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Equating Permanence of Emission Reductions and Carbon Sequestration: Scientific and Economic Foundations for Policy Options

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Abstract

Terrestrial (biological) carbon sequestration is the process by which carbon dioxide (CO_2) is removed from the atmosphere through photosynthesis and stored in terrestrial stocks of biomass or soil organic carbon. A ton of carbon (or CO_2 equivalent) sequestered in terrestrial systems can be used as an offset credit against emissions from sources such as power plants, factories, or automobiles. However, carbon stored in terrestrial carbon pools is particularly susceptible to re-release (reversal), raising the so-called permanence issue. When a reversal occurs, crediting adjustments are necessary to restore the integrity of the offset mechanism. This paper explores the permanence issue from both an atmospheric and economic perspective, showing that adjustments for reversals can depend on a variety of factors, including the assumed decay rate of the initial emissions pulse, the timing of any stored carbon release, a policy-determined "equivalency period" reflecting the relevant policy time horizon, the time-dependent economic value of carbon mitigation units, and the relevant discount rate for comparing economic flows over time.

1. Introduction

Terrestrial (biological) carbon sequestration is the process by which carbon dioxide (CO_2) is removed from the atmosphere via photosynthesis and stored in terrestrial stocks of biomass (trees, other vegetation, ground litter, roots, etc…) or soil organic carbon (SOC). This process is essentially the reverse of what happens when CO_2 is emitted to the atmosphere through fossil fuel combustion, land clearing and other human activity. As such, terrestrial carbon sequestration projects have entered the greenhouse gas (GHG) reduction policy arena as a potential *offset* for capped emissions from other sources. In other words, if there are certain activities like energy production that face a restriction on GHG emissions, a regulated entity can meet its compliance obligations by cutting its emissions and/or buying credits from other entities who either reduce their emissions or landowners who increase the amount of carbon they retain in forests, agricultural lands, wetlands or other terrestrial ecosystems.

One way to enact such an offset activity is to have the government pay landowners to store more carbon, or reduce the amount they release through deforestation, degradation, cultivation or other forms of land management that cause the carbon stored to be released to the atmosphere. Another way is to create a market for offset credits that compliance entities can buy to meet their commitments. The latter has received more attention in policy circles and thus we will use examples of credits and offset markets for illustrative purposes. But the issues of permanence discussed below are just as applicable if a government payment program is envisioned to create real quantifiable results.

The basic idea behind using a ton of carbon (or CO_2 equivalent) sequestered in terrestrial systems as an offset is that it can legitimately be used as a credit against an (allowed or capped) emission if it completely negates the climatic impact of that emission.[1] When trading a pure emission reduction between two sources (e.g., two factories) in the same period, this works fine, as long as one can verify that the offset credit's emission reduction occurred that period. Some adjustment will be necessary to equate global warming potential if the gases are different.[2] When the credit comes from sequestering carbon through forests or soils projects or from avoiding emissions from deforestation, this complicates matters because the carbon that was removed from the atmosphere (or emission avoided from deforestation, deforestation, cultivation or conversion) is stored in terrestrial carbon pools that are particularly susceptible to re-release in the future. This re-release or *reversal*, can be caused by natural events such as fires, insects, disease or flooding, or through human actions such as future harvesting. This form of carbon reversal is sometimes referred to as the permanence issue in terrestrial carbon sequestration activity.

If the carbon stored in the terrestrial pool remains there forever, then it clearly has served its offsetting function. However, if the carbon is re-released in the *near* future (within a few years), the action has

[1] "Ton" throughout the document will refer to a metric ton or megagram (Mg) of CO_2 equivalent.

[2] Non-CO2 GHGs can be transformed in terms of CO_2 equivalence, which is established in terms of their global warming potential (GWP) relative to a ton of CO2. For instance, methane (CH4) is 21 times more potent than CO2 (IPCC 2007); therefore its GWP is 21 and one ton of methane emissions is equivalent to 21 tons of CO_2 emissions.

not effectively negated the emission allowed, and the offset's function has been compromised. Crediting adjustment will be necessary to restore integrity of the offset mechanism. If the carbon is released in the distant future (decades or more) the consequence is not as clear for reasons we discuss below.

The "permanence" of sequestered carbon could be defined as the point in time at which stored carbon has essentially fulfilled its role as offsetting the global warming potential of the original emission. This "permanence" period is not necessarily forever. As we will show in this paper, determining the equivalence of a unit emitted and sequestered in the same year is complicated by the matter of how long and at what rate do CO_2 and other GHGs reside in the atmosphere. The original emission that created the offset opportunity does not itself remain in the atmosphere forever. It decays over time, as would have the CO_2 that was removed from the atmosphere and stored in a terrestrial sink via carbon sequestration.

This paper will explore the permanence issue from both an atmospheric and economic perspective, with the former focusing on equating the climate impacts of an initial emission pulse with carbon storage over time. The economic perspective will consider variations in the economic value of climate mitigation over relevant time periods. These calculations can depend on a variety of factors including the assumed decay rate of the initial emission pulse, the timing of any stored carbon release, a policy-determined "equivalency period" reflecting the relevant policy time horizon, the time-dependent economic value of carbon mitigation units, and the relevant discount rate for comparing economic flows over time. The paper will perform uncertainty analysis on these parameters to provide more robust estimates of the permanence equivalence values.

2. Key background concepts

Several key concepts underlie the role of permanence in the role of terrestrial carbon sequestration as an emissions offset. Each is discussed below.

2.1 Emission, offset and reversal

The permanence situation we are focused on is described by a simple illustration in Figure 1. Consider a carbon sequestration project that removes a ton from the atmosphere starting now (Year 0) and stores it in a terrestrial carbon sink managed by the project. The -1 value identifies this as a sink. At the same time, a ton of CO_2 is emitted from some industrial process denoted by a +1 value. At the time of simultaneous occurrence in Year 0, the sink (-1) effectively counters the emission source (+1) and the net effect of these two activities on atmospheric CO_2 is zero. If nothing happens to the carbon stored in the sink, this can be considered a pure offset. However, the issue of permanence central to this paper introduces the possibility that the carbon sequestered in Year 0 may end up back in the atmosphere through some type of natural or man-made disturbance. This is depicted in Figure 1 by the subsequent release of the stored ton in Year T, depicted by a CO_2 pulse of +1.

