to 150 ton-years of temporary storage to cover one permanent ton (and is based on forest rotation ages). Rather than the authority establishing a conversion factor, market forces might be relied on to determine the conversion rate between (permanent) emissions reduction and temporary removals of CO_2 from the atmosphere [9, 10]. However, temporary credits are likely to be discounted quite highly because of greater uncertainty (due to the risk of unanticipated release of stored carbon), higher transaction costs (related to measurement and monitoring), and seller-host liability for the sink at the end of the contract period (reducing supply of sink-related carbon uptake services).

The instrument adopted by the UNFCC for forestry projects under the CDM is the temporary certified emission reduction unit, denoted tCER. A tCER is purchased for a set period of time and, upon expiry, has to be covered by substitute credits or reissued credits if the original project is continued. Transaction costs are high because monitoring and verification (measurement) are more onerous and international bookkeeping will be required to keep track of credits. Countries can obtain carbon credits early, while delaying payment to a future date (a problem discussed further below).

III. COMPARING CARBON CREDIT VALUES WHEN DURATION DIFFERS ACROSS PROJECTS

Consider a comparison between two climate change mitigation options, neither of which results in permanent removal of CO_2 from the atmosphere. Suppose that the more permanent of the two, say a policy that leads to a lower current rate of CO_2 emissions, leads to an increase in CO_2 emissions *N* years from now, as argued by Herzog et al. [8]; the more ephemeral project generates temporary offset credits through sequestration of CO_2 in a forest ecosystem, but releases the CO_2 in *n* years. (The comparison could just as well be between two carbon sequestration projects of different durations.) What then is the value of a forest-sink offset credit relative to an emissions reduction credit? Suppose that a unit of CO_2 not in the atmosphere is currently worth $\$q$, but that the shadow price rises at an annual rate $\gamma<r$, where r is the discount rate. Then the value of emissions reduction is:

$$P = \sum_{t=1}^{N} \frac{(1+\gamma)^t q}{(1+r)^t} = \frac{1+\gamma}{r-\gamma} q \left[1-\left(\frac{1+\gamma}{1+r}\right)^N\right], \quad (1)$$

while a sink offset would be worth some proportion α of the emissions reduction, or:

$$\alpha P = \sum_{t=1}^{n} \frac{(1+\gamma)^t q}{(1+r)^t} = \frac{1+\gamma}{r-\gamma} q \left[1-\left(\frac{1+\gamma}{1+r}\right)^n\right]. \quad (2)$$

Upon taking the ratio of (2) to (1) and simplifying, we obtain the value of 'temporary' relative to 'permanent' storage:

$$\alpha = \frac{1-\left(\frac{1+\gamma}{1+r}\right)^n}{1-\left(\frac{1+\gamma}{1+r}\right)^N}, \quad (3)$$

which depends on the discount rate (r), the time it takes a ton of CO_2 stored in a forest ecosystem to return to the atmosphere (n), and the time it takes a ton of CO_2 not emitted today to increase emissions at a future date (N). Notice that the value does not depend on the price of carbon (q). As indicated in Table 3, the proportional value of a sink credit to an emissions reduction credit (α) varies depending on the relationship between *n* and *N*, the discount rate, and the growth rate (γ) in damages from atmospheric concentrations of CO_2. It is possible to prove some general results.

Table 3: Value of a Temporary Relative to a Permanent Carbon Credit (α), Various Scenarios; Note: n.a. indicates not applicable as calculation cannot be made

