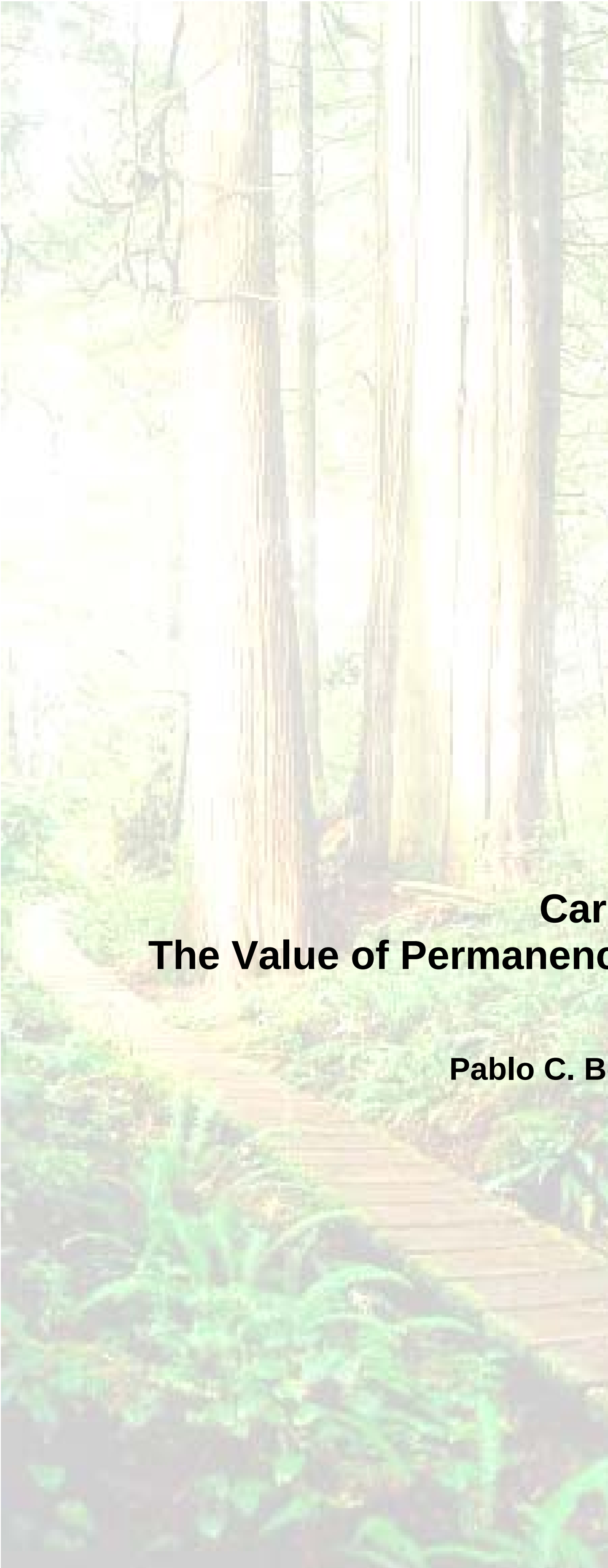

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Carbon Sinks and Reservoirs: The Value of Permanence and Role of Discounting

Pablo C. Benítez and G. Cornelis van Kooten

October 2005

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Carbon Sinks and Reservoirs:
The Value of Permanence and Role of Discounting

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Abstract

Scientists are enthusiastic about storing carbon in terrestrial sinks and geological reservoirs in order to obviate the need for lifestyle-changing reductions in fossil-fuel use. Estimating relative costs of various options depends on how permanence is assessed and whether physical carbon is discounted. We demonstrate that, in carbon markets, terrestrial sinks credits cannot be traded one-for-one for emission reduction credits and the conversion factor would depend on how long sinks keep CO_2 out of the atmosphere as compared with emission reductions and, discounting physical carbon. As a result, the authority could not determine a conversion factor and the market would be required to do so.