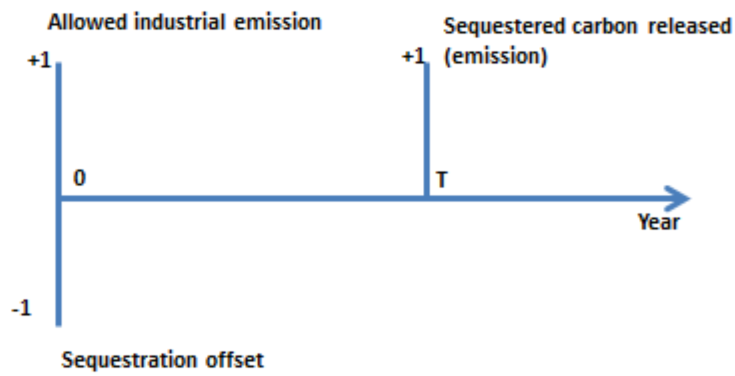

Figure 1. Carbon sequestration emission offset followed by release. *The carbon sequestered at Time 0 offsets the allowed emission in the same year, but these effects are reversed when the carbon is subsequently released in Year T.*

This pattern of emission, sequestration and release is a very real possibility as carbon stored in terrestrial ecosystems is inherently at risk of clearing, burning or degradation that can return the stored carbon to the atmosphere. The operative question is whether the carbon returned to the atmosphere completely negates the climate benefit of the emission offset or does the timing of the subsequent release matter? The answer to that question is a function of the residency time of CO_2 in the atmosphere and the time horizon over which CO_2 concentrations matter. These factors are discussed below.

2.2 An atmospheric chemistry perspective on permanence

Increases in atmospheric greenhouse gas concentrations alter the radiative balance of the atmosphere by enhancing the atmospheric absorption of outgoing long-wave radiation, in turn leading to an increase in global temperature and climate change.

An important consideration in linking changes in GHG atmospheric concentrations to GHG emissions is the time profile of atmospheric residency for a unit of CO2 emitted to the atmosphere. From an atmospheric chemistry perspective, a pulse of 'excess' CO_2 released to the atmosphere (for example, from fossil fuel combustion), decays over time (see Figure 2).

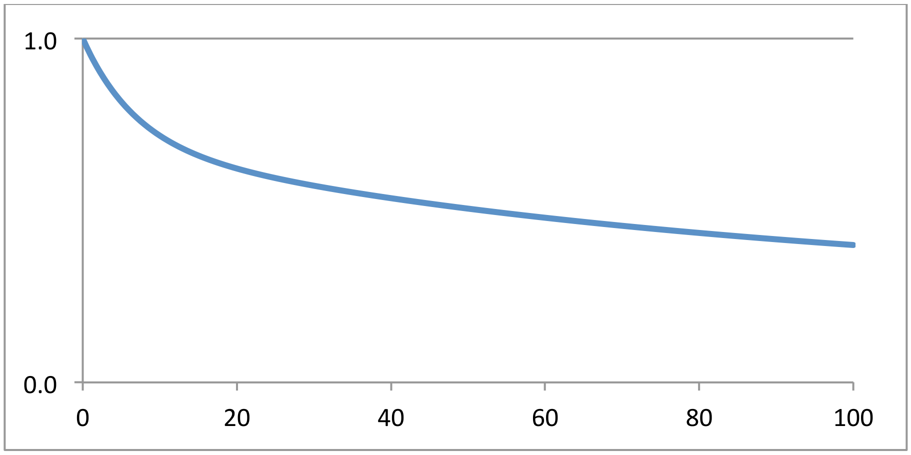

Figure 2. Representative decay function for CO_2 in the atmosphere following emission. *The horizontal axis displays time and the vertical axis represents the portion of the initial CO2 remaining in the atmosphere.*

Since atmospheric CO_2 interacts with terrestrial and oceanic carbon reservoirs, this decay cannot be approximated by a first-order process with a constant lifetime i.e. the decay cannot be approximated as an exponential decay with a single e-folding time constant. Nevertheless, simple analytical expressions are available to approximately calculate the fraction of excess CO_2 that remains in the atmosphere at some point in time following the initial pulse (see for example, footnote #a of Table 2.14 of the IPCC Assessment Report 4 Working Group 1 report (IPCC 2007). These simple expressions reveal that a fraction of the emitted excess CO_2 remains in the atmosphere essentially indefinitely. It follows therefore that any new sink created to offset the excess CO_2 pulse is equivalent only if remains indefinitely. Release of CO_2 from the offset sink back into the atmosphere will have the same integrated climate forcing as the original pulse; the only effect would be a delay in when the forcing would start. This infinite horizon view of CO_2 residency underlies carbon accounting approaches that require any re-release (reversal) of terrestrial stored to fully cancel any offset credits generated by the project. Accounting methods and their correspondence to the residency/time horizon perspective are discussed further below.

2.3 Permanence for a finite policy horizon – ton year approach

From a policy perspective however, one is often interested in the warming potential that is created over a prescribed time horizon (for example, over the next century). In this case, the quantity of interest is the integrated radiative forcing of the pulse of excess CO_2 over the same time horizon. Thus, the effect any delay (for example by uptake of CO_2 in a newly planted forest for a period of time followed by the loss of all the CO_2 accumulated in the forest in a subsequent year within the time horizon of interest) manifests itself as a reduction in the integrated radiative forcing due to the fact that the accounting period is not infinite but rather ends at the time horizon of interest.

The atmospheric effects of a sink reversal under a finite time horizon of 100 years is displayed in Figure 3. The creation of the sink ton in Year 0 produces an atmospheric credit value of -1. At the same time, the emission that is allowed by generating a sink offset credit produces a debit value of +1. As discussed above, the emission ton allowed by the offset decays over time (depicted by the red line). But so would the ton of CO_2 that was removed from the atmosphere during sink creation (the blue line, which is the inverse mirror image of the blue line). Therefore, if the sink ton stays intact for the full 100 years, it will clearly have offset the atmospheric effects of the corresponding emitted ton in Year 0. For the purposes of this 100 year time horizon, that sink will have met the permanence requirement.

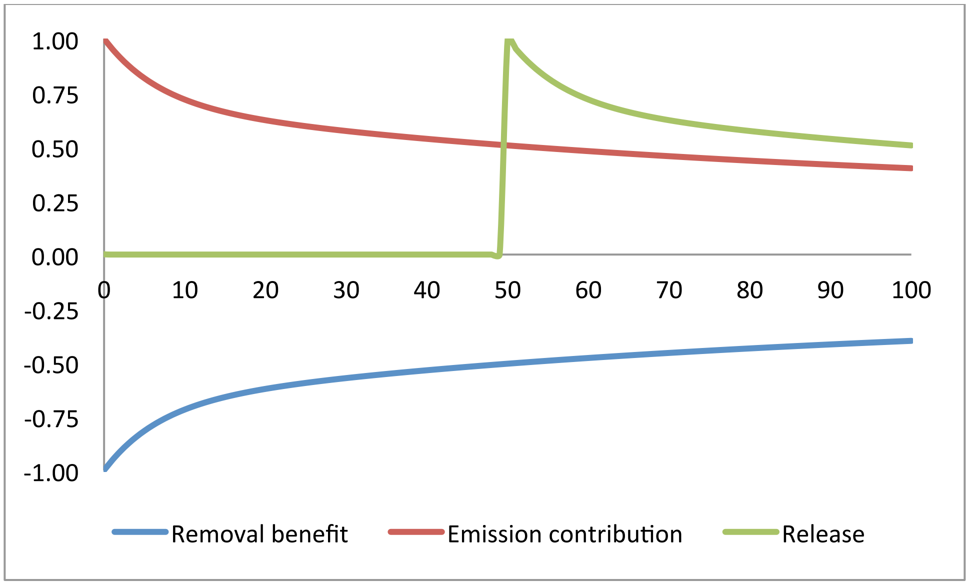

Figure 3. Atmospheric residency over 100 years of Yr 0 emission, removal by sequestration and release at Yr 50