n to *N*	*N*=100 years Discount rate			*N*=200 years Discount rate			*N*=500 years Discount rate		
ratio	2%	5%	10%	2%	5%	10%	2%	5%	10%
Growth rate of shadow price of carbon, ã=0									
0.01	0.023	0.048	0.091	0.040	0.093	0.174	0.094	0.216	0.379
0.05	0.109	0.218	0.379	0.183	0.386	0.614	0.390	0.705	0.908
0.10	0.208	0.389	0.615	0.333	0.623	0.851	0.629	0.913	0.991
0.15	0.298	0.523	0.761	0.457	0.769	0.943	0.774	0.974	0.999
0.20	0.379	0.628	0.851	0.558	0.858	0.978	0.862	0.992	1.000
0.25	0.453	0.710	0.908	0.641	0.913	0.991	0.916	0.998	1.000
0.30	0.520	0.775	0.943	0.709	0.947	0.997	0.949	0.999	1.000
Growth rate of shadow price of carbon, ã=0.01									
0.01	0.016	0.039	0.082	0.023	0.075	0.157	0.048	0.177	0.347
0.05	0.077	0.180	0.347	0.109	0.322	0.574	0.220	0.621	0.882
0.10	0.150	0.329	0.574	0.208	0.540	0.819	0.392	0.857	0.986
0.15	0.219	0.451	0.722	0.297	0.688	0.923	0.526	0.946	0.998
0.20	0.285	0.551	0.819	0.378	0.789	0.967	0.631	0.979	1.000
0.25	0.348	0.634	0.882	0.452	0.857	0.986	0.713	0.992	1.000
0.30	0.408	0.703	0.923	0.519	0.903	0.994	0.778	0.997	1.000
Growth rate of shadow price of carbon, ã=0.02									
0.01	n.a.	0.030	0.073	n.a.	0.056	0.140	n.a.	0.135	0.314
0.05	n.a.	0.143	0.315	n.a.	0.252	0.530	n.a.	0.516	0.849
0.10	n.a.	0.266	0.530	n.a.	0.441	0.779	n.a.	0.765	0.977
0.15	n.a.	0.373	0.678	n.a.	0.583	0.896	n.a.	0.886	0.997
0.20	n.a.	0.466	0.780	n.a.	0.688	0.951	n.a.	0.945	0.999
0.25	n.a.	0.546	0.849	n.a.	0.768	0.977	n.a.	0.973	1.000
0.30	n.a.	0.615	0.897	n.a.	0.827	0.989	n.a.	0.987	1.000
Growth rate of shadow price of carbon, ã=0.04									
0.01	n.a.	0.015	0.055	n.a.	0.022	0.106	n.a.	0.047	0.245
0.05	n.a.	0.076	0.245	n.a.	0.107	0.429	n.a.	0.215	0.754
0.10	n.a.	0.148	0.431	n.a.	0.204	0.674	n.a.	0.383	0.939
0.15	n.a.	0.217	0.571	n.a.	0.293	0.814	n.a.	0.516	0.985
0.20	n.a.	0.283	0.677	n.a.	0.373	0.894	n.a.	0.621	0.996
0.25	n.a.	0.345	0.757	n.a.	0.446	0.939	n.a.	0.704	0.999
0.30	n.a.	0.405	0.817	n.a.	0.512	0.965	n.a.	0.768	1.000

Proposition 1: *For fixed and finite N>0, as n/N→0, the value of temporary storage relative to permanent emissions reduction goes to zero. The more ephemeral a sink project, the less valuable it is relative to emissions reduction.*

Proof: This proposition is obvious. Nonetheless, differentiate equation (3) with respect to *n* and *N*, and sign the results.

$$\frac{\partial\alpha}{\partial n} = -\frac{\left(\frac{1+\gamma}{1+r}\right)^n \ln\left(\frac{1+\gamma}{1+r}\right)}{1-\left(\frac{1+\gamma}{1+r}\right)^N} > 0 \,. \tag{4}$$

$$\frac{\partial\alpha}{\partial N} = \frac{\left[1-\left(\frac{1+\gamma}{1+r}\right)^n\right]\left(\frac{1+\gamma}{1+r}\right)^N \ln\left(\frac{1+\gamma}{1+r}\right)}{\left[1-\left(\frac{1+\gamma}{1+r}\right)^N\right]^2} < 0 \,. \tag{5}$$

The reason for the signs is that the natural logarithm of a number less than 1 is negative (recall $\gamma<r$). Clearly, as the length of temporary storage decreases relative to the 'permanent' CO_2 emission reduction, result (4) indicates that the value of a temporary sink relative to an emission reduction falls (because all other things are held constant – the *ceteris paribus* condition); thus, for a given N, as $n/N\rightarrow0$, $\alpha\rightarrow0$. Likewise, the value of a temporary sink decreases as the 'duration' of an emission reduction (N) increases, *ceteris paribus*, because the period of sequestration (n) becomes too small to have any value. This might well be the case for carbon stored in soil as a result of zero tillage.

Proposition 2: *For fixed n/N, an increase in N narrows the difference in importance between an emissions reduction and a carbon sequestration activity, ceteris paribus. An increase in N 'lengthens' n so that, with discounting, the eventual release of stored carbon (at time n) is valued much less today. If N→∞ so that an emission reduction is truly permanent, then the value of temporary storage depends only on the length of time that carbon is sequestered.*

Proof: The second term in the denominator of (3) approaches 0 as $N\rightarrow\infty$, so that the value of a temporary sink credit relative to a permanent one depends only on n (given γ and r). Since storage is not infinite, temporary offsets will always be less valuable than permanent emission reductions.

