The Time Value of Carbon Storage

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Research Article

Keywords: carbon storage, natural climate solutions, climate mitigation

Posted Date: October 13th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-966946/v1>

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Abstract

Widespread concern about the risks of global climate change is increasingly focused on the urgent need for action (IPCC, 2018; IPCC, 2021), and natural climate solutions are a critical component of global strategies to achieve low temperature targets (e.g. Griscom et al. 2017, Roe et al. 2019). Yet to date, the full potential of natural systems to store carbon has not been leveraged because policy-makers have required long-term contracts to compensate for permanence concerns, and these long-term contracts substantially raise costs and limit deployment. In this paper, we lay out the rationale that our time preference for early action embedded in the Global Warming Potentials (GWP) leads to the conclusion that multiple tons of short-term storage of carbon in ecosystem stocks can be considered to have equal value – as measured by the social cost of carbon – as 1 ton of carbon sequestered permanently. This equivalence can be used to quantify the value of short-term carbon storage, thereby removing one of the most significant barriers to participation in the carbon market and enabling the full climate mitigation potential of the land sector to be realized.

Main

Widespread concern about the risks of global climate change is increasingly focused on the urgent need for action^{1,2}. IPCC's most recent report, for example, finds that "unless there are immediate, rapid and large-scale reductions in greenhouse gas emissions, limiting warming to close to 1.5°C or even 2°C will be beyond reach"². Most scenarios for the future suggest that limiting global-average warming to 1.5° will require massive deployment of negative emissions technologies (NETs)^{1,3,4}. There is a growing consensus⁵⁻⁷ that Natural Climate Solutions (NCS), in the form of improved land stewardship practices, can provide as much as one-third of the emissions reductions needed through 2030 in order to achieve a high likelihood of holding warming to less than 2°C.

Recent studies have shown that for the land-use, land-use change, and forestry (LULUCF) sector to achieve its potential contribution, it must become carbon neutral by 2030, it must provide net abatement for the remainder of the century, and forest area may need to increase by up to 900 million ha.⁷. Numerous studies have suggested that this level of abatement is possible through application of forest conservation⁸, improved forest management⁶, afforestation and reforestation^{9,10}, soil carbon storage, and other land-based practices. Furthermore, the commitments in country-level Nationally Determined Contributions for the Paris Agreement suggest that national policymakers also expect that the LULUCF sector could play a critical role^{11,12}. To date, progress toward widespread implementation of these solutions has fallen well short of what will be required¹³.

In response to concern over the rising concentration of atmospheric CO₂ and the likely impacts of climate change, countries, communities, and corporations are committing to aggressive emissions reduction goals. Progress toward near-term emission reduction targets for a given entity often involves purchase of

carbon offsets – including tradeable emission reductions or carbon storage credits - that one entity can purchase from another to reduce net carbon emissions.

One critical factor that has slowed implementation of LULUCF options as C offsets has been debate over permanence. Because forest and soil ecosystems are susceptible to natural and human disturbances that could cause some or all of the stored carbon to be emitted over time, many analysts have been skeptical about the durability of forest or agricultural soil C sinks^{14,15}. Typically, crediting rules require forest-based offsets to ensure that any carbon used to offset emissions is maintained on the site “permanently”, often taken to mean at least 100 years. Offset providers may be required to carry insurance or to hold some of the potential credits in a buffer pool which cannot be sold. All of these approaches to managing permanence in carbon removal raise costs and lower the supply of potential credits. What is needed to allow a private market to flourish is an effective, scientifically valid approach to quantifying and valuing short-term carbon storage in ecosystem stocks.

This paper describes a quantitative approach to define an equivalence factor between accounting for “permanent” and short-term carbon storage. Section 2 of the paper describes the rationale for crediting temporary carbon storage. Section 3 discusses the relationship between a ton of carbon sequestered in the biosphere and the concentration of CO₂ in the atmosphere, and then defines a ton-year accounting metric. Section 4 develops the explicit mathematics of the value of delaying or offsetting emissions. Section 5 explores the time preference for confronting CO₂ emissions and explains how this bears on the climate impact and financial value of short-term carbon offsets. Section 6 draws practical conclusions on the relative value of permanent and short-term carbon storage and delayed emissions.

Short- versus long-term carbon storage

It has long been recognized that short-term carbon storage has value¹⁶⁻²⁷ yet the literature has not established an equivalence between 1 ton sequestered “permanently” and 1 ton stored over a shorter time period. Although some authors are skeptical about the value of short-term carbon storage²⁸, others recognize that “whenever there is a positive time value to carbon there is a positive value to temporary capture and storage”²⁹. This paper uses a standard representation of the global carbon cycle, along with the logic of the Global Warming Potential (100 year GWP), to show how 1 ton of carbon, sequestered permanently, can be considered equivalent to multiple tons of short-term storage of carbon in ecosystem stocks. The resulting formulation may be used to increase market participation and lower the transaction costs of trading between emitting sources and individual units of land that can generate carbon credits – without strict time constraints.