However, it is the possibility that the ton sequestered in Year 0 is released before 100 years that raises the more nuanced issue of partial or equivalent permanence. In Figure 3, this situation is depicted by the green line showing the effects of a sink reversal in Year 50. For 50 years, the ton of carbon has been kept out of the atmosphere, yielding no radiative forcing, but a disturbance in Year 50 leads to a release of the sequestered ton. [3] This automatically creates an atmospheric debt of +1, which declines over time as the CO_2 decays in the atmosphere. Because, in this case, one is concerned only with the radiative forcing in the 100 year time horizon, the reversal negates some, *but not all*, of the sink removal benefit that occurred for the first 50 years.

This accounting aspect can be used to estimate the credits that offset projects should accrue as a function of time. in this context , a key metric is the time-integrated amount of carbon sequestered over the duration of the offset project. This *ton-year* accounting procedure, in which one ton year represents one ton of carbon held in stock and out of the atmosphere for a one year period, has been used to estimate how credits would be allocated over time to a project which offset a certain quantity of emissions at the initial time (see for example, Section 2.3.6.3 in the Noble et al chapter of the IPCC Special Report on Land Use, Land-Use Change and Forestry (Noble et al 2000) for a review of ton year accounting approaches).

Following the ton year approach, the net benefit of the sink created in Year 0 and released in Year 50 can be computed by taking the cumulative contribution of CO_2 to the atmosphere over 100 years from the sink/reversal scenario (the total area under the green line in Figure 3) and dividing it by the cumulative CO_2 contribution over 100 years of the emission allowed in Year 0 (the area under the red line). Using a representative CO_2 atmospheric decay function, Moura Costa and Wilson (2000), compute the area under the red line as the *ton year equivalent* over 100 years of one ton emitted in Year 0.[4] This number is approximately 54.7 ton years, or the equivalence of having one ton in the

[3] Note that the radiative forcing (global warming potential) is the indirect consequence of the emission residency depicted here. The common assumption is that a X% increase in GHG concentrations leads to a X% increase in radiative forcing, so we use emissions residence as a proxy for radiative forcing and warming potential.
[4] Moura Costa and Wilson (2000) decay function: [t] = $0.3003\, e^{(-t/6.6993)} + 0.34278\, e^{(-t/71.109)} + 0.3568\, e^{(-t/815.727)}$.

atmosphere for 54.7 years. To calculate the ton year equivalent for the release in Year 50, we take the same decay function and compute the cumulative contribution to the atmospheric content for 50 years (the areas under the green line for Years 50-100). This produces a 100-year ton year equivalent of 32.4. This suggests that a 1 ton sink in Year 0 that is reversed in Year 50 produces about 60% percent of the radiative forcing over 100 years as does a ton emitted in Year 0. As such, one might issue a partial credit of 0.40 for a ton stored for 50 years.[5] Following the same principle, Table 1 creates a table of partial permanence equivalencies of sinks that remain intact for periods leading up to 100 years (based on Noble et al, 2000).

Table 1. Partial credit as a function of project duration using "ton year accounting."

StorageLength	Percentage of Full Credit
0	0.0
10	7.4
20	15.0
30	22.9
40	31.2
50	39.9
60	49.3
70	59.4
80	70.6
90	83.3
100	100.0

Source: Noble et al. 2000

It should be emphasized that a fraction of the excess CO_2 added to the atmosphere remains in the atmosphere essentially indefinitely. For example, for Moura Costa and Wilson (2000) decay function holds, 10% of the original pulse remains in the atmosphere after a 1000 years. Full credit therefore requires that the project remain in place indefinitely. The accounting of credit accrual as a function of time therefore depends on the policy specification as to what constitutes permanence. For example, if the policy decision is that 20 years constitutes permanence, a project duration of 10 years would qualify for a partial credit of 45% and a project of duration of 20 years would qualify for 100% credit. On the other hand, if the policy decision is that 1000 years constitutes permanence, a project duration of 20 years would qualify for a credit of only 1.6%; in this case, a project duration of 500 years would qualify for a credit of 41%, and a project duration of 1000 years would be needed to qualify for full credit.

[5] Note that this is somewhat different than the equivalence calculation proposed by Moura Costa and Wilson (2000), who suggest that once a ton has been stored for 55 years it should be treated as 100 percent permanent. We believe this is not correct as it ignores the decay that ton sequestered would have experienced has it remained in the atmosphere. This point was analyzed in Noble et al (2000).

3. Approaches to permanence in policies and existing carbon standards

At this time, there are a number of carbon accounting rules and standards to address crediting of carbon offsets. The most prominent standards and how they deal with permanence of terrestrial sinks are listed in Table 2.

Clean Development Mechanism of the Kyoto Protocol

The most prominent regulatory standard for offsets is through the Clean Development Mechanism (CDM) of the UN Framework Convention on Climate Change (UNFCCCC) Kyoto Protocol. The CDM is the mechanism by which offset projects in developing countries are able to generate credits (called certified emission reductions, or CERs) that developed (Annex I) countries can use to meet part of the emission reduction commitments under the Kyoto Protocol. The CDM has a fairly limited range of terrestrial carbon activities for which credits can be generated, primarily afforestation and reforestation (AR). However, the credits generated by AR projects are deemed to be *temporary certified emission reductions* (tCERs), specifically because of the permanence issue. The Annex I buyers of temporary credits must eventually replace them at some point in the future. In other words, if an Annex I country uses 1 million tCERs to meet its commitments for an initial commitment period, it must ultimately replace those 1 million tons of credit with either new tCERs or regular ("permanent") credits after a designated time period, the commitment period after which the tCERs were originally issued. Currently under the Kyoto Protocol, commitment periods are specified in 5-year intervals. As an alternative to tCERs, projects can choose to generate long-term credits (or lCERs) that expire at the end of either a 30-year or 60-year crediting period. Like tCERs, lCERS must be replaced by other credits when they expire. Unlike tCERs, lCERs cannot be replaced with other lCERs when they retire.

Voluntary carbon market approaches

In addition to CDM and the UN process, there are a number of voluntary carbon standards that have emerged throughout the world that deal with terrestrial carbon, particularly AR, improved forest management (IFM), and reduced emissions from deforestation and degradation (REDD). Prominent among these are the Verified Carbon Standard (2011), Climate Action Reserve (2009), American Carbon Registry (2010), and Plan Vivo (2008). Table 2 outlines how each of these voluntary standards addresses permanence.