Keywords: climate change, carbon offset, carbon sinks, discounting physical carbon

Funding support from BIOCAP/SSHRC is greatly appreciated

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1. INTRODUCTION

Scientists and engineers are particularly enthusiastic about the possibility of storing carbon in terrestrial sinks and geological reservoirs, thereby creating CO_2 offsets that could obviate the need for lifestyle-changing reductions in fossil fuel use. (1) Soil scientists claim that, by adopting 'better' management practices (e.g., zero tillage, improved crop residue management), by restoring degraded soils and by converting marginal croplands to permanent grasslands or forests, increases in soil organic carbon can offset 20% or more of countries' fossil fuel emissions (e.g., see Lal, 2004a; Lal, 2004b). (2) The Government of Canada (2002) plans to rely on tree planting and improved forest management to meet nearly one-third of its Kyoto commitment. (3) 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 (Parson and Keith, 1998; Gale, 2002; Riahi et al., 2004).

This enthusiasm needs a reality check. One purpose of this paper is to point out that there are some real limits to what may at first glance appear to be a perfectly reasonable approach to reducing growth in atmospheric CO_2. In particular, we focus on two issues that determine if mitigation activities are economically feasible: permanence and the rate at which physical carbon is discounted.

Regarding permanence, there is the question about whether terrestrial carbon storage is somehow less permanent than emission reductions as fossil fuels not burned today remain available in the future. Most commentators believe that the carbon embodied in trees or agricultural soils is always at risk of accidental or deliberate release, and that the CO_2 kept in a reservoir could leak out at some future time and enter the atmosphere, but that avoided emissions are more permanent. If all mitigation policies are in some sense non-permanent, what then is the value of one policy relative to another? How should emerging markets for emissions trading value permanence? And how do analysts treat differences in the permanence of mitigation activities in cost-benefit analyses that seek to rank alternative policy strategies? While a few studies have dealt with this issue (Marland et al., 2001; Sedjo and Marland, 2003; Herzog et al., 2003; Locatelli and Pedroni, 2004), none have done so in a comprehensive fashion. Further, most studies have failed to link permanence with the problem of discounting physical carbon and its valuation (Garcia-Oliva and Masera, 2004; Richards and Stokes, 2004). Discounting physical carbon is particularly perplexing when carbon offsets and CO_2 emission reduction permits are tradable and exchangeable, and when carbon offsets are provided on a temporary basis. These issues are discussed in detail in the remainder of this paper.

2. NON-PERMANENCE OF GHG MITIGATION

Terrestrial Sinks

Land use, land-use change and forestry (LULUCF) activities can lead to carbon offset credits (or debits). Tree planting and activities that enhance tree growth clearly remove carbon from the atmosphere and store it in biomass, and thus are eligible activities for creating carbon offset credits. However, there is concern that tree plantations will release a substantial amount of their stored carbon once harvested, which could happen as soon as five years after establishment if fast-growing hybrid species are planted.

In addition to forest ecosystem sinks, agricultural activities that lead to enhanced soil organic carbon (SOC) and/or more carbon stored in biomass can be used to claim offset credits. Included are revegetation (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 carbon 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 (Lewandrowski et al., 2004). Likewise, there is concern that soil management practices could be stopped by farmers at any time as a consequence of changes in prices and technologies. Finally, given that costs of conservation tillage have declined dramatically in the past several decades, it is questionable whether the increases in soil organic carbon that result from conservation tillage can be counted towards Kyoto targets, simply because they cannot be consider 'additional' as they are being undertaken by farmers to reduce costs and conserve soil (not to sequester carbon per se).

Carbon Capture and Storage in Geological Reservoirs

There is increasing interest in CO_2 capture and storage in geological reservoirs (Parson and Keith, 1998; Gale, 2002). The storage capacity of depleted gas fields could be around 690 Gt CO_2, in depleted oil fields 120 Gt CO_2, and in deep saline aquifers some 400 to 10,000 Gt CO_2 (Gale, 2002).[1] Compared with current anthropogenic greenhouse gas emissions from the use of fossil fuels that are about 23 Gt CO_2 per year (WRI, 2005), there might be enough capacity to store more than a century of CO_2 emissions and, perhaps wistfully in an attempt to control climate, actually remove CO_2 from the atmosphere and store it underground. It is very likely that storage in geological reservoirs is more permanent than storage in biological sinks, but how permanent is it compared to reducing emissions?