A ton of carbon sequestered from the atmosphere has value, and the longer it is stored the greater the value. Economically, a ton stored for 100 years is valued today at the prevailing carbon price, while a ton stored for only one year is worth an annual rental value that is derived from the carbon price³⁰ (Supplemental Material). Although it is true that tons stored for a short time period are ultimately released, these short-term sinks still put us on an improved climate change mitigation pathway that

would not otherwise be available. The requirement of “permanent” carbon storage discourages participation in an offset market, suggesting that consideration of shorter duration storage would increase participation³¹⁻³³.

The ton-year metric

The impact of CO₂ emissions on the climate system and its associated future damages are a consequence of the mass of additional CO₂ in the atmosphere and its persistence over time. The Bern Simple Climate Model³⁴⁻³⁷, has been used to estimate how an emission of one ton of carbon into the atmosphere is subsequently redistributed into the biosphere and the oceans. The withdrawal of one ton of carbon from the atmosphere should inversely decrease gradients, thus having the inverse effect on the distribution of carbon. The Bern model has been used to show the consequences of an impulse of CO₂ emissions to the atmosphere, and we assume that a withdrawal of CO₂ will cause the inverse rebalancing of the global carbon cycle³⁸.

Following the Bern Simple Climate Model, the decay in the extra atmospheric burden of CO₂ following a pulse emission of CO₂ can be represented by an impulse response function (Figure 1 and Equation 1)³⁶. At the end of 100 years, for example, approximately 41% of the original CO₂ impulse is expected to remain in the atmosphere.

$$CO_{2\text{ ATM}}(t) = 21.73 + 22.4 e^{-\frac{t}{394.4}} + 28.24 e^{-\frac{t}{36.54}} + 27.63 e^{-\frac{t}{4.304}} \quad (\text{Equation 1})^{36}$$

A ton-year is defined as one ton of carbon held for a period of one year in any carbon pool. Using the Bern model, we determine the number of ton-years removed from the atmosphere as the result of one ton “permanently” sequestered into the biosphere. This is the area under the curve in Figure 1, which is 53.07 ton-years of impact on the climate system. In our approach, we track the tons for 100 years to be consistent with the 100-year GWPs (GWP₁₀₀) convention, although we track tons out to a much longer time (infinite time in the formal calculations) in the Supplemental Material for mathematical consistency.

Time preference and discounting

Global Warming Potentials (GWPs) were developed to assess the relative costs and benefits of policies aimed at mitigating emissions of the different greenhouse gases when these gases have different residence times in the atmosphere. In the literature, GWPs assessed over 100 years have been used to express CO₂ equivalence for emissions or reductions of different greenhouse gases. However, the decision about the time-period over which to assess the GWPs of the different greenhouse gases reflects a social choice about the relative damages of the gases in the near- and long- terms²⁹. Recent studies^{39,40} have illustrated that the decision of the time period over which to assess the GWPs of the different greenhouse gases is a choice related to the discount rate. A GWP assessed over 100 years is

consistent with using a 3.3% discount rate to assess the damages caused by the emissions over time, while a shorter or longer-term assessment of GWP would be consistent with a higher or lower discount rate, respectively³⁹.

Our time preference leads to the use of a discount rate for aggregating current and future costs. By exploiting the link between the widely-accepted time period for determining GWPs and the resulting discount rate (100 years in this case, and the corresponding discount rate of $\lambda=3.3\%$), we are able to develop a clear trade-off between ton-years and “permanent” tons of stored carbon. The analysis is not dependent on the specific GWP time period and can be undertaken with GWPs over any time interval.

With a discount rate of λ , the value of one ton of carbon released to the atmosphere can be computed with Equation 2 (see the Supplemental Material for a full derivation), where $CO_{2ATM}(t)$ is the amount of CO_2 in the atmosphere at time t resulting from a 1-ton release at time 0, and $X(t)$ is the instantaneous rate (the value of 1 ton stored for 1 year) on the tons of carbon remaining in the atmosphere due to the release.

$$\text{Emission Value} = \int_0^{\infty} CO_{2ATM}(t) X(t) e^{-\lambda t} dt \quad (\text{Equation 2})$$

For the following, we assume that $X(t) = X$ (a constant), although as noted in supplement carbon value can refer to monetary prices, so λ would be reformulated as the real discount rate (r) minus the rate of increase in carbon prices (g), $\lambda = r-g$.