The common approach across these standards is to establish a project contract or crediting period, which essentially establishes a time horizon that the project proponent commits to keep the carbon in place. As we see in Table 2, this contract period for the voluntary market ranges anywhere from 20-100 years . As discussed below, these contract periods do not necessarily connect to any notional definition of permanence, but are tied more toward the practical limitations of how long one can expect private parties to engage in a contract.

These programs generally require replacement of any credits for carbon that has been deemed to have been reversed before the end of the contract. The key aspect of this is that the credits are issued and can be sold as soon as the carbon is sequestered. In essence, sink creation is being paid fully in advance of serving its offsetting function over time. But with the buffer requirement that is a part of each of the voluntary programs, some share of the credits generated are required to be set aside and used to cover any reversal of credits during the project. For instance, a project being issued 1000 sequestration offset credits in one year may be required to set aside 300 (30%) in a buffer account to cover any future reversals should they occur. Covering means that when a reversal is detected and reported, that an equivalent amount of credits (tons) in the buffer account will have to be retired without ever being used for compliance purposes. The buffer account evolves over time with additions from new credit entries and withdrawals to cover losses.[6]

In many ways, the buffer approach is a rough insurance scheme, with buffer percentage requirement serving as the insurance premium that must be paid to cover any future losses that the buffer needs to cover. Indeed, some crediting systems allow the use of private insurance to replace these buffer requirements, if an approved insurance product is purchased. One of the difficulties with such a system is that there is little information and data on reversal risk *ex ante* on which to establish actuarily sound insurance premiums or buffer requirements. This could put the entire offset system at risk of major default if the risks are underestimated.[7] Recent studies of forest carbon storage and release in response to natural hazards such as droughts suggest that reversal magnitudes could be quite large.[8] Modeling these risks and structuring mechanisms for dealing with them remains an area of active research by a co-author.

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[6] Note that the Waxman-Markey bill (HR 2454), the U.S. cap-and-trade bill that passed the House of Representatives, but stalled in the Senate, established a buffer approach for terrestrial carbon offsets in forests and agriculture.
[7] Murray, Olander and Kanak, 2009.
[8] See article in the journal Science by Lewis et al (2011) on CO2 emissions associated with recent Amazon droughts, similar in magnitude to annual U.S. CO2 emissions from fossil use.

Table 1. Comparison of permanence approaches in existing standards.

Standard		Intentional v. Unintentional Reversals	Permanence Mechanism	Mechanism Details	Minimum Contract Period
VCS	APD AUFDD AUMDD	No direct distinction. Catastrophic vs non-catastrophic used instead with similar consequences	Pooled Buffer Account	Projects required to guard against reversals by withholding a certain percentage of their credits in a Pooled Buffer Account. The share of credits withheld is based on project-specific risk evaluation. For reversals, credits from the buffer are used to replace the loss. Risk rating based on variety of project-specific risk factors (e.g., clarity of land tenure, local deforestation pressure, financial viability): Depending on project's risk rating, between 10%–40% of credits could be withheld in buffer. The registry retains ownership of buffer credits and retires in case of actual reversal. Possibility of returning buffer credits to projects for sale if long-term performance demonstrated. Under some conditions, project proponent is required to replace all reversed credits (over and above credits already set in a buffer) before new credits are issued. If project proponent fails to monitor and report carbon within a fixed period of time after a reversal event, the carbon is assumed gone and all issued credits are replaced with buffer credits. Considers replacement of buffer with private insurance if available.	20–100 years
CAR		Intentional	Project Implementation Agreement	Projects' CAR credits account debited to compensate for "avoidable" reversals (negligence, gross negligence, or willful intent).	100 years
		Unintentional	CAR Pooled Buffer Account	Projects required to guard against "unavoidable" reversals (fire, pests) by withholding a certain percentage of their credits in a Pooled Buffer Account. The share of credits withheld is based on project-specific risk evaluation (determined prior to registration and recalculated every year the project undergoes a verification site visit); conservation easements lower a project's risk rating. In instance of "unavoidable" reversals, credits from Buffer used to replace the loss.	
ACR		Distinction	Pooled buffer Account	Similar to VCS including use of VCS risk analysis and buffer tool. ACR, though, distinguishes between intentional and unintentional reversals. Intentional reversals must all be replaced by the project entity. Unintentional reversals are covered by the buffer pool like an insurable risk, though project must re-establish buffer after conversion. Buffer percentages can be updated after risks re-assessed.	40 years, with opt-out allowed if credits replaced
Plan Vivo		No Distinction	Buffer Account	Must undertake (1) comprehensive analysis of reversal risks, (2) implement risk management and mitigation measures, and (3) withhold a certain percentage of credits in a buffer to compensate for any unexpected carbon losses based on a project-specific assessment of risks. All projects must withhold a minimum of 10% of credits.	Not specified (but crediting periods can range from 10-100 years)
CDM		Distinction	Temporary credits	Note: CDM does not include REDD projects but does include afforestation/reforestation (A/R) projects that have permanence requirements imposed. Under the CDM approach, A/R projects are issued either temporary certified emission reductions (tCER) or long-term CERs (lCERs). tCERs expire each subsequent commitment period (e.g., after 5 years) and must be replaced. National registries must contain a tCER replacement account.. lCERs expire after a credit period of either 30 years or 60 years and require full replacement.	Credits expire after 5, 30-60 years (see mechanism details)

Acronym Key: VCS = Verified Carbon Standard; AUMDD = Avoided Unplanned Mosaic Deforestation and Degradation (D&D); AUFDD = Avoided Unplanned Frontier D&D; APD = Avoided Planned Deforestation; CAR = Climate Action Reserve, CDM = Clean Development Mechanism, ACR = American Carbon Registry

The basic problem is that reversal risk introduces a contingent liability for any crediting system that issues credits as soon as the tons of carbon are stored. Buffers and insurance schemes are ways to recognize and manage the risk, but they require information on the risk that may not be widely understood at the outset. This raises the question of whether credits should be issued all up front, or only when permanence has been achieved. We will return to the ton-year concept to outline a system that in essence takes (some aspects of) the contingent liability out of the equation, by paying credits out in small increments commensurate with the amount of permanence achieved.

Do any of these protocols have a "permanent" equivalency period?

Each of the crediting protocols described in this section acknowledge the reversal problem and permanence issue. They develop mechanisms for addressing the problem, but none explicitly claim that a sequestered ton is atmospherically equivalent to a permanent reduction once it remains stored for a set period of time. There are stipulated contract periods, and some are quite long, but the connection of these contract periods to actual permanence is, at most, indirect.

