From: Spencer Meyer <spencer.meyer@ncx.com>
Sent: Monday, 10 October, 2022 22:48
To: Supervisory-Body <Supervisory-Body@unfccc.int>
Subject: Call for input 2022 - activities involving removals under the Article 6.4 Mechanism of the Paris Agreement

Dear Chair Qui,

Thank you for the opportunity to provide input on the draft recommendation, information note, and in-meeting working document regarding removals under the Article 6.4 mechanism. On behalf of NCX, I am submitting the attached comment letter and peer-reviewed paper, “The Time Value of Carbon Storage.”

Thank you again for the opportunity to provide input to your important process. Please don’t hesitate to reach out if you have any questions or want to explore the underlying scientific research that supports our work.

Best,
Spencer

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NCX

October 10, 2022

Ms. Kristin Qui, Chair
Article 6.4 Mechanism Supervisory Body

Re: Call for input 2022 - activities involving removals under the Article 6.4 Mechanism of the Paris Agreement

Dear Chair Qui,
Thank you for the opportunity to provide input on the draft recommendation, information note, and in-meeting working document regarding removals under the Article 6.4 mechanism.

NCX (www.ncx.com) is a data-driven company that facilitates the creation and sale of high-quality, science-based forest carbon credits. As such, NCX empowers landowners to access new revenue streams by sequestering additional carbon in their forests and helps businesses and public sector organizations purchase carbon credits with unprecedented transparency, scale, and impact. Our work relies on using tonne-year crediting, which allows us to provide private landowners with a flexible means of managing their forests to capture carbon and thus reduce climate change, while enabling corporations to meet their net zero emission pledges. Our tonne-year accounting methods have been developed by forest scientists and are purchased by Fortune 500 companies. To date, we have worked with nearly 4,000 landowners on 4.6 million acres of forest. We are scaling roughly 15 times faster than all other improved forest management carbon projects in the U.S. because our tonne-year accounting program is attractive to landowners. As a result, we are the number one provider of high-quality carbon credits to the voluntary carbon market (VCM).

Your work in writing the rules for accounting for and selling carbon removals is critical to ensuring the integrity of international carbon credit markets, and NCX fully supports the Supervisory Body including tonne-year carbon crediting under the Article 6.4 mechanism. Tonne-year crediting provides numerous benefits to both sellers and buyers, including enhancing credibility for all nature-based offsets by greatly reducing the risk of carbon credits, allowing for shorter yet quantifiably additional contracts, and driving climate action today, rather than paying for carbon removal decades from now.

Our approach is simple, yet supported by rigorous scientific research. Using cutting-edge remote sensing technology, NCX generates Basemap, which includes high-resolution, cost-effective measurements of forest carbon sequestration for the entire U.S., year over year. With Basemap, we precisely measure the amount of carbon sequestered on U.S. forests - for every acre, every landowner, every year. This allows us to determine how much carbon each acre of forest is accumulating over a given period. We then use our proprietary harvest risk tool to accurately calculate the climate benefit and carbon credits generated by projects, above and beyond the business as usual scenario.

NCX's innovative approach to forest carbon markets eliminates barriers to entry, democratizes access for all landowners, and unlocks a scalable supply of high-impact forest carbon credits. Landowners are paid on delivery at the end of the one-year period, for the amount of carbon sequestration that actually occurred on their forest. This eliminates risky "climate IOUs" created by other programs that pay landowners upfront for climate benefits delivered at the end of a decades-long or even 100-year contract. For each landowner, we determine whether carbon was sequestered at a rate above their property-specific business-as-usual scenario for that year, building transparency and accountability into the system. Tonne-year accounting is a critical way we eliminate risk of non-delivery for carbon credits.

As additional support and academic underpinning for ongoing use and inclusion of tonne-year crediting in the Article 6.4 mechanism, NCX is attaching a peer-reviewed, paper "The Time Value of Carbon Storage" published last month in *Forest Policy and Economics* (linked here and attached), co-authored with Professor Brent Sohngen from Ohio State University, Professors Eric Marland and Gregg Marland from Appalachian State University, and Dr. Jennifer Jenkins. This paper provides the scientific and economic framework for comparing the climate, social and economic value of short term carbon storage with carbon stored indefinitely.

By quantifying carbon storage in terms of its ability to reduce economic costs, we can motivate carbon-sequestering actions right now, which have both near- and long-term benefits, such as slowing and reducing the peak of global warming. This is accomplished by applying a time preference to capture the "time value" of immediate action to confront the impacts of climate change. The paper presents a formula for calculating the number of tonnes that must be stored for a given duration in order to have equivalent economic value as one tonne of CO2 stored out of the atmosphere forever. Using a time preference of 3%, a value consistent with United States federal guidance on how to estimate the Social Cost of Carbon, this formula shows that 33.8 tonnes held out of the atmosphere for one-year has the same the value of a tonne of carbon held out of the atmosphere indefinitely.

