Title: 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 (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 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\textsuperscript{1,2}. The IPCC’s 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\textdegree{}C or even 2\textdegree{}C will be beyond reach\textsuperscript{2}”. Most scenarios for the future suggest that limiting global-average warming to 1.5\textdegree{} will require massive deployment of negative emissions technologies (NETs)\textsuperscript{1,3,4}. 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\textsubscript{2}) in the atmosphere. There is a growing consensus\textsuperscript{5-7} that these 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\textdegree{}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 hectares.\textsuperscript{7} Numerous have suggested that this level of abatement is possible through application of forest conservation\textsuperscript{8}, improved forest management\textsuperscript{6}, afforestation and reforestation\textsuperscript{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\textsuperscript{11,12}. To date, however, progress toward widespread implementation of these solutions has fallen well short of what will be required\textsuperscript{13}.

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In response to concern over the rising concentration of atmospheric CO\textsubscript{2} 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 carbon offsets – including tradeable emission reductions or carbon storage credits that one entity can purchase from another to reduce their net carbon emissions.

One critical factor that has slowed implementation of LULUCF options as C offsets has been discussion of 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 subsequently emitted over time, many analysts have been skeptical about the durability, and hence the value, of forest or agricultural C offsets\textsuperscript{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, reduce participation, and lower the supply of potential credits. What is needed to allow a private market to flourish is agreement on the role of short-term carbon offsets and an effective, scientifically valid approach to quantifying and valuing this short-term carbon storage in ecosystems.

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 CO\textsubscript{2} in the atmosphere, and then defines a ton-year accounting metric. Section 4 develops the explicit mathematics of the value of delaying or offsetting carbon emissions. Section 5 explores the time preference for confronting CO\textsubscript{2} 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.

2. Short versus long-term carbon storage

It has long been recognized that short-term carbon storage away from the atmosphere has value\textsuperscript{16-27} 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\textsuperscript{28}, others have recognized that “whenever there is a positive time value to carbon there is a positive value to temporary capture and storage”\textsuperscript{29}. 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 to increase market participation and lower the transaction costs of trading between sources of emissions and individual units of land that can generate offset credits.

Moura Costa and Wilson (2000), Fearnside et al. (2000) and Chomitz (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\textsubscript{2} impulse emission to the atmosphere, Moura Costa and Wilson 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\textsubscript{2}. In a longer, 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\textsubscript{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 was never developed, nor was consensus achieved on how to establish a useful measure of comparison.

In the extensive published literature on accounting for time in carbon accounting Korhonen et al. (2002)\textsuperscript{31} argued that temporary carbon storage had no value and that it could actually “impede achievement of the concentration stabilization target of CO\textsubscript{2}” and that “only ‘permanent’ carbon sequestration is meaningful”. Kirschbaum (2006)\textsuperscript{28} 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)\textsuperscript{32} 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.\textsuperscript{32} 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\textsuperscript{33} proposed a similar approach in “temporary certified emissions reductions” (tCERs), but the tCERs would need to be replaced if the carbon was subsequently released. 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 is despite the conclusion from 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.”

Thus 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. We accept that 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 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 \(^{33}\) (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 participation \(^{34-36}\) and increase the net amount of carbon stored in the biosphere.

3. The ton-year metric

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 \(^{37-40}\), 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 CO\(_2\) emissions to the atmosphere. For the purposes of this paper, we assume that a withdrawal of CO\(_2\) will cause the inverse rebalancing of the global carbon cycle \(^{41}\).

Following the Bern Simple Climate Model, the decay of the extra atmospheric burden of CO\(_2\) following a pulse emission of CO\(_2\) can be represented by an impulse response function, shown following the carbon released at time \(t=0\) in Figure 1 and Equation 1 \(^{39}\). At the end of 100 years, for example, approximately 41% of the original CO\(_2\) impulse is expected to remain in the atmosphere.

\[
CO_{2ATM}(t) = 21.73 + 22.4 e^{-\frac{t}{394.4}} + 28.24 e^{-\frac{t}{36.54}} + 27.63 e^{-\frac{t}{4.304}} \quad \text{(Equation 1)}^{39}
\]
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.

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 Figure 1. The calculation of ton-years can be defined over a finite interval $T$ after the initial release as shown in Equation 1. In our example in the next section, 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 Supplemental Material, for mathematical consistency. For the 100-year interval, the value $TY_A$ is 53.07 ton-years where:

$$\text{ton-years} = TY_A = \int_{t=0}^{t=0+T} CO_{2,A}(t) \, dt \quad \text{(Equation 2)}$$

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 Figure 1 (see Supplement section Ib).

Note that the ton-year literature often assesses short-term storage by holding the time period constant (e.g. Moura-Costa and Wilson, 2000; Fearnside et al., 2000; and Korhonen et al., 2002). In terms of equation (2), 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 Figure 1. Evaluated over the interval from 0 to 100, the
gain in ton-years associated with a 10-year delay is the area under curve B that is simply pushed out of the end of the accounting period (see also IPCC, 2000). If the analysis is limited to 100 total years the area under curve B appears smaller that the area under curve A in spite of the fact that the long term impact on the climate system is unchanged. This shift in only one limit on the integral creates quite a few downstream problems (see Supplement section Ic).