Under these CDM temporary credits, the implicit presumption is that the sink offset is temporary and will reverse at some point in the future. And since the replacement requirement for tCERs and lCERs is 1:1, the system implicitly does not value temporary storage from an atmospheric residency, or ton year approach as outlined above (i.e., the notion that a terrestrial ton intact for 50 years and then released has had 40 percent of the global warming benefit as a permanent emission reduction in Year 0). In this system, sequestered tons are never permanent.

Perhaps the clearest statement on the relationship (or lack thereof) between contract length and permanence is made by the American Carbon Registry (ACR), which in explaining its 40 year contract period, states (ACR 2010, p.30)

> *AFOLU carbon protocols sometimes confuse permanence with the length of time for which a Project Proponent or landowner must commit to maintain, monitor and verify the project activity. In fact, minimum project duration and the assurance of permanence are unrelated. No length of time short of perpetual is truly permanent, nor is there a sound scientific basis or accepted international standard around any particular number of years... ACR requires Project Proponents to commit to a Minimum Project Term of forty (40) years for project continuance, monitoring and verification. ACR views forest and other AFOLU activities as a "bridge" strategy to achieve near-term reductions cost-effectively over the period from now through 2050 – the timeframe over which U.S. legislative frameworks and international negotiations propose effective de-carbonization of major emitting sectors, with reductions of around 80% below current GHG emissions. Requiring Project Proponents to commit to 40 years ensures these activities will continue over the relevant timeframe, or if they or their landowners choose to discontinue activities, that any credited ERTs will be replaced.*

In other words, ACR sees the contract length as a means to keep sequestered carbon on par with time commitments required by the underlying climate policy process. There is not a single cap-and-trade program for carbon that establishes a cap into infinity. To be symmetric to that situation, neither is stored carbon obligated forever. Terrestrial carbon is seen as a bridge to a new regime when low carbon alternatives are more abundant and, perhaps, cap levels adjusted.

The Climate Action Reserve's Forest Carbon Protocol (2010, p. 61) does make a connection between its minimum contract period of 100 years and the notion of permanence, but the connection is made by assertion rather than direct reference to the scientific literature on atmospheric equivalence.

> *The Reserve requires that credited GHG reductions and removals be effectively "permanent." For Forest Projects, this requirement is met by ensuring that the carbon associated with credited GHG reductions and removals remains stored for at least 100 years.*

One hundred years is a common time period equated with permanence, with reference often made to the Intergovernmental Panel on Climate Change (IPCC 2007) use of 100 year residency for computing its Global Warming Potential (GWP) factors. While it is necessary to compare gases on the same period of time in order to compute relative factors, there is no consensus on what that period of time should be or that there is some period of time that satisfies the notion of permanence.

4. Revised Ton-year Approach to Provide Incremental Credits when Permanence is Earned

Although the ideal outcome from an atmospheric standpoint would be that any carbon stored by a project remains stored forever, the ton year discussion in Section 2 implies that even temporary storage has climate mitigation value as long as there is a finite time horizon for which climate policy objectives are being targeted.   Here, we further explore the ton-year accounting concept to see whether it can be deployed to come up with a mechanism for incorporating (im)permanence and reversal risk into carbon accounting in ways that maintain the atmospheric integrity of the exchange and allow for more stable management of the forest carbon account by minimizing residual liability for payback if reversals occur.

We focus on two aspects of the problem: (1) the robustness of the ton-year approach when one accounts for the interaction of the atmospheric CO_2 reservoirs with terrestrial and oceanic CO_2 reservoirs; and (2) the allocation of credits in the case where a newly-created offset sink continues to accumulate carbon over a period of years. Our analysis is based on a simple carbon cycle model which is described in the next section.

4.1 The Carbon Cycle Model

The carbon cycle models used in our analysis is based on the simplified 8-reservoir model of Chameides and Perdue (1997). Figure 4 shows the interactions between the various reservoirs represented in the model.

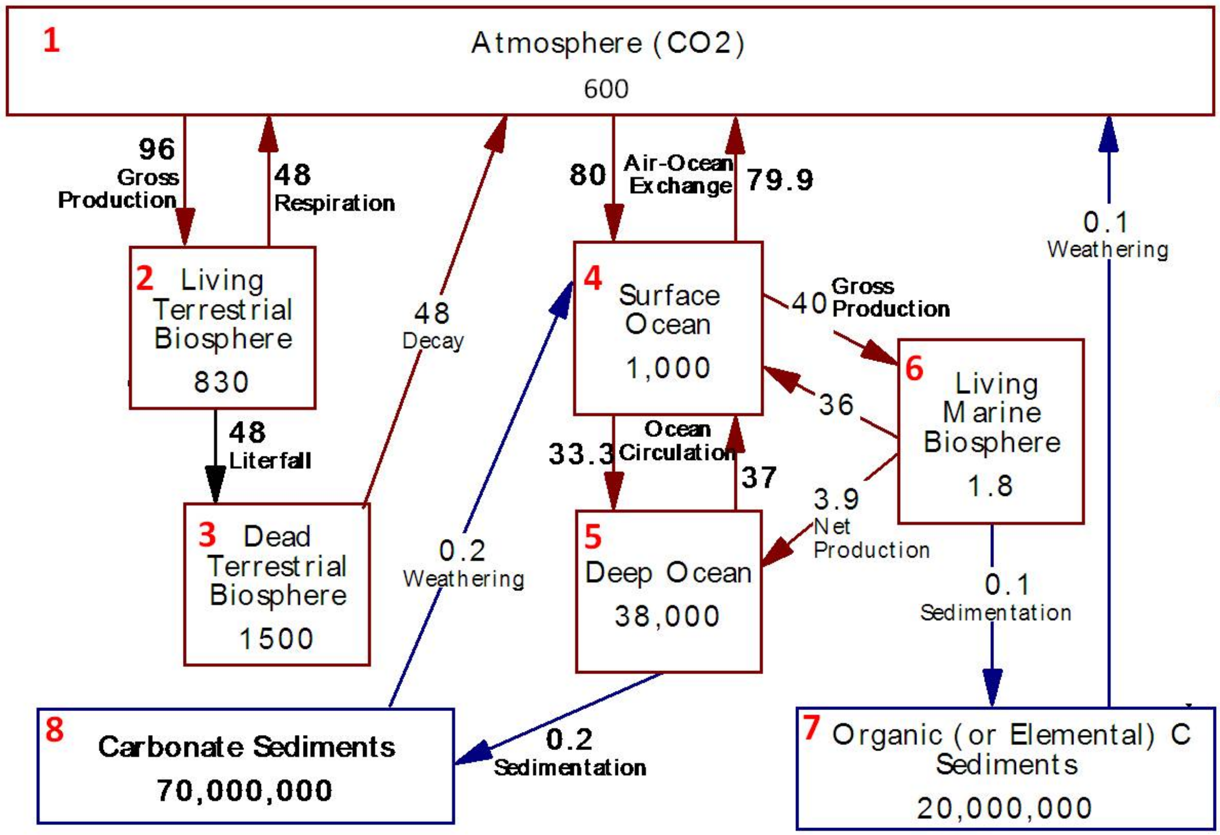

Figure 4: Simplified carbon cycle model. *Red boxes and arrows represent short-term carbon stocks and fluxes, respectively. Blue boxes and arrows represent long-term carbon stocks and fluxes, respectively. Number in boxes and along arrows represent pre-industrial carbon stocks in units of gigatons of carbon (Gt C) and fluxes in units of Gt C/year), respectively. Source: Chameides and Perdue (1997)*