Thank you again for the opportunity to provide input to your important process. Please don't hesitate to reach out if you have any questions or want to explore the underlying scientific research that supports our work.

Respectfully submitted,

Dr. Spencer Meyer, Head of Science
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The time value of carbon storage

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ABSTRACT

Widespread concern about the risks of global climate change is increasingly focused on the urgent need for action, and natural climate solutions are a critical component of global strategies to achieve low temperature targets. Yet to date, the full potential of natural systems to store carbon has not been leveraged because policymakers 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 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.

1. Introduction

Widespread concern about the risks of global climate change is increasingly focused on the urgent need for action (IPCC, 2018). The IPCC's recent Working Group I 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” (IPCC, 2021). Most scenarios for the future suggest that limiting global-average warming to 1.5°C will require massive deployment of negative emissions technologies (NETs) (Gasser et al., 2015; Hilaire et al., 2019; IPCC, 2018). Negative emissions technologies, such as growing trees to remove carbon from the atmosphere, have long been recognized as a potential mechanism for limiting the amount of carbon dioxide (CO_2) in the atmosphere. A number of studies have now shown that at relatively low cost, Natural Climate Solutions (NCS) in the form of improved land stewardship practices could provide as much as one-third of the emissions reductions needed through 2030 to achieve a high likelihood of holding warming to less than 2 °C (Fuss et al., 2014; Griscom et al., 2017; Roe et al., 2019).

Recent studies have shown that for the global 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 hectares (Roe et al., 2019). Numerous studies have suggested this level of abatement is possible through application of forest conservation (Busch and Engelmann, 2017), improved forest management (Griscom et al., 2017), afforestation and reforestation (Bastin et al., 2019; Lewis et al., 2019), soil carbon storage, and other land-based practices. Furthermore, the commitments in country-level Nationally Determined Contributions for the Paris Agreement show that national policymakers also expect that the LULUCF sector will play a critical role (Forsell et al., 2016; Fyson and Jeffery, 2019). To date, however, progress toward widespread implementation of these solutions has fallen well short of what will be required (IPCC, 2022).

In response to concern over the rising concentration of atmospheric CO_2 and the likely impacts of climate change, countries, communities, and corporations are committing to aggressive emissions reduction goals, for example through net-zero commitments. Progress toward near-term emission reduction targets for a given entity often involves carbon offsets – including tradeable emission reductions or carbon storage credits that one entity can purchase from another to reduce their net carbon emissions.

A critical factor that has slowed implementation of LULUCF options

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as C offsets has been concern about the stability of forest carbon stocks – permanence. Because forest and soil ecosystems are susceptible to natural and human disturbances that could cause some or all of the stored carbon subsequently to be emitted, many analysts have been skeptical about the durability, and hence the value, of forest or agricultural C offsets (Gren and Aklilu, 2016; Thamo and Pannell, 2016; van Kooten, 2009). Typically, crediting rules require forest-based offsets to ensure that any project activities, or carbon used to offset emissions, are maintained and managed on the site "permanently", often taken to mean at least 100 years (Verra, 2013). In addition to being required to hold and verify carbon on an offset site for 100 years, suppliers typically also have to carry insurance and place a large proportion of the potential credits into a buffer pool which cannot be sold. The approaches currently used to manage permanence in the carbon market are not based on economics, and as a result, raise costs, reduce participation, and lower the supply of potential credits. A change that could help the private market flourish is agreement on the role of short-term carbon offsets and an effective, scientifically valid approach to quantify and value short-term carbon storage in ecosystems.

As a way to circumvent this problem, a static horizon ton-year approach has been suggested as a way to account for physical tons of carbon stored for a short period of time so they can be traded with CO_2 emitted through energy combustion (Korhonen et al., 2002; Moura Costa and Wilson, 2000). However, as we show in this paper, the static horizon concept relies on an arbitrary end date for the comparison of two different carbon flux streams. Further this approach relies on a comparison of undiscounted carbon fluxes over time, which weighs future storage of carbon the same as current storage of carbon. While there is debate over the proper discount rate to use for climate change problems (Nordhaus, 2008; Stern, 2007; Weitzman, 2014), economic models rely on discounting to appropriately weight welfare outcomes over time. More importantly for the question of permanence in land-based sinks, failing to discount the future benefits and costs of land-based carbon streams versus energy emissions could lead to less-than-optimal investments in forests or other land-based sinks. All of the economic studies reviewed in the recent analysis of economic potential by Roe et al. (2021) valued outcomes with traditional economic valuation techniques, including discounting. Carbon accounting frameworks that use ton-years without properly valuing carbon over time, or other approaches that ignore the time-value of money, will systematically over-estimate costs, and tilt investment decisions away from nature-based solutions.