Since natural gas has effectively been trapped in situ for millions of years, there is no reason to think that a gas field could not contain CO_2 for a similarly long period (Wildenborg

[1] Gale (2002) cites data from the International Energy Agency.

and van der Meer, 2002). If there happens to be some CO_2 leakage, it may well be possible to take action to fix the problem and prevent further CO_2 release. Unfortunately, there currently do not exist enough studies to support the degree to which CO_2 storage in geological reservoirs might be permanent.[2] Ultimately the permanence of any CO_2 capture and geological storage depends on our ability to manage such reservoirs properly and responsibly.

Emission Reductions

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, this only delays their eventual use and, as with carbon sequestered in a terrestrial sink, results in the same obligation for the future (Herzog et al., 2003). 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 for future use than would otherwise be the case. However, fossil fuels left in the ground may not be used in the future, because, if society commits to de-carbonize the economy, behavior may change and technology evolve in ways that reduce future demand for fossil fuels. Carbon in terrestrial sinks, on the other hand, always has the potential to be released.

Permanence remains problematic in the case of emissions because of the different types of greenhouse gases and the need to compare them. For example, burning methane emissions from landfills not only reduces the amount of CH_4 entering the atmosphere (released as CO_2 instead), but might also offset some CO_2 emissions if the energy replaces an equivalent amount

[2] To address this deficiency, the IPPC intends to release in September 2005 a special report on the potential, costs and risks of CO_2 storage. Indications are that the report favors the use of carbon capture and storage (David Keith, personal communication).

of energy from fossil fuel burning. It is known that methane contributes more to global warming than carbon dioxide because its potential to trap long-wave heat energy radiated from Earth is much greater. However, methane remains in the atmosphere for only 12 years in contrast to CO_2 that stays for hundreds of years. To deal with this, the IPCC employs a global warming potential (GWP) for each gas as a simplified means for quantifying the relative abilities of greenhouse gases to affect future radiative forcing and thereby the global climate. GWPs are measured relative to CO_2 and have been updated several times. The GWPs of gases depend on the time span or *integration time horizon* that is chosen for making comparisons. If the integration time horizon is 100 years, the GWP of methane is 21, but it is 6.5 if the integration time horizon is 500 years. In determining the GWP, the IPCC does not discount physical carbon.

3. DISCOUNTING PHYSICAL CARBON

By discounting carbon, one acknowledges that it matters when CO_2 emissions or carbon uptake occur – carbon removed from the atmosphere today is more important and has greater potential benefits than that removed at some future time. Yet, the idea of discounting physical carbon is anathema to many who would discount only monetary values. However, the idea of weighting physical units accruing at different times is entrenched in the natural resource economics literature, going back to economists' definitions of conservation and depletion (Ciriacy-Wantrup, 1968). One cannot obtain consistent estimates of the costs of carbon uptake unless both project costs and physical carbon are discounted, even if different rates of discount are employed for costs and carbon. This is easy to demonstrate with an example where a project involves two or more sources of carbon flux with different time paths (see van Kooten 2004, pp.76-77).

The rate at which physical carbon should be discounted depends on what one assumes about the rate at which the damages caused by CO_2 emissions increase over time (Herzog et al., 2003; Richards, 1997; Stavins and Richards, 2005). If the damage function is linear so that marginal damages are constant (i.e., damages per unit of emissions remain the same as the concentration of atmospheric CO_2 increases), then the present value of reductions in the stock of atmospheric CO_2 declines at the social rate of discount. Hence, it is appropriate to discount future carbon uptake at the social rate of discount. "The more rapidly marginal damages increase, the less future carbon emissions reductions should be discounted" (Richards 1997, p.291). Thus, use of a zero discount rate for physical carbon is tantamount to assuming that, as the concentration of atmospheric CO_2 increases, the damage per unit of CO_2 emissions increases at the same rate as the social rate of discount – an exponential damage function with damages growing at the same rate as the social rate of discount. A zero discount rate on physical carbon implies that there is no difference between removing a unit of carbon from the atmosphere today, tomorrow or at some future time; logically, then, it does not matter if the carbon is ever removed from the atmosphere. The point is that use of any rate of discount depends on what one assumes about the marginal damages from further CO_2 emissions or carbon removals.