Each of the carbon fluxes depicted in Figure 4 is assumed to be a first-order process, and the corresponding first-order rate coefficients are calculated from the assumed pre-industrial fluxes and stocks. In addition, we approximate the non-linearity of excess atmospheric carbon uptake by the living terrestrial biosphere (reservoir #2) and the surface ocean (reservoir #2) as in Chameides and Perdue, 1997. We applied the model to simulate the contemporary CO2 cycle by adding a flux term from box 7 (the organic C sediment reservoir) to box 1 (the atmospheric reservoir) representing an idealized approximation of anthropogenic CO_2 emissions since pre-industrial (see left panel, Figure5) .This simplified carbon model reproduces fairly well the trend in annual-average atmospheric CO_2 concentrations in the last half-century (see right panel, Figure 5).

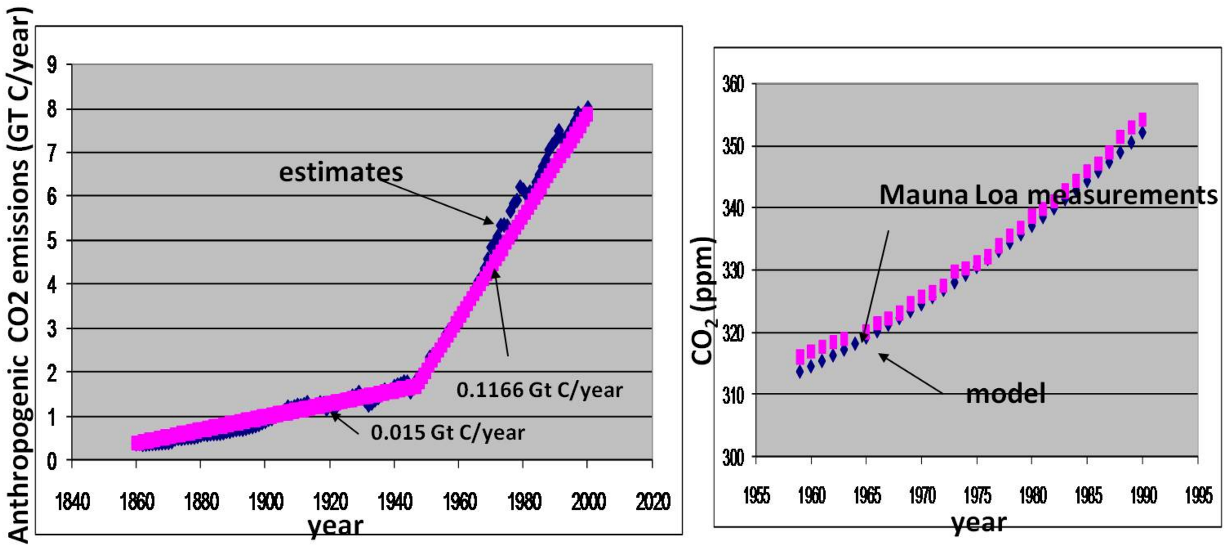

Figure 5: Left Panel - Estimated anthropogenic carbon emissions from inventories (blue) and idealized emissions used in the model (pink). Right panel – Comparison of model-predicted atmospheric CO_2 concentrations (blue) with measurements from Maua Loa (pink).

4.2 Cumulative ton-year approach

We used the atmospheric model described above to explore the permanence issues outlined above. We examine the integrated radiative forcing associated with a pulse of anthropogenic CO_2 by considering two scenarios:

(i) a baseline scenario in which anthropogenic emissions increase at the rate shown in Figure 5 up to 2010 and then are held constant, and

(ii) a perturbation scenario which is identical to the baseline case except for an addition emission of 1 Gt CO_2-C in 2010.

The perturbation case also includes a 'new' zero-order sink (i.e. unlike a first-order process, the magnitude of the sink is not dependent on the magnitude of the mass of CO2 in the reservoir) associated with a hypothetical offset project starting in 2010 and that remains in effect for a finite offset-project period. At the end of the offset period, all the carbon that has accumulated in the offset sink from the 2010 onwards is released to the atmosphere. We compare the integrated radiative forcing over the 2010-2110 time period for the perturbation scenario with the corresponding forcing from the baseline scenario to estimate the fraction of credits associated with the original anthropogenic carbon pulse that the offset project accrues over the duration of the project. In our analysis, we assume that the radiative forcing efficiency of atmospheric CO_2 is constant, in other words, an X% increase in excess atmospheric CO_2 translates to an X% increase in radiative forcing (and global warming potential). This avoids the confounding effect of the choice of baseline scenario. In effect, we therefore compare the integrated atmospheric CO_2 time profiles from the two scenarios to assess the effective accrual of offset value.

We first estimated the 100-year integrated radiative forcing associated with a 1 Gt C pulse (RAD1) by comparing the radiative forcing from perturbation scenario with no offset sink with that from the baseline scenario. We then performed additional perturbation scenario simulations with a prescribed offset sink. In these simulations, we allowed the offset to remain operational for a certain period of time and then released the entire store of C accumulated due to the offset back to the atmosphere. This allowed us to estimate the 100-year integrated radiative for the case with a 1 GT C pulse plus an offset sink (RAD2) and to estimate the fractional credit (1-RAD2/RAD1) associated with the offset sink. We repeated the calculation with various offset uptake rates (0.5 Gt C/year, 1 Gt C/year, and 2 Gt C/year) and offset duration periods to explore the variation of fractional credit with integrated ton-years of carbon accumulated over the lifetime of the offset project. Our results (see Figure 6) show that the credit accrued varies almost linearly with ton-years accumulated over the lifetime of the project. It is particularly important to note that the curves for the various zero-order uptake rates considered are almost identical. The slight differences between the curves arise due to the fact that different uptake rates have slightly disproportionate effects on the decay of excess atmospheric CO_2 that remains in the atmosphere and, but this effect is not significant. It is also important to note that 100% credit accrual corresponds to roughly 120 ton-years of carbon – the reason for that this is not exactly 100 ton-years is again because of the effect of the offset sink on the excess atmospheric CO_2 that remains in the atmosphere owing to perturbations in the first-order exchanges with other reservoirs.