Economic approaches that utilize carbon rental concepts avoid this problem by valuing short-term carbon storage through carbon rental (Marland et al., 2001; Sohngen and Mendelsohn, 2003), which values a ton of carbon stored for a year with a carbon rent derived from the market price, or the social cost of carbon, appropriately discounted. Renting short-term storage in forests or other nature-based solutions can be economically efficient, but requires energy emission sources to hold an equivalent stock of rented carbon tons indefinitely to net-out their CO_2 emission. However, it is also possible to exploit the relationship in value between a current emission and a delayed emission to derive a formula that expresses the number of tons N that need to be held for 1 year (or "n" years) to equilibrate the present value of 1 ton of current emissions with N tons of delayed emissions. Such a formula is based on the standard representation of forest carbon stocks in integrated assessment models, and economic analyses of nature-based solutions. In the sections that follow, we derive this formula and demonstrate how it can be used as the basis for market trading so all tons stored or emitted can be traded in current years while accounting for permanence.

2. Short versus long-term carbon storage

It has long been recognized that short-term carbon storage away from the atmosphere has value (Brandão and Levasseur, 2011; Chomitz, 2000; Dornburg and Marland, 2008; Fearnside, 1995, 1997; Fearnside et al., 2000; Lashof and Hare, 1999; Maréchal and Hecq, 2006; Marshall and Kelly, 2010; Moura Costa and Wilson, 2000; Moura-Costa, 1996) yet the literature has not established a quantitative relationship between 1 ton stored "permanently" and 1 ton stored over a shorter time period. Although some authors have expressed concern about the value of short-term carbon storage (Kirschbaum, 2006), others have recognized that "whenever there is a positive time value to carbon there is a positive value to temporary capture and storage" (Richards, 1997). This paper uses a standard model of the global carbon cycle to show how multiple tons of short-term storage of carbon in ecosystem stocks have the same economic value as 1 ton of carbon sequestered permanently. The resulting formulation can be used in a carbon trading market to allow participation by individual landowners of forests who intend to hold their carbon stocks only for short periods. The formula may increase market participation and lower the transaction costs of trading between sources of emissions and individual units of land that can generate offset credits.

Chomitz (2000), Fearnside et al. (2000), and Moura Costa and Wilson (2000) all recognized the need for a method that addressed the short-term value of carbon storage in ecosystems. They asked how long carbon should be sequestered to balance the climate effect of emitted carbon. Using a carbon cycle model to analyze the decay pattern of a CO_2 impulse emission to the atmosphere, Moura Costa and Wilson (2000) estimated an equivalence time of 55 years, so that a ton of carbon withheld from the atmosphere for 55 years could presumably balance the emission of one ton of carbon as CO_2. In a contemporary paper, Fearnside et al. (2000) argued that the product of tons of carbon withheld from the atmosphere and the time over which it was withheld could provide a ton-year equivalence and allow "temporary sequestration of CO_2 to be compared on an equitable and consistent basis with permanent C sequestration or fossil fuel emission avoidance." The IPCC (2000) observed that "a ton-year accounting system would provide a basis for temporary sequestration or delayed deforestation to be credited", although they noted that the Kyoto Protocol seemed to preclude credit for such temporary activities. This estimation of ton-year equivalence, they argued, "removed the need for long-term guarantees". The search for an equivalence factor was important but an approach that treated emissions and sequestration similarly has not been developed.

There has been considerable debate about short-term storage of carbon. Carbon cycle scientists in particular have expressed considerable concern. Korhonen et al. (2002), for example, argued that temporary carbon storage had no value and that it could actually "impede achievement of the concentration stabilization target of CO_2" and that "only 'permanent' carbon sequestration is meaningful". Kirschbaum (2006) added that "temporary carbon sequestration cannot prevent climate change" and that "it is, therefore, not warranted to provide policy incentives for temporary carbon storage". At the same time Marland et al. (2001) noted that "There are a variety of reasons, both environmental and economic, that it may be advantageous for some parties to acquire temporary credits." These included the facts that some temporary sequestration may turn out to be permanent and that even if individual projects are temporary the collective of projects should result in greater total carbon sequestration. Marland et al. proposed that if carbon offsets could be sold they could also be rented and that the market would establish the relative value of permanent and temporary offsets. The Government of Colombia proposed a similar approach in "temporary certified emissions reductions" (tCERs), but the tCERs would need to be replaced if the carbon was subsequently released (Colombia Ministry of the Environment, 2000). Dornburg and Marland (2008) noted that "even temporary sinks put us on a lower path for climate change, a path that will not otherwise be accessible." The IPCC (2000) recognized the difference between a ton of carbon in the atmosphere, which degrades with time, and a ton of carbon in biomass, which is constant with time, and the fact that some crediting schemes succeeded simply in pushing some atmospheric carbon beyond the time interval of project accounting.

In summarizing the outcome of an expert workshop on temporary carbon storage Brandão and Levasseur (2011) wrote “Despite significant efforts to develop robust methods to account for temporary carbon storage, there is still no consensus on how to consider it.” This conclusion, however, seems to ignore IPCC (2000), which summarized that, “as long as the policy time horizon is finite or a non-zero discount rate is applied to determine the present value of future emissions/removals, even short term will have some value.” We argue that the consensus is that temporary storage does have value and that the value is a result of our time preference, because we value near time management of carbon emissions over future management. As summarized by Brandão and Levasseur (2011) “it is impossible to give a value to temporary carbon storage without using time preferences.”