Proposition 3: *The value of storage increases with the discount rate (∂α/∂r>0), as illustrated in Table 3. The reason that ephemeral activities are more important relative to emission reductions as the discount rate increases is because the inevitable release of sink CO_2 at some future date is weighted much less than the early sequestration. Thus, a policy requiring the use of low discount rates for evaluating climate change activities militates against carbon uptake in terrestrial sinks.*

Proof: Differentiate (3) with respect to r:

$$\frac{\partial\alpha}{\partial r} =$$

[illegible] (6)

The sign of $\frac{\partial\alpha}{\partial r} > 0$ as long as $\frac{n}{N} > \frac{\left(\frac{1+r}{1+\gamma}\right)^n - 1}{\left(\frac{1+r}{1+\gamma}\right)^N - 1}$, which holds for all n, $N > 0$, $n<N$ and $\gamma<r$. The proof is numerical. Clearly, if n=N, $\frac{\partial\alpha}{\partial r}$=0. Assume r=0.04 and γ =0.02. Then, if n=1 and N=2, we find ½ >0.4951; if n=50 and N=100, ½ >0.2747; if n=250 and N=500, ½ >0.0077; and so on.

Proposition 4: *As the rate at which the shadow price of carbon (γ) increases, the value of temporary storage relative to a 'permanent' emission reduction decreases. This implies that landowners would supply less carbon when the price of carbon is rising over time.*

Proof: Differentiate (3) with respect to γ:

$$\frac{\partial\alpha}{\partial\gamma} =$$

(7)

[illegible]

The result $\partial\alpha/\partial\gamma<0$ can only be proven numerically. Assume $\partial\alpha/\partial\gamma<0$. Then, it is possible to rearrange (7) as: $\frac{n}{N} > \frac{\left(\frac{1+r}{1+\gamma}\right)^{n}-1}{\left(\frac{1+r}{1+\gamma}\right)^{N}-1}$, which holds in all cases as indicated in Proposition 3. Thus, $\partial\alpha/\partial\gamma<0$. Now denote by $S(\alpha, \boldsymbol{P}; \boldsymbol{Z})$ the supply of carbon sink credits, where α is the relative price of 'temporary' (short duration) versus 'permanent' (long duration) credits (as before), **P** is a vector of carbon input prices and the price of a permanent credit, and **Z** is a vector of characteristics that describes the offset project. $\frac{\partial S(\alpha, \mathbf{P}; \mathbf{Z})}{\partial\alpha} > 0$ because supply of sink credits increases as their price increases. Then, because $\partial\alpha/\partial\gamma<0$, $S(\alpha, \boldsymbol{P}; \boldsymbol{Z})$ shifts down when the rate of the carbon price increase goes up.

Proposition 5: *The minimum value of a carbon sink credit relative to an emission reduction credit equals the ratio of the lifetimes of the 'temporary' and 'permanent' credits, n/N.*

Proof: Only $\gamma<r$ is possible because, if $\gamma>r$, economic agents would pursue climate mitigation (by purchasing carbon sink credits) to such an extent that the rate of growth in atmospheric CO_2 (the price of carbon credits) falls enough to equalize γ and r. Consider $r\rightarrow^{+}\gamma$. In that case, (1) becomes $P = \sum_{t=1}^{N} q = Nq$ and (2) becomes $\alpha P = \sum_{t=1}^{n} q = nq$, so that $\alpha=n/N$.

IV. DISCUSSION

The forgoing results have important policy implications that relate to the duration problem. It is clear that sink offset credits cannot generally be traded one-for-one for emission reduction credits, even if the latter are not considered permanent; nor can credits from different sink projects be traded one-for-one without some adjustment for duration (say using Table 3). The conversion rate will depend on the length of time that each project keeps CO_2 out of the atmosphere, and, crucially, on the discount rate. For example, if a sequestration project can ensure that carbon remains sequestered for 10 years, it is worth only 0.11 of an emission reduction that ensures no future increase in emissions for 200 years if the discount rate (r) is 2% and the growth rate of damages (γ) is 1% (Table 3).