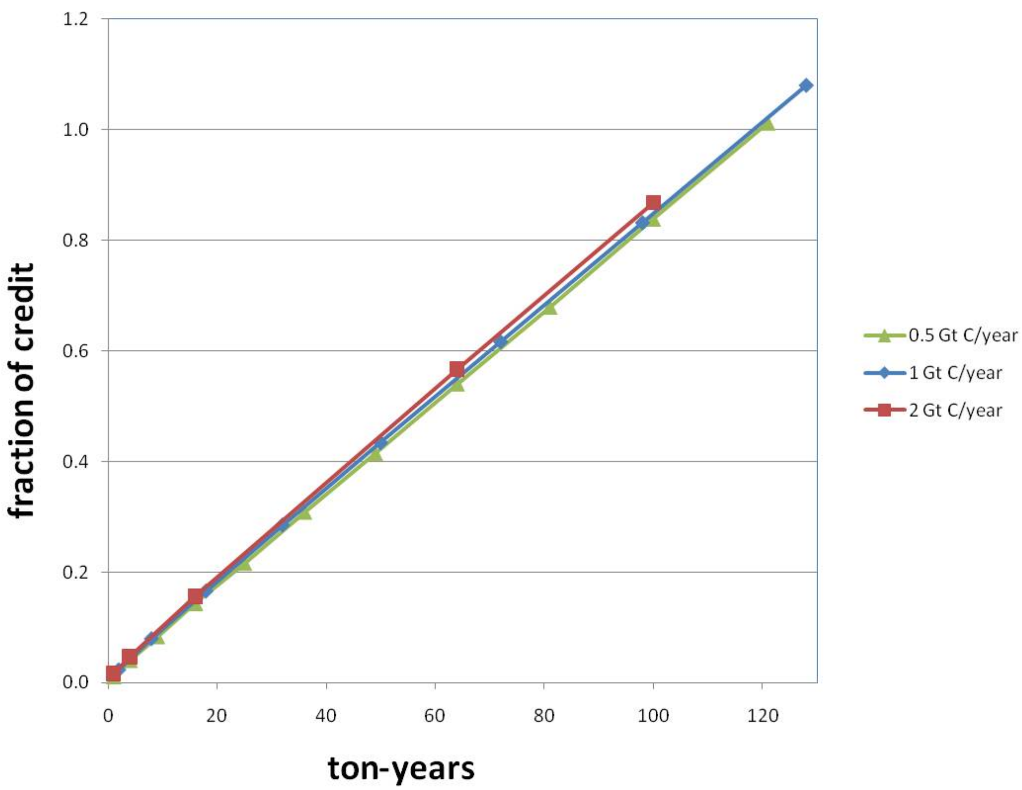

Figure 6. Fraction of permanent credit earned from cumulative ton years achieved

Our results indicate that a relatively straightforward crediting scheme can be used for offset projects. Under this method, an offset project accumulates credits associated with the initial carbon it was intended to offset, even if the accumulation occurs in subsequent years. That is, if an offset project begins in 2010, the additional carbon sequestered in a subsequent year (2015) will continue to count towards the original carbon offset until the project has an integrated value of approximately 120 ton-years. For each 120 ton years accumulated, one ton of credit can be considered to have been permanently earned. So for instance, a project that has generated 12,000 ton years worth of carbon will have earned 100 tons worth of permanent credit.

Counting ton years for a project is conceptually straightforward (see Figure 7). A ton year is counted for every year a ton is stored, so as the carbon stock accumulates over time, the ton years accumulate as a result of two factors: (1) the carbon stock is getting larger, and (2) time of storage is getting longer. The first tons stored in Year 1 of the project continue to generate ton years in Years 2, 5, 10, 50,… as long as the carbon is still stored. In the simple linear case of Figure 7, the ton years (TY) can be expressed as a function of time (t) and the constant annual accumulation rate, r

$$TY = r\,(t^2/2) \qquad [1]$$

So, for example, a process storing one ton of carbon per year will have stored 50 ton years by Year 10, 200 ton years by Year 20, and 1250 ton years by Year 50.

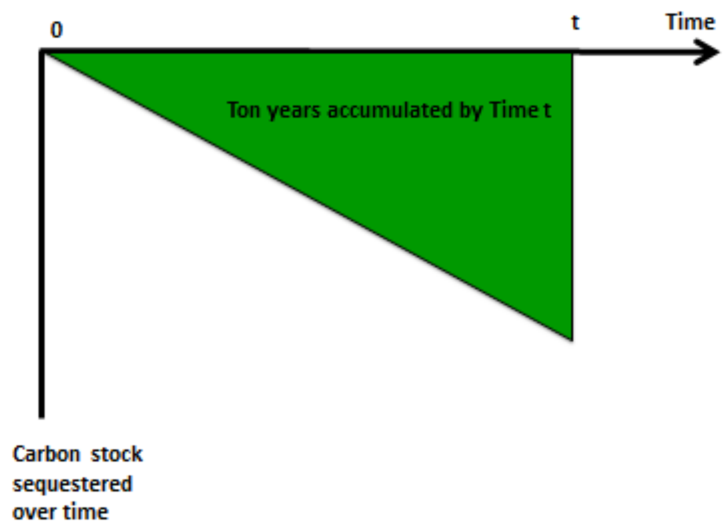

Figure 7. Ton year accumulation over time with a linear carbon stock accumulation process.

4.3 Implications of cumulative ton year crediting for economic returns

Table 3 presents the case of a 100-hectare forest carbon project that is sequestering 1,000 tons of CO_2 equivalent (CO_2e) carbon per year. After 5 years, the project has accumulated 12,500 ton years of CO_2. With the exchange rate of 120 ton years equivalent to one permanent ton given above, this equates to about 104 permanent tons worth of credit. Valued at \$15/t CO_2e, a mid-range price for compliance carbon in the compliance and voluntary markets,[9] the market value of permanent credits generated to date equals about \$1,563, or roughly \$16/hectare. As the ton-years accumulate, so do the redeemable permanent credits and the economic value of the carbon sequestration enterprise. Table 3 traces this out over a 100-year time period to give a sense of the carbon credit value per hectare that can be earned if the CO_2 price rises with the real discount rate and thereby maintained its present value per ton over time.[10]

This simple example illustrates a situation in which carbon is not paid for until it achieves permanence. Of course, this means returns are fairly low at the beginning of the project, but slowly build over time. After 5 years, the project has sequestered 5000 tons of CO_2, but has paid out only 104 tons worth of permanent credit, or just over 2 percent of the total amount sequestered. By year 50, the amount sequestered goes up by a factor of 10, but the permanent credits earned goes up by a factor of 100 (earned/total is then around 20 percent). After 100 years, the total amount of permanent credits earned is about 42 percent of the total amount of carbon sequestered. Note that even though the stipulated policy horizon is 100 years and the project period in this example is 100 years, it does not mean that all tons sequestered can be deemed permanent once the 100 year project mark has been hit. That is because most of the carbon that has been sequestered has been for less than 100 years and is still earning its keep from a permanence standpoint. As the project period goes on into perpetuity, and the carbon is maintained, the ratio of permanent credits issued to total quantity sequestered approaches 1:1. In other words, true permanence yields a corresponding number of permanent credits.