In summary, the early literature on carbon offsets recognized that there was value in short term sequestration but did not produce a consensus on how to establish a useful measure of comparison. Following economic principles, however, any ton of carbon sequestered from the atmosphere has value, and the longer it is stored the greater the value. Economically, a ton stored indefinitely is valued today at the prevailing social cost of carbon, while a ton stored for only one year is worth an annual rental value that is derived from the carbon price. Although it is true that some tons may only be stored for a short time period, these short-term sinks nonetheless have value, and 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 participation (Kerchner and Keeton, 2015; Ruseva et al., 2017; Wise et al., 2019) and increase the net amount of carbon stored in the biosphere.

3. The ton-year metric

The primary purpose of this paper is to derive a closed form solution that equilibrates the present value of 1 ton of current emissions with N tons of delayed emissions. We start with a simple climate model that describes the time path of 1 ton of CO_2 emitted to the atmosphere. The simple climate model allows us to define the concept of a ton-year, as it has been described in the literature. The impact of CO_2 emissions on the climate system and its associated future damages are a consequence of the mass of additional CO_2 in the atmosphere and its persistence over time. The Bern Simple Climate Model (Joos et al., 2013, 2001, 1996; Strassmann and Joos, 2018) 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. For the purposes of this paper, we assume that a withdrawal of CO_2 will cause the inverse rebalancing of the global carbon cycle (Zickfeld et al., 2021).

Following the Bern Simple Climate Model, the tons of CO_2 remaining in the atmosphere after a pulse of CO_2 emitted can be represented by an impulse response function, shown in Fig. 1 and eq. (1) (Joos et al., 2013). The impulse response function accounts for the decay of the released CO_2 into other pools, such as the ocean or the biosphere. At the end of 100 years, approximately 41% of the original CO_2 impulse is expected to remain in the atmosphere.

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

A ton-year was originally defined in the literature as one ton of carbon held for a period of one year in any carbon pool. Dealing with carbon dynamics in different pools, however, has led to confusion in the literature over the years, so for our purposes we limit our discussion to tons of carbon in the atmosphere only. A ton-year in this paper is then one ton of carbon (as CO_2) residing in the atmosphere for one year (Appendix A.Ib).

Using the Bern model, we determine the number of ton-years resident in the atmosphere as the result of one ton of carbon released into the atmosphere by integrating the mass of a released pulse over a set period of time, T, measured from the time of release $t = 0$. This is the area under curve (A) in Fig. 1. The calculation of ton-years can be defined over a finite interval T after the initial release as shown in Eq. (1). In this example, we track the tons for 100 years to be consistent with the 100-year GWP (GWP_{100}) convention, although we track tons out to a much longer time (infinite time in the formal calculations) in the Appendix, for mathematical consistency. For the 100-year interval, the value TY_A is 53.07 ton-years where:

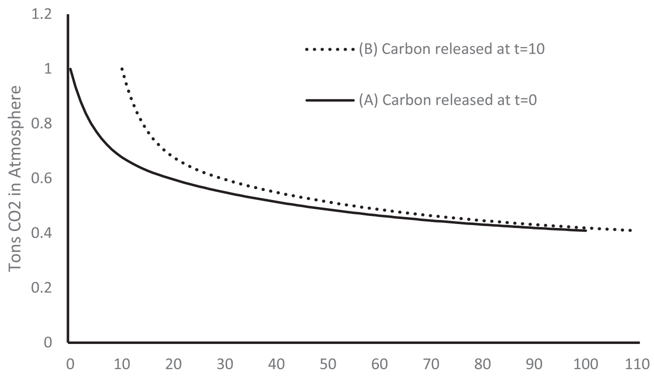

Fig. 1. Decay profile over time (using eq. (1)) of a 1 ton impulse of CO_2 into the atmosphere released at time = 0 (A) and as released at time = 10 (B), with both followed for 100 years using eq. (1) (Joos et al., 2013).

$$\text{Ton} - \text{Years} = TY_A = \int_{t=0}^{t=0+T} CO_{2,A}(t)dt \tag{2}$$

Note that in the calculations here, we use the constant (and subscript) “A” to denote release at the initial time and “B” to denote release at the delayed time. If we consider the short-term storage of 1 ton of carbon in trees for 10 years, followed by the release of that ton into the atmosphere, we could calculate the effect of that delay by subtracting the corresponding integrals for the two curves shown in Fig. 1:

$$\begin{aligned}\text{Ton} - \text{years changed} &= TY_{t_0} - TY_{(t_0+10)} \\ &= \int_{t_0}^{t_0+T} CO_{2,A}(t)dt - \int_{(t_0+10)}^{(t_0+10)+T} CO_{2,B}(t)dt\end{aligned} \tag{3}$$

However, the difference in the integral of the two curves in Fig. 1 and eq. (3), where both are integrated for 100 years, is 0, as shown in Appendix A.Ic. The result that the difference is exactly zero also assumes that the dynamics of CO_2 remain the same as a function of time, which is consistent with the ton-year literature, and which we believe to be a reasonable assumption for short delays.