When the damages from atmospheric concentrations of CO_2 (shadow carbon prices) rise over time, the value of temporary sequestration will also fall. As a consequence, there might be a reduced demand for short-term sequestration. If the rate of increase rises, landowners will further delay investing in land-use activities that create carbon credits so as to obtain a higher price in the next period (see proposition 4). Equivalently, a landowner is willing to delay an investment in a carbon sink activity if the opportunity cost of time falls, which essentially happens when CO_2 damages rise over time (the shadow price γ increases).

Given the difficulty of determining not only the discount rate and the growth rate in damages, but also the uncertainty surrounding n and N, it will simply not be possible for the authority to determine a conversion factor between activities leading to carbon credits of differing duration. Perhaps one can rely on the market to determine conversion rates, but even the market will have difficulty resolving all uncertainty. In the absence of a certifying authority that guarantees equivalence and thereby resolves uncertainty, sink credits will be worth a lot less. To judge sink projects in the absence of market data requires that the analyst make arbitrary judgments about the discount rate, the rate of increase in damages, and the conversion rate between projects to remove CO_2 from the atmosphere to account for differing durations. These are over and above assumptions and uncertainty related to vegetation growth rates, uptake of carbon in soils, wildfire, disease, pests and so forth, the majority of which are not explicitly spelled out in most analyses of terrestrial sink projects.

While some advocate for the use of low discount rates, we demonstrated that low rates of discount militate against terrestrial sink activities (proposition 3). We do not know the rate at which economic damages increase as more anthropogenic emissions of CO_2 enter the atmosphere. If the rate of increase in damages equals or exceeds the discount rate, then CO_2 offset credits from sink activities are only worth n/N of an emissions-reduction credit (proposition 5). This is equivalent to assuming a zero discount rate for physical carbon.[3] But this implies that temporary offsets from biological sink activities are overvalued because, as $N \to \infty$, the value of a temporary offset credit falls to zero. It is reasonable to assume that $N \to \infty$ if an emissions-reduction policy results in behavioural changes that cause permanent reductions in CO_2 emissions (e.g., car manufacturers stop producing SUVs as people demand smaller vehicles).

Finally, a country that uses carbon sequestration credits to achieve some proportion of its CO_2 emissions-reduction target during Kyoto's first commitment period has avoided emissions reductions. If it is to remain committed to long-term climate mitigation, however, the country must increase its emissions-reduction target in the next commitment period. It must meet that target plus the shortfall from the previous period – it still needs to reduce the emissions that were covered by forestry activities. Further, the country is technically liable for ensuring that the stored carbon remains there, which will be difficult given the non-permanence of forest sinks. For example, a country that relies on forest sinks for one-third of a 6% reduction in emissions and commits to a further 7% reduction for the second commitment period must still reduce emissions in the second commitment period by an incredible 11%. It has only reduced emissions by 4% in the first period, and must thus reduce emissions by 9% during its second period commitment. But, as the forest sink releases its carbon to the atmosphere, the country must also cover that loss, which amounts to a further 2% reduction in emissions. The temporal shifting in the emissions-reduction burden caused by reliance on carbon sinks therefore results in an onerous obligation for future generations, one which they may not be willing to accept.

[3] For a discussion of discounting physical carbon in this context see [19] and [20].

V. CONCLUSION

The main argument of this paper is that terrestrial ecosystem activities to generate CO_2 offset credits are a distraction from the actual job of mitigating climate change. While there is no question that carbon can be stored in terrestrial sinks, and that care should be taken to foster such sinks and ensure that carbon is not unwontedly and needlessly released (e.g., via deforestation), this is no reason to justify their inclusion in international agreements to mitigate climate change or in international trading schemes. There are simply too many obstacles to warrant their consideration. Measurement, monitoring and verification of sink activities is particularly difficult, serving to raise transaction costs. Rent seeking by opportunistic sellers of carbon credits, and even by environmental groups, highlights another important problem: terrestrial sinks remove CO_2 from the atmosphere at different rates and store it for varying lengths of time, with both removal rates and storage times embodying significant uncertainty, thereby facilitating dubious claims of sink carbon offset credits. While this duration problem can readily be solved (e.g., taxing emissions and subsidizing removals at the time they occur), given the high transaction costs of including sink activities and the reluctance of countries to make sinks work, the only conclusion is that terrestrial ecosystem sink activities should not be included in international agreements to mitigate climate change.

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Enter address of the corresponding author:

- Author: G. Cornelis van Kooten
- Institute: Department of Economics, University of Victoria
- Street: PO Box 1700, Stn CSC
- City: Victoria, BC V8W 2Y2
- Country: Canada
- Email: kooten@uvic.ca