Whereas the total carbon represented under the curve of Figure 1 is 53.07 ton-years, discounting future atmospheric concentrations at 3.3% results in 18.69 ton-years of present value of climate impact if the integral is truncated at 100 years, or 19.12 ton-years if the integral is truncated at 1000 years. Delaying emissions by one year does not change the area of undiscounted ton-years, but the discounted ton-years from a one-year delay total up to 18.07 if truncated at 100 years or 18.50 if integrated out to 1000 years. The value of a one-year delay in emissions, at a discount rate of 3.3% is thus $18.69 - 18.07 = 0.62$ ton-years if integrated out to 100 years (or $19.12 - 18.50 = 0.62$ ton-years if integrated to 1000 years). The greater the time preference, i.e. the larger the discount rate, the greater will be the value of a one-year delay. Note that the value of the delay calculated above is the same for 100 years or for 1000 years because of its relation to the discount rate. This approach leads to a straightforward formula (Equation 3) for calculating the number of tons Z required to be held for 1 year that has the equivalent value to the climate system as 1 ton of “permanent” C sequestration, a formula that depends only on the time delay τ and the discount rate λ .

$$Z = \frac{1}{1 - e^{-\lambda \cdot \tau}} \quad (\text{Equation 3})$$

The discount rate λ is in turn a function of the assumption of the GWP_{100} . This outcome results from the assumption that the effect of a carbon emission in year 0, and in year 1, follow the same path. The formula can also be used under a range of carbon price assumptions, including the likelihood that they rise over time.

The approach is equivalent at any carbon price to the carbon rental approach utilized in the integrated assessment model of Sohngen and Mendelsohn (2003)³⁰, however, the formulation in (3) allows market participants to determine the exact number of tons Z that need to be stored for τ years to offset 1 ton of permanent emissions. The number of ton-years is τZ . The longer the storage period, the fewer the tons that need to be stored because each ton is worth more in terms of the abatement it does. The approach is also equivalent to the carbon tax and subsidy scheme suggested by van Kooten (1995)⁴¹, and used by the country of New Zealand, however, unlike the tax and subsidy approach, existing forest landowners are not penalized for emissions from stocks they already hold.

It can also be shown (see the Supplemental Material) that a series of delays in carbon release, extending forward in time, in sum approaches the value of that same amount of carbon permanently sequestered from the atmosphere. This means, for example, that except for risk deductions, the value of one ton kept out of the atmosphere for 100 years has the same value as one ton kept out of the atmosphere for 1 year, when it is renewed for each of the following 99 years. Figure 2a shows the relationship between the length of a delay in emissions and the number of tons delayed required to be equivalent to a permanent sequestration.

Time preference and short-term offsets

The choice of a 3.3% discount rate for this analysis is based on the 100-year assumption of the widely-accepted GWP_{100} . This discount rate, however, is close to the discount rate used by others, such as the U.S. Interagency Working Group on Social Cost of Greenhouse Gases (2021)⁴², that adopted a 3% discount rate in calculating the social cost of carbon. At the 3.3% discount rate used in this analysis, we calculate 30.8 tons of carbon need to be stored for 1 year to be equivalent in value to 1 ton of carbon stored in perpetuity. An increase in the discount rate would reduce the number of ton-years required to be equivalent to the 1-ton stored “permanently”, while a decrease would have the opposite effect (Figure 2b).

Conclusions

Our analyses show that, given the time preference embodied in the widely-accepted 100 year GWP, e.g. a discount rate of 3.3%, a one-ton “permanent” sequestration of carbon now has a present value of 18.69 ton-years (over 100 years) while a one-year storage of one ton, whether it is removed from the atmosphere directly or is a delay in an expected emission (Figures SM1 and SM2), provides a benefit of $18.69 - 18.07 = 0.62$ ton-years. The ratio suggests that 30.1 tons (30.8 tons if integrated out to infinity) of carbon sequestered from the atmosphere for one year beginning today have the same economic value

as one ton withheld from the atmosphere for 100 years. A commitment to withhold discharge for 2 years would require 15.29 tons (in the 100 years calculation, 15.65 tons in the 1000 year calculation) of delayed emissions to have equal value as 1 ton held “permanently” from the atmosphere, and so on (Figure 2a).

This numerical equivalence between long-term and short-term carbon storage enables offset programs to avoid the pitfalls and issues related to permanence and reversal risk, thereby removing a significant barrier to participation in carbon markets for landowners and better enabling the full climate mitigation potential of the land sector to be realized.

Declarations

Acknowledgments

We thank Fortunat Joos and Kuno Strassmann for their help in application of the Bern Simple Climate Model.

Author contributions

This paper is the result of a true collaborative effort among all of the co-authors. While all authors participated in drafting and reviewing the final product, Parisa conceived of the paper and prepared the first draft. G. Marland supplied vision and contextualization in the larger scientific framework. E. Marland provided key mathematical and analytical structure. Sohngen provided critical background on economic theory and discount rate applications. As corresponding author, Jenkins prepared the final draft and readied the paper for submission.

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Figures

Figure 1

Decay profile over time of a 1 ton impulse of CO₂ into the atmosphere, as described by and drawn following Equation 136.

Figure 2

2a (left). The number of ton-years needed to be equivalent to a “permanent” ton as a function of the number of years the CO₂ release is delayed, at three different discount rates. 2b (right). The relationship between ton-years considered equivalent to one “permanent” ton and the discount rate.

Supplementary Files

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