The effect of discounting physical carbon is to increase the costs of creating carbon offset credits because discounting effectively results in 'less carbon' attributable to a terrestrial carbon project. Discounting financial outlays, on the other hand, reduces the cost of creating carbon offsets. Since most outlays occur early on in the life of a forest or CO_2 storage project while benefits of carbon sequestered are spread over time, costs of creating carbon offsets are not as sensitive to the discount rate used for costs as to that used for carbon.

Discounting physical carbon has important implications. For example, discounting physical carbon implies that temporary carbon storage is more valuable. Also, by discounting physical carbon, the global warming potential of non-CO_2 gases will be different than what it is now, which affects the emission inventories of countries that have ratified the Kyoto Protocol.

4. APPROACHES FOR DEALING WITH PERMANENCE

The permanence problem could be addressed by providing partial instead of full credits for stored carbon according to the perceived risk that carbon will be released from the sink at some future date. The buyer or the seller may be required to take out an insurance policy, where the insurer will substitute credits from another carbon sink at the time of default. Alternatively, the buyer or seller can provide some assurance that the temporary activity will be followed by one that results in permanent emission reductions. For example, arrangements can be put in place prior to the exchange that, upon default or after some period of time, the carbon offsets are replaced by purchased emission reductions. Again, insurance contracts can be used. Insurance can also be used if there is a chance that the carbon contained in a sink is released prematurely. It is also possible to mark down the number of offset credits by the risk of loss (e.g., a provider may convert more land into forest than needed to sequester the contracted amount of carbon).

Three ‘practical’ approaches to non-permanence of sinks have been discussed in the literature. One is to specify a conversion factor that translates years of temporary carbon storage into a permanent equivalent. The concept of ton-years has been proposed to make the conversion from temporary to permanent storage (Dutschke, 2002; Herzog et al., 2003; IPCC, 2000). Suppose that one ton of carbon-equivalent GHG emissions are to be compensated for by a ton of permanent carbon uptake. If the conversion rate between ton-years of (temporary) carbon sequestration and permanent tons of carbon emissions reductions is k, a LULUCF project that yields one ton of carbon uptake in the current year generates only $1/k$ tons of emission reduction – to cover the one ton reduction in emissions requires k tons of carbon to be sequestered for one year.[3] The exchange rate ranges from 42 to 150 ton-years of temporary storage to cover one permanent ton.

Many observers have condemned the ton-year concept on various grounds (Herzog et al., 2003; Marland et al., 2001). Yet, the concept of ton-years has a certain appeal, primarily because it provides a simple, albeit naïve, accounting solution to the problem of permanence. The choice of an exchange rate, or, rather, timeframe, is arbitrarily based on rotation length, and is a political decision not unlike the choice of GWPs, which facilitated a common CO_2-equivalent measure. Once an exchange rate is chosen, carbon uptake credits can be traded in a CO_2-emissions market in straightforward fashion. Yet, the ton-years approach has been rejected by most countries, because it disadvantages carbon sinks relative to emissions avoidance (Dutschke, 2002).

A second approach that has been adopted by the Kyoto Protocol for dealing with CDM-afforestation and reforestation projects is the creation of a 'temporary' certified emission reduction (CER) unit, denoted tCER. The idea is that a tCER is purchased for a set period of time (the time between commitment periods of the Protocol) expiring thereafter. Upon expiry, tCERs would have to be covered by substitute credits or reissued credits if the original project were continued. Compared to ton-years, monitoring and verification are more onerous because a more complex system of bookkeeping will be required at the international level to keep track of credits. Countries favor this approach over other approaches because they can obtain carbon credits early, while delaying their 'payment' to a future date.

A third approach to the problem of temporary versus permanent removal of CO_2 from the

[3] This interpretation is slightly different from the original intent. The original idea is to count a temporary ton as equivalent to a permanent one only if the carbon is sequestered for the full period of time given by the exchange rate. The advantage of the interpretation here is that it enables one to count carbon stored in a sink for periods as short as one year (as might be the case in agriculture).

atmosphere is to employ a market device that would obviate the need for an arbitrary conversion factor or other forms of political maneuvering. Marland et al. (2001) and Sedjo and Marland (2003) propose a rental system for sequestered carbon. A one-ton emission offset credit is earned when the sequestered carbon is rented from a landowner, but, upon release, a debit occurs. "Credit is leased for a finite term, during which someone else accepts responsibility for emissions, and at the end of that term the renter will incur a debit unless the carbon remains sequestered and the lease is renewed" (Marland et al., 2001). The buyer-renter employs the limited-term benefits of the asset, but the seller-host retains long-term discretion over the asset, including responsibility for the liability after the (short-term) lease expires.