The ton-year literature avoids this problem by holding the time period constant (e.g. Moura Costa and Wilson, 2000; Fearnside et al., 2000; and Korhonen et al., 2002). That is, rather than assessing both curves in Fig. 1 over $T = 100$ years, only the initial release is assessed over 100 years, while the delayed release is assessed over 90 years (see Appendix A.Ib). We call this the static horizon approach. In eq. (3), if one considers a 10-year delay in release and conducts the analysis over 100 total years, then the ending period in the integral would be 100 according to that formulation, not 110 years as seen in Fig. 1 (Eq. (4)).

$$\begin{aligned}\text{Ton} - \text{years changed} &= TY_{t_0} - TY_{(t_0+10)} \\ &= \int_{t_0}^{t_0+T} CO_{2,A}(t)dt - \int_{(t_0+10)}^{t_0+T} CO_{2,A}(t)dt\end{aligned} \tag{4}$$

Evaluated over the interval from 0 to 100, the gain in ton-years associated with a 10-year delay is 4.14, which is also the area under curve B from years 100 to 110 (see also IPCC, 2000). The problem with this static horizon approach used in the literature is that limiting the analysis to 100 total years allows the area under curve B to appear smaller that the area under curve A, although the long-term impact on the climate system is unchanged. This shift in only one limit on the integral is arbitrary, and creates quite a few downstream problems.

As suggested in the carbon cycle literature, the physical quantities of CO_2 by themselves have no difference in atmospheric effect simply due to a delay in the release (Korhonen et al., 2002). Existing ton-year approaches have imputed an atmospheric effect arbitrarily by setting a terminal period for analysis which compares the same carbon flux pathways over decomposition periods of two different time lengths (see Appendix A.Ic). While there is no difference in the effect on the atmosphere in the long run, because society has a time preference for carbon impacts, the delay in release can be valued.

4. Valuing the delay in carbon release: Discounted ton-years

While delaying a carbon release has no long-term physical impact on the atmosphere, delaying a release does have value because society benefits from having less carbon in the atmosphere, as represented by the social cost of carbon (e.g., Nordhaus, 2017). The social cost of carbon changes over time, meaning that future emissions are worth something different than today's emissions. Thus, the delayed profile of released carbon in path (B) in Fig. 1 has a different value than the released carbon in path (A). Furthermore, because society has time preferences, the two pathways in Fig. 1 must be evaluated not only by using the social cost of carbon, but also by using discounting, to account for social preference over when the releases (or storage) occur.

If a ton of carbon is released into the atmosphere from burning fossil fuels it is worth something to avoid the emission, even if only for a short period of time. It is worth the social cost of carbon, $SCC(t_0)$, to avoid the emission forever. To avoid the emission for a shorter period of time, the value of that delay can be determined by valuing the non-permanent carbon stored in a forest stock with the annual carbon rental value. That is, the permanent withdrawal of a ton of carbon from the atmosphere is worth the price of carbon, or $SCC(t_0)$, while a ton withdrawn from the atmosphere for only one year is worth the annual rental value of a ton, $R(t_0)$. Critically, from the perspective of today, a ton of carbon released today has a different value than that same ton released tomorrow.

With a discount rate of r, the value of one ton of carbon released to the atmosphere can be computed with eq. (5) (Appendix A.Id),

$$\text{Emission} \quad \text{Value}_A = \int_0^\infty CO_{2,A}(t)R(t)e^{-rt}dt \tag{5}$$

where R(t) is the value of one ton stored for one year for the tons of carbon remaining in the atmosphere due to the release. For the valuation of carbon emissions, we present the formula to infinity rather than the 100-years commonly used in the ton-years literature because we are interested in valuing the full effect of the delay, not just the next 100 years. Our interest lies in determining the value of a delay of τ years in the release of a ton of carbon, which mathematically is (see Appendix A. Id for derivation):

Change in Emission Value = Value of the delay =

$$\int_0^\infty CO_{2,A}(t)R(t)e^{-rt}dt - \int_0^\infty CO_{2,A}(t)R(t+\tau)e^{-r(t+\tau)}dt \tag{6}$$