What is unique about this situation, however, is that in principle this project could terminate at any time and as long as the permanent credits were issued for ton years generated to date, no repayment for reversals would be necessary to ensure atmospheric integrity. This system does not pay for mitigation in advance, as some other systems do, and try to recover prepaid credits that are reversed. Rather they pay after permanence has been achieved and thus no residual liability remains. An analogy to this is an apartment building that is rented out one of two ways. Under one approach, the owner of the apartment building requires 10 years' rent up front. If the building burns down, the tenants are owed back their prepaid rent. Under the other (far more common) approach, apartments are rented on a monthly basis. If the building burns down the owner has lost a valuable asset and the tenant needs to find another place to live, but there is no need to reclaim years of prepaid rent.

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[9] See PointCarbon.com and Ecosystemmarketplace.com for representative carbon prices (\$/t CO2e) in EU regulatory markets and voluntary markets respectively.

[10] Economic models typically assume that the carbon allowances rise at the real rate of discount and maintain their present value when allowance banking and borrowing are permitted. This is referred to as a Hotelling price path based on economist Harold Hotelling's seminal work in the pricing of non-renewable resources (cite Hotelling).

Table 3. Returns to a 100 hectare project under the cumulative ton-year approach

Year	Carbon stock ($t\ CO_2e$)	Cumulative ton-years	Permanent credits earned	Cumulative value of credits @ $15/t CO_2e (present value)	PV Credit value per hectare (100 ha)
0	0	0	0	$ -	$ -
5	5,000	12,500	104	$ 1,563	$ 16
10	10,000	50,000	417	$ 6,250	$ 63
15	15,000	112,500	938	$ 14,063	$ 141
20	20,000	200,000	1,667	$ 25,000	$ 250
25	25,000	312,500	2,604	$ 39,063	$ 391
30	30,000	450,000	3,750	$ 56,250	$ 563
35	35,000	612,500	5,104	$ 76,563	$ 766
40	40,000	800,000	6,667	$ 100,000	$ 1,000
45	45,000	1,012,500	8,438	$ 126,563	$ 1,266
50	50,000	1,250,000	10,417	$ 156,250	$ 1,563
55	55,000	1,512,500	12,604	$ 189,063	$ 1,891
60	60,000	1,800,000	15,000	$ 225,000	$ 2,250
65	65,000	2,112,500	17,604	$ 264,063	$ 2,641
70	70,000	2,450,000	20,417	$ 306,250	$ 3,063
75	75,000	2,812,500	23,438	$ 351,563	$ 3,516
80	80,000	3,200,000	26,667	$ 400,000	$ 4,000
85	85,000	3,612,500	30,104	$ 451,563	$ 4,516
90	90,000	4,050,000	33,750	$ 506,250	$ 5,063
95	95,000	4,512,500	37,604	$ 564,063	$ 5,641
100	100,000	5,000,000	41,667	$ 625,000	$ 6,250

5. Conclusions and Policy Implications

The permanence issue is one of the defining characteristics of terrestrial carbon sequestration as a GHG mitigation strategy. Carbon stored in terrestrial ecosystems is susceptible to re-release or reversal which can create a liability and system integrity issues if the carbon credits have already been issued. Some existing carbon standards, such as the CDM, address this issue by stipulating that all terrestrial carbon credits are in a sense temporary and should be canceled after a given period of time and replaced with other credits demonstrating real and permanent reductions. This may be an unnecessarily restrictive way to address the permanence issue, as evidenced by the very weak investment in terrestrial carbon projects under the CDM.[11] Some approaches to permanence and

[11] As of January 1, 2012, only 61 afforestation and reforestation (AR) projects have been approved by the CDM Executive Board, which is less than one percent of all project approvals. To date, no CERs have been issued for

reversal risk in the voluntary market require that all carbon be maintained in place for at least a fixed period of time and/or require replacement of previously issued credits if the carbon has been released, regardless of how long that carbon was held in place. Provisions for repayment are made by requiring that a project or a program aggregating across projects hold credits aside in a buffer escrow account to be accessed when a reversal occurs, or perhaps by relying on private insurance or self-insurance to cover losses. The potential for large-scale reversals to undermine such a risk management system is troubling, however, given the limited experience with reversal risks, buffer mechanisms and insurance products to date. Moreover, although contract periods as long as 100 years are required for these projects, even that length of time cannot be considered "permanent" from an atmospheric point of view. These contract periods are tied more to policy and contract realities than to atmospheric residence, which occurs over much longer periods of time.

A third approach that is less conservative than temporary crediting and more conservative than prepaid credits and buffer provisions is to award permanent credits after a certain number of carbon ton years of storage have been accumulated. Ton year accumulation allows storage periods of different lengths to be expressed in equivalent and fungible units. When a certain number of ton years have been accumulated, a certain amount of permanence has been earned and cannot be reversed. More permanence can be earned, however, as more carbon is stored for longer periods of time. This approach does require policy makers to stipulate a time period (often 100 years) over which aggregated radiative forcing and global warming potential are being targeted. While this may not be atmospherically equivalent to a permanent emission reduction, it serves here as a policy-relevant target for de facto permanence. It does not mean, however, that all carbon must be stored that long to achieve any measure of permanence. Permanence, and payments for permanence can be achieved much earlier in the project and accumulate exponentially over time. This creates a tradeoff between lower risk (not having to repay prepaid credits) and lower return (not receiving credits until later). However, this approach seems to reduce vulnerability of the entire system to reversal risk. That said, one can envision that the financial and insurance sectors would develop sophisticated instruments to deal with the risk of prepaid credit reversal through hedging, derivatives and other risk management tools if the market were sufficiently large. In fact, insurance companies such as ForestRe are now developing such products to serve this market.

More research is needed on several key issues to clarify the pathway for addressing permanence. While atmospheric residency of CO_2 and other GHGs is relatively well understood, the nature of the reversal risks that cause the residency and permanence issues are not. More modeling of carbon reversal risks using ground data is essential to better understand the magnitude and frequency of risks at different spatial scales. Without analysis of actual risks on the ground, determining the appropriate size of a buffer system for handling reversals is little more than educated guesswork. Research on the value of combining individual projects into geographically diverse portfolios can help clarify program rules and commercial strategies for diversifying reversal risk to make it more manageable. This will require time series data on georeferenced disturbances to examine independent and correlated risks. Companies

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those approved projects and the expected volume is still less than 1 percent of all CDM project credit volume (UNEP 2012), deciding whether to offer forest carbon insurance products are presumably engaged in this work internally. Voluntary programs that require buffers and other risk management mechanisms should be engaged aslo, as long as they are setting rules for projects to manage risks and trying to ward off system failure from underappreciated risks of the credit portfolio.

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