Rather than the authority establishing a conversion factor, the interaction between the market for emission reduction credits and that for carbon sink credits can determine the conversion rate between permanent and temporary removals of CO_2 from the atmosphere. The rental rate for temporary storage is based on the price of a permanent energy emissions credit, which is determined in the domestic or international market. The annual rental rate (q) is simply the market-determined price of a permanent emission credit (P) multiplied by the discount rate (r), which equals the established financial rate of interest (if carbon credits are to compete with other financial assets) adjusted for the risks inherent to carbon uptake (e.g., fire risk, slower than expected tree growth, etc.). Thus, $q = P \times r$, which is a well-known annuity formula. If emissions are trading for \$25 per t CO_2, say, and the risk-adjusted discount rate is 10%, then the annual rental for a terrestrial offset credit would be \$2.50 per t CO_2. Like the ton-year concept, a rental scheme makes terrestrial sink projects less attractive relative to emissions reduction.

Notice that a rental system of the type proposed by Sedjo and Marland (2003) works best if we are dealing with credit trading as opposed to allowance trading. Under a cap-and-trade scheme, it would be necessary to set not only a cap on emissions from fossil fuel consumption, but also a cap on sinks. In that case, one might expect separate markets to evolve for emissions and carbon sink allowances.

5. SUPPLY OF CARBON OFFSET CREDITS: THE ROLE OF RELATIVE PRICE

Consider the case where no climate change mitigation option is permanent. Suppose that, if fossil fuels are left in the ground because of a decision to emit less CO_2, this action actually results in greater emissions in *N* years. Likewise, CO_2 sequestered in a forest or reservoir results in its release in *n* years. What then is the value of a carbon offset credit relative to an emission reduction credit? Suppose that a unit of CO_2 not in the atmosphere is currently worth $\$q$, but that carbon price rises at an annual rate $\gamma < r$ (see van 't Veld and Plantinga, 2005). Then the value of an emission reduction credit is:

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

while an offset credit would be worth some proportion α of the emissions credit, or:

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

By taking the ratio of (2) to (1) and simplifying, we obtain:

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

The value of ‘temporary’ storage relative to ‘permanent’ emissions reduction depends on the discount rate, the time that it takes for a ton of sequestered CO_2 to return to the atmosphere, and the time it takes for a ton of avoided CO_2 emissions to result in higher future emissions compared to not having reduced the emissions today. Notice that it does not depend on the price of carbon. As indicated in Figure 1, the proportional value of an offset credit compared to an emissions-reduction credit (α) varies depending on the relationship between n and N, the discount rate r, and the growth rate (γ) in damages from CO_2. It is possible to prove some of the more important general findings.

[FIGURE 1 ABOUT HERE]

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.*

Proof: Partial 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 increases relative to the 'permanence' of a CO_2 emission reduction (because of the *ceteris paribus* condition), the value of a temporary sink relative to an emission reduction increases; thus, as $n/N\to 0$, $\alpha\to 0$. The value of a temporary sink decreases as the 'permanence' of an emission reduction 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 due to conservation tillage.

Proposition 2: *An increase in N results in a narrowing of the difference in importance between an emissions reduction and a carbon sequestration activity, ceteris paribus. For fixed n/N, 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 $N \to \infty$, so that the value of a temporary sink credit relative to a permanent one depends only on n (as well as γ and r). Since storage is not infinite, temporary offsets are still less valuable than permanent emission reductions.