Rental rates are used to value the emission flows because we are valuing the stock of carbon stored in the atmosphere due to the release, rather than the instantaneous release itself. Rental rates and carbon prices are related. For instance, the value of an instantaneous release today of one ton of carbon to the atmosphere left there forever (i.e., the value of 1 ton of energy combustion CO_2 release) is the price of carbon, $P_C(t)$. Note that $P_C(t)$ is a general form of the carbon price, while SCC(t) is a specific carbon price, notably the social cost of carbon as derived from a dynamic integrated assessment model (Nordhaus, 2017). $P_C(t)$ could alternatively be the price of carbon in a specific market, such as the California cap and trade system, or the New Zealand emissions trading system. The value of an instantaneous release next year of the same amount of carbon (1 ton) to the atmosphere left there forever (i.e., the value of 1 ton of energy combustion CO_2 release) is the price of carbon, $P_C(t+1)$. The discounted difference between these two values is the rental rate:

$$\text{Carbon rental rate} = R(t) = P_C(t) – P_C(t+1)e^{-r} = P_C(t)(1-e^{-r}) \tag{7}$$

Carbon prices may be rising or falling in eq. (7). Most integrated assessment models find that carbon prices are rising as the amount of carbon accumulating in the atmosphere increases and climate damages grow (Nordhaus, 2017). If carbon prices are rising at a constant rate equal to "g" over time, eq. (7) can be rewritten:

$$\begin{aligned}\text{Carbon rental rate} = R(t) = P_C(t) – P_C(t+1)e^{g}e^{-r} = P_C(t)\left(1-e^{-(r-g)}\right) \\ = P_C(t)\left(1-e^{-(\lambda)}\right)\end{aligned} \tag{8}$$

For the purposes of this paper, we use the net discount rate equal to the difference between the discount rate and the rate of growth of carbon prices, $\lambda = (r\text{-}g)$, in the equations that follow.

Whereas the total carbon represented under the curve of Fig. 1 out to 100 years is 53.07 ton-years, discounting future atmospheric concentrations results in a smaller present value of climate impact. 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 as a function of the discount rate. The greater the time preference, the larger the discount rate, the greater will be the value of a one-year delay. Note that the value of the delay is the same for 100 years or for 1000 years because of its relation to the discount rate.

The goal of this paper is to determine if there is a number of tons N held for a short period of time, τ, that has equal value to a 1-ton release of CO_2 from energy combustion today. As shown in Appendix A.1e, a straightforward formula can be derived to calculate N. Under the assumption that carbon prices are constant, this formula depends only on the time delay τ, the discount rate r, and the rate of growth of carbon prices g

$$N = \frac{1}{1-e^{-\lambda\tau}} \tag{9}$$

Note that Eq. (9) does not depend on the exact dynamics of CO_2 in the atmosphere, except in that the derivation requires that the dynamics of an initial release and a delayed release follow the same time course in the atmosphere (see Fig. 1). While this is a reasonable approximation for short time periods, longer-time comparisons could be subject to additional uncertainty. If carbon prices are rising, for any interest rate r, λ will be suppressed and the value of delaying carbon releases will be diminished. This means that for any interest rate r, N must be larger the faster carbon prices rise. As the rate of growth of carbon prices approaches the discount rate, N approaches infinity, meaning that the value of delay is small.

Thus far, we have shown how the value of delaying a carbon release will result in a simple formula to calculate the number of tons that need to be held for the delay period to be equivalent with a ton of carbon released into the atmosphere (eq. (9)). The derivation of the formula relied on the basic carbon dynamics of a one ton release of carbon into the atmosphere using the model suggested by (Joos et al., 2013). The same formula can also be derived from the definition of the social cost of carbon and carbon rents. For example, one year of carbon rental is the value of holding a ton of carbon out of the atmosphere for one year (Sohngen and Mendelsohn, 2003). The social cost of carbon is, by definition, the present value of the long-term damages that result from releasing a ton of carbon to the atmosphere, which is the present value of the carbon rent on 1 ton, forever:

$$SCC(0) = \int_0^\infty R(0)e^{-\lambda t}dt \tag{10}$$

When carbon is valued with the social cost of carbon, the short-term storage problem resolves to determining the number of tons of carbon N that needs to be stored for τ years to be equivalent to the storage of one ton forever (i.e. $\tau = \infty$), or for T years if there is an agreed upon time limit:

$$SCC(0) = N\int_0^\tau R(0)e^{-\lambda t}dt \tag{11}$$

As shown in Appendix A.II, N can be solved for the same solution as in eq. (9).

The same derivation of N, then, can be obtained both from a careful comparison of the value of two carbon fluxes – an immediate emission and a delayed emission – to the atmosphere as from a comparison of the present value of a short-term rental of N tons for τ years with the social cost of carbon of 1 ton. It turns out that the most important consideration for determining the number of tons that needs to be held for a given period of time in order to equal the economic value of 1 ton of energy emissions today is the discount rate, or the net discount rate in cases where the price of carbon is changing.