Proposition 3: *The value of storage increases with the discount rate, as illustrated in Figure 1. 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:

$$\frac{\partial \alpha}{\partial r} = \frac{\left(\frac{1+\gamma}{1+r}\right)^{n} n}{(1+r)\left(1-\left(\frac{1+\gamma}{1+r}\right)^{N}\right)} - \frac{\left(1-\left(\frac{1+\gamma}{1+r}\right)^{n}\right)\left(\frac{1+\gamma}{1+r}\right)^{N} N}{\left(1-\left(\frac{1+\gamma}{1+r}\right)^{N}\right)^{2}(1+r)} \tag{6}$$

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 $n, N > 0$, $n<N$, if $\gamma<r$. 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, somewhat surprisingly, that landowners would supply less carbon when the price of carbon is rising over time. The reason is that the supply of offset credits is a positive function of α, and ∂α/∂γ < 0. Van t'Veld and Plantinga (2005) come to the same conclusion, but their argument relies on a strictly concave growth function for trees while the forgoing result requires only that the supply of carbon sequestration services be an inverse function of α.*

Proof: Differentiate (3) with respect to γ:

$$\frac{\partial\alpha}{\partial\gamma} = -\frac{\left(\frac{1+\gamma}{1+r}\right)^{n} n}{(1+\gamma)\left(1-\left(\frac{1+\gamma}{1+r}\right)^{N}\right)} + \frac{\left(1-\left(\frac{1+\gamma}{1+r}\right)^{n}\right)\left(\frac{1+\gamma}{1+r}\right)^{N} N}{\left(1-\left(\frac{1+\gamma}{1+r}\right)^{N}\right)^{2}(1+\gamma)} \tag{7}$$

The result $\partial\alpha/\partial\gamma<0$ can only be proven numerically, which is easier to do by rearranging (7) as $\frac{n}{N} > \frac{\left(\frac{1+r}{1+\gamma}\right)^{n}-1}{\left(\frac{1+r}{1+\gamma}\right)^{N}-1}$. Denote by $S(\alpha,\boldsymbol{P};\boldsymbol{Z})$ the supply of carbon offset credits, where α is the relative price of 'temporary' versus 'permanent' 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. Since $\frac{\partial S(\alpha,\boldsymbol{P};\boldsymbol{Z})}{\partial\alpha} > 0$, $S(\alpha,\boldsymbol{P};\boldsymbol{Z})$ shifts up with an increase in the price of carbon offset credits relative to emission reduction credits because $\partial\alpha/\partial\gamma<0$.

Proposition 5: *The minimum value of a carbon offset 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 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. Thus, consider $r\rightarrow^{+}\gamma$ and replace in (1). Then the value of an emission reduction credit is Nq and from a carbon offset credit is nq. This leads that $\alpha=n/N$.

6. CONCLUDING REMARKS

Our results have important policy implications, which arise from the non-permanence of some policy instruments and the necessity of discounting physical carbon.[4] It is clear that carbon offset credits cannot generally be traded one-for-one for emission reduction credits, even if the latter are not considered permanent. The conversion rate will depend on the length of time that each keeps CO_2 out of the atmosphere, and, crucially, on the discount rate. For example, if a sequestration project can insure 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 is 2%. Given the difficulty of determining not only the discount rate but the uncertainty surrounding n and N, it is not possible for the authority to determine a conversion factor. Rather, one must rely on the market to determine the exchange rate. While another approach might be considered ad hoc, lack of market data for use in cost-benefit analysis requires that the analyst make some arbitrary judgments about the conversion rate between permanent and temporary removal of CO_2 from the atmosphere. While it is possible that carbon

[4] Discounting of carbon is not relevant only for integrated assessment of climate change and project-based studies, but also for estimating the global warming potentials of non-CO_2 gases, which, in turn, determine the emission inventories of countries and the way they will allocate resources for targeting each gas.

prices will be increasing in time, the value of temporary sequestration will be even lower. As a consequence, there might be a reduced demand for short-term sequestration.

While some advocate for the use of low discount rates, we demonstrated that rates can go no lower than the rate of increase in global environmental damage resulting from anthropogenic emissions of CO_{2e}. When discount rates are set at their lowest value, however, carbon offset credits are only worth n/N as much as emission-reduction credits. This implies that 'temporary' offsets related to biological sink activities are undervalued.

Finally, it is still uncertain how permanent are the different CO_2 storage options. In contrast to forestry where trees have been planted and harvested for centuries, there is little experience storing CO_2 in geological reservoirs and aquifers. While scientists claim that reservoirs could store CO_2 for centuries, is it possible that capture and storage offers a more 'permanent' option compared to reducing fossil fuel emissions? In principle, the answer is yes, because, with the CO_2 capture-and-storage option, fossil fuels must be burned beforehand, guaranteeing that they will not be burned in the future. In contrast, when renewable energy sources replace fossil fuels, there is always a chance that those fossil fuels are burned in the future. Further research is needed on this regard.

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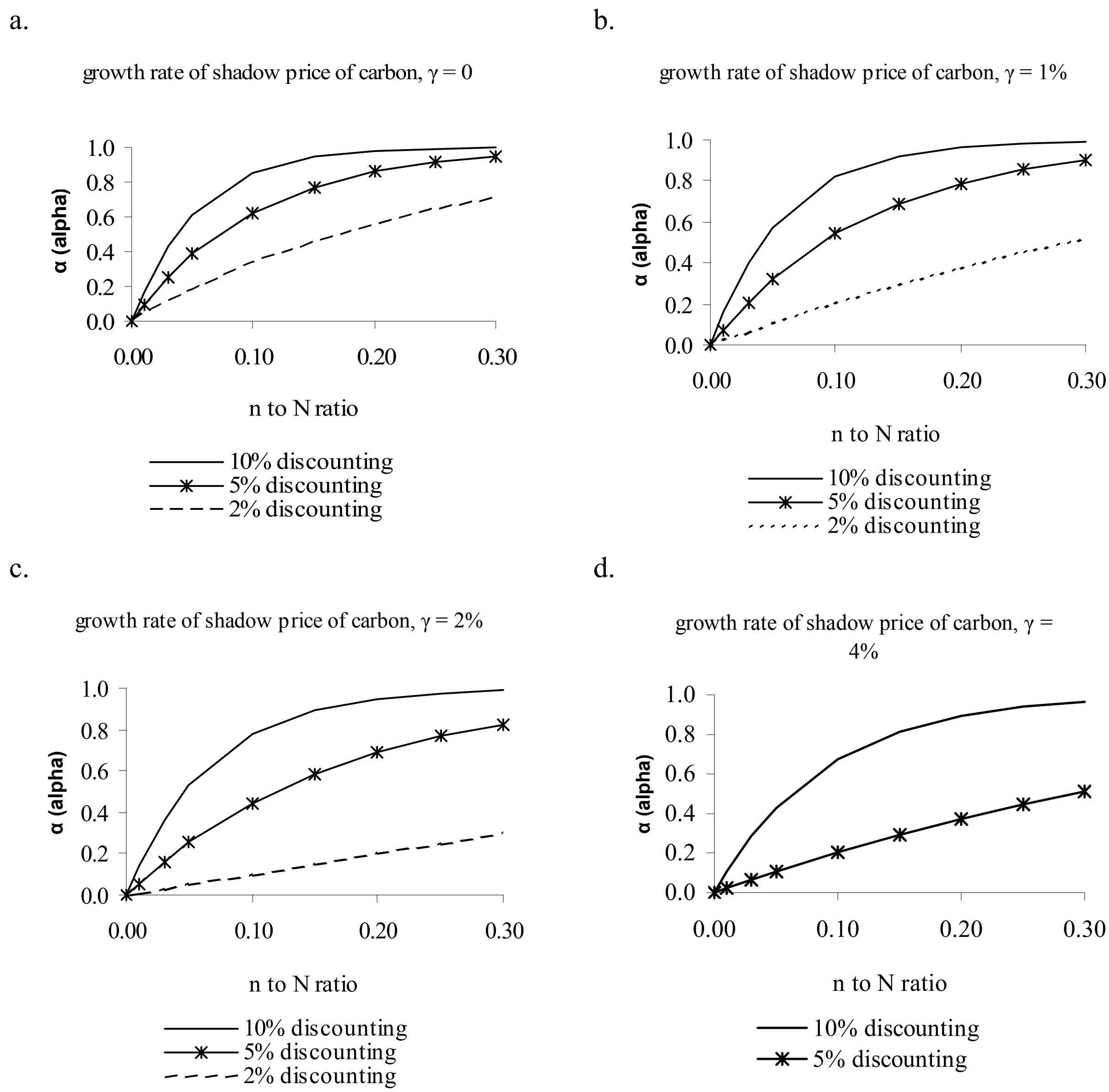

Figure 1: Value of a Temporary Relative to a Permanent Carbon Credit (α), Various Scenarios, N=200