5. Example

The choice of the discount rate and the rate of change of the price of carbon are policy choices. The issue of discounting for climate change problems has been widely discussed in the economics literature and a range of discount rates have been recommended. In one of the most widely used integrated assessment models, the DICE model (Nordhaus, 2017)[42], the discount rate averages 4.25% over the first century, although it is declining over time. Concerns about large-scale, yet uncertain, events in the future, however, have led some analysts to recommend using parameters that result in a much lower discount rate when evaluating climate change (e.g., Stern, 2007). A recent study that incorporates uncertainty directly into an integrated assessment model calculates a lower discount rate for climate damages of 2.4% (Cai and Lontzek, 2019). The US Government Office of Management and Budget under Circular No. A-4 suggests that 3% and 7% real discount rates be used, however, this circular also provides arguments to use lower rates when long-term intergenerational questions like climate change are being considered. The US Government Interagency Working Group analyzes the social cost of carbon along a set of pathways using discount rates ranging from 2.5% to 5% (IWG, 2022). An analysis of the widely used Global Warming Potentials (GWPs) shows that focus on 100-year GWPs is consistent with social choices using a 3.3% discount rate (Sarofim and Giordano, 2018).

To develop an example, we start by assuming that $r = 5.0\%$ and $g = 1.7\%$, and $\lambda = 3.3\%$. We also assume that the carbon price, or social cost of carbon, is \$30.81, resulting in a carbon rent in the initial period of \$1.00 per ton per year. We then calculate the value of short-term storage over a finite time interval of 100 or 1000 years, and in discrete time. The supplemental spreadsheet is provided with these calculations, described in Appendix A.III. Whereas the total carbon represented under the curve of Fig. 1 is 53.07 ton-years, discounting the value of future atmospheric concentrations where $\lambda = 3.3\%$ results in a discounted emission value of \$18.69 if the integral is truncated at 100 years, or \$19.12 if the integral is truncated at 1000 years. Delaying emissions by one year does not change the area of undiscounted ton-years, the physical impact on the climate system, but the discounted emission value after a one-year delay equals \$18.07 if truncated at 100 years or \$18.50 if integrated out to 1000 years. The economic value of a one-year delay in emissions is thus \$18.69 – \$18.07 = \$0.62 if integrated out to 100 years or \$19.12 – \$18.50 = \$0.62 if integrated to 1000 years (see Appendix A.III and spreadsheet). The greater the time preference, i.e. the larger the discount rate, the greater will be the economic 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. Fig. 2 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. A shorter delay will require more tons to be held for a short duration to be equivalent to a 1-ton emission. As the net discount rate increases, the number of tons that need to be held for any delay period declines, as shown by the shift in the curves downward for higher net discount rates in Fig. 2.

At $\lambda = 3.3\%$, we calculate that 30.81 (\$19.12/\$0.62) 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 net 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 (see Fig. 2b). The number of tons that needs to be stored for a short period of time does not depend on the initial SCC. It only depends on the discount rate, r, and the rate of growth of the SCC, g. The value of 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.

In practice, the tradeoff between 30.81 tons CO_2 stored for one year and one ton emitted forever can be implemented directly in a market. Because trees hold C and not CO_2, the 30.81 tons is emitted CO_2 which is stored as 8.4 tons C in tree biomass. For example, suppose a company

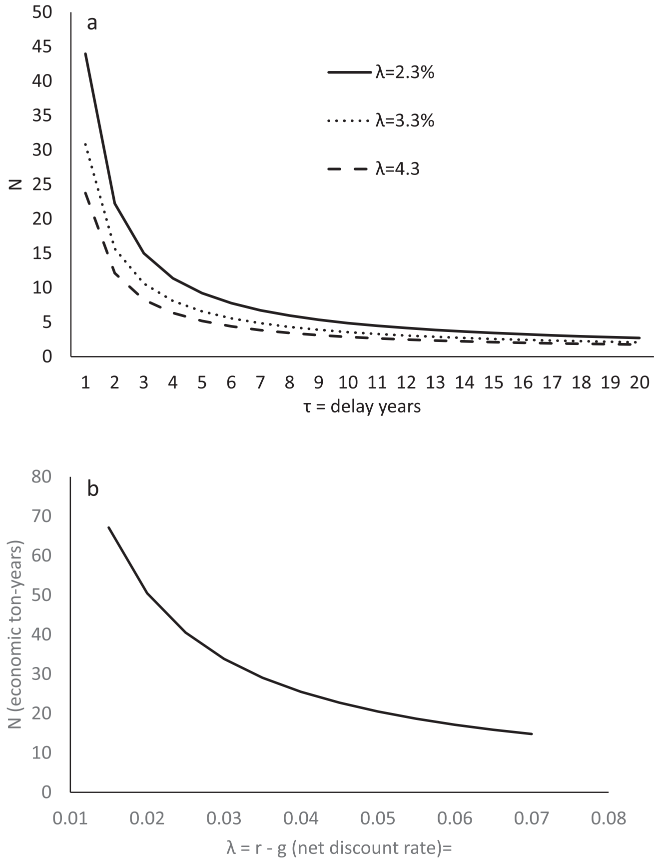

Fig. 2. a: The number of tons of emissions delayed for τ years needed to have the same value as a "permanent" ton delayed as a function of the number of years the CO_2 release is delayed, at three different net discount rates. b: The relationship between ton-years considered to have the same economic value as one "permanent" ton as a function of the discount rate. The figure uses the net discount rate, λ.

generates carbon credits by paying pine plantation landowners in the Southern United States to extend their timber harvesting rotation period by one year on forests they are about to harvest. If the carbon content in aboveground biomass of just the trees in the plantation is 73.6 tons C per hectare, or 270 tons of CO_2 per hectare if emitted, and the landowner has 10 ha of land available on which to delay harvest, the landowner has generated 2700 tons of delayed CO_2 emissions for one year. By the assumptions over discount rates and carbon price growth rates, the landowner could be compensated for offsetting 87.6 tons CO_2 of energy emissions (2700/30.81). If the carbon price is $50 per ton CO_2 then the landowner will be paid $4380, which is the carbon price times the tons offset ($50*87.6). The value $4380 also equals the carbon rent of $1.62 per ton CO_2 per year, or $\$50*(1\text{-}e^{-0.033})$, times the 2700 tons CO_2 held for one year (note there will be some differences due to rounding). By this approach, one can see that if the landowner holds the additional tons for one year, the landowner will get paid exactly the rental value associated with holding those tons for one year.

With this formulation, however, neither the landowner nor the individual (or company) who emitted the carbon to the atmosphere is liable for future storage to offset those tons. By paying the landowner to hold onto 2700 tons CO_2 for one year, the buyer has reduced damages by an equivalent value ($4380) to their original 87.6 tons of emissions. This approach requires determining the reference level of harvested carbon content so the storage can be proved additional. Measuring, monitoring and verifying that the carbon is there happens during the year of the contract. No buffer pools or deductions for buffer pools need to be developed because the carbon traded is the actual carbon measured. If a fire or other disturbance happens, the additional tons obviously are not held on the landscape and thus cannot be used as offsets. A deduction for leakage could be included if appropriate.

In contrast, other approaches, such as the Verra VM0003 Methodology for Improved Forest Management through Extension of Rotation Age, v1.2 (Verra, 2013), rely on *ex ante* projections of carbon changes over a 100-year projection period under a reference case and under a scenario case with extended rotations. Project developers produce estimates of the average carbon change over the 100-year period, which are the basis for the offsets. However, uncertainties associated with possible losses due to fires or other disturbances would be deducted from the potential pool and stored in a buffer that cannot be sold. Additional deductions would be made for leakage. To produce an offset, the site must be contracted, measured, monitored and verified over the entire 100-year period.

Existing methodologies impose substantial additional burdens on project developers, namely the long-term contracts, whereas an approach based on the formula in eq. (9) above is much simpler. It preserves the value proposition that the value of short-term storage should equal the value of the damage caused by the carbon emission. It also ensures that carbon on the landscape is priced along its marginal cost function, and that only actually stored carbon is priced. In contrast, the current Verra and similar methodologies pay for the average carbon change due to proposed long-term changes in forest management without reference to different value carbon changes will have depending on when they occur over the 100-year agreement. The approach requires that landowners agree to specific management practices that must occur 75 to 100 years in the future. Handling possible uncertainty requires removing some of the potential credits generated so they cannot be sold, thus raising costs.

6. Conclusion

This paper shows how to derive a simple closed-form solution for the number of tons N of C that must be stored temporarily to equate their value with the value of a ton of C emitted permanently. We start with the static horizon approach that has been widely discussed in the literature. However, the static horizon approach only provides an answer to the question of temporary storage under arbitrary assumptions about the starting and ending points for integrating across two different pathways of a carbon flux to the atmosphere. This means that a rationale for short-term carbon storage cannot be based on this current approach, which compares purely physical flows of carbon.

Yet, short-term storage has value. Analyzing the problem using economics, we derive an answer to the question “how many C tons N must be stored for 1 year to equilibrate the present value of those tons with the present value of the release of 1 ton of C from fossil fuel combustion today.” The benefit of delay exists only when there is a positive discount rate, that is, when society has time preferences. However, given these time preferences and an assumed time path for the social cost of carbon, the derivation of N is straightforward. Our approach to determining N is derived by using the Bern simple climate model to evaluate the path of a carbon emission to the atmosphere, and by using the social cost of carbon directly. Thus, our result provides a derivation of an economically efficient ton-year metric that is consistent with economic valuation and integrated assessment modeling approaches. The approach can be used for carbon trading applications directly.

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 background on economic theory and discount rate applications. As corresponding author, Jenkins provided inputs to analysis and writing, including preparing and revising drafts. The authors claim that there are no conflicts of interest or financial interests beyond that clearly expressed in the addresses of authors Parisa and Jenkins.

Declaration of Competing Interest

The authors claim that there are no conflicts of interest or financial interests beyond that expressed by the fact that Lead Author Zack Parisa and co-author Jennifer Jenkins both are employed by NCX, which could use the resulting trading rules in their business model.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.forpol.2022.102840.

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