In our approach, a shift in the release of carbon to the atmosphere is applied to the entire integral. Note that the time interval of integration is then the same for both integrals, 100 years - to remain consistent with our definition of the ton-year. The result is that the difference is exactly zero, assuming that the dynamics of CO₂ remain the same as a function of time (a reasonable assumption for short delays).

\[
\text{ton-years value} = TY_{(t_0+10)} - TY_{t_0} = \int_{(t_0+10)}^{T} CO_{2,A}(t) \, dt - \int_{t_0}^{T} CO_{2,A}(t) \, dt \quad (\text{Equation 3})
\]

This means that the physical quantities by themselves have no difference in value simply due to a delay in the release. Existing ton-year approaches have imputed value arbitrarily by setting a terminal period for analysis which compares the same carbon flux pathways over decomposition periods of two different time lengths (see Supplement Ic). However, because society has a time preference for carbon impacts, the delay can be valued economically. This time preference may be purely economic, based on an incentive program, due to our urgency in addressing climate change, or due to some other measure. Whatever the reason, it is this time preference that provides value to delays in the release of CO₂ to the atmosphere.

4. Time preference and discounting

This paper examines the value of the delay in the release of carbon as shown in Figure 1. Delaying the release of carbon has 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 Figure 1 has a different value than the released carbon in path (A). Furthermore, because society has time preferences, the two pathways in Figure 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 economically, where non-permanent carbon stored in a forest stock is valued by renting carbon. Critically, a ton of carbon released today has a different value than that same ton released tomorrow.

Our time preference leads to the use of a discount rate for aggregating current and future costs.
With a discount rate of \( r \), the value of one ton of carbon released to the atmosphere can be computed with Equation 4 (see Supplement Id), where \( \text{CO}_2 \text{ATM}(t) \) is the increment of \( \text{CO}_2 \) in the atmosphere at time \( t \) resulting from a 1-ton release at time 0 (following equation 1), and \( X(t) \) is the rental rate (the value of 1 ton stored for 1 year) on the tons of carbon remaining in the atmosphere due to the release.

\[
\text{Emission Value} = \int_{0}^{\infty} \text{CO}_2 \text{ATM}(t) \ X(t) \ e^{-rt} \ dt
\]  
(Equation 4)

For the following discussion we assume that \( X(t) \) increases over time at a constant rate "\( g \)”, so \( X(t) = Xe^{gt} \). As such, we define \( \lambda = r-g \), where \( \lambda \) is a net discount rate that accounts both for the increase in the social cost of carbon over time, and the effect of discounting on the emission value. Equation 4 can be written with \( \lambda \) in place of \( r \) (see Supplement Id).

Whereas the total carbon represented under the curve of Figure 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. This approach leads to a straightforward formula (Equation 5) for calculating the number of tons \( N \) required to be held for 1 year that has the equivalent economic value as 1 ton of “permanent” C sequestration, a formula that depends only on the time delay \( \tau \) and the net discount rate \( \lambda \) (see Supplement Id):

\[
N = \frac{1}{1-e^{-\lambda \tau}}
\]  
(Equation 5)

Economically, 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, and therefore the value of holding a ton of carbon out of the atmosphere forever. It then also represents the present value of the carbon rent on 1 ton, forever. When carbon is valued with the social cost of carbon and a time preference, we can address the essence of the short-term storage problem: What is the number of tons of carbon \( N \) that needs to be stored for \( \tau \) years to be equivalent to the storage of one ton forever (i.e. \( T=\infty \)), or for \( T \) years if there is an agreed upon time limit?

Note that Equation (5) does not depend on the exact dynamics of \( \text{CO}_2 \) 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 Figure 1). While this is a reasonable approximation for short time periods, longer-time comparisons are subject to substantial uncertainty. Equation (4) also illustrates that the number of tons, \( N \), decreases for a higher net discount rate \( \lambda \) and a longer time period over which the carbon is held in forests, \( \tau \). As a result, the value of short-term storage is greater the higher the discount rate.
The approach in equation (5) is equivalent to the carbon rental approach utilized in the integrated assessment model of Sohngen and Mendelsohn (2003)\textsuperscript{30}, although that study did not show the formulation in (5) which allows market participants to determine the exact number of tons N that need to be stored for \( t \) years to offset the value of 1 ton of permanent emissions. Here, we want to determine the number of tons of carbon that we store in forests, \( N \), whose present value when rented over the time the tons are stored equals the social cost of carbon. Starting from Equation 3, then:

\[
\text{SCC}(0) = N \int_0^T CR(0)e^{-\lambda t} dt
\]  
(Equation 6)

The Supplement section II shows how \( N \) can be derived from equation (6), and is the same \( N \) shown in equation (5). The formulation of \( N \) illustrates that any ton of carbon stored away from the atmosphere for any positive time period has value, and the longer it is stored the greater the value. 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 net discount rate, the measure of time preference as modified by the rate of growth in the price of carbon.

The issue of discounting for climate change problems like the one presented here has been widely discussed in the economics literature and a range of discount rates have been endorsed. In one of the most widely used integrated assessment models, the DICE model\textsuperscript{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\textsuperscript{43}). A recent study that incorporates uncertainty directly into an integrated assessment model calculates a lower discount rate for climate damages of 2.4\%\textsuperscript{44}. 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\textsuperscript{45}.

5. Time preference and short-term offsets

Recognizing that many calculations for the value of short-term storage are likely to be made over finite time intervals and in discrete time, we follow a specific example through the implication, with a spreadsheet available for readers and described in Supplement section III. Whereas the total carbon represented under the curve of Figure 1 is 53.07 ton-years, discounting the value of future atmospheric concentrations where \( X=1, r=5.0\%. g=1.7\% \text{ (i.e., } \lambda=3.3\% \text{) 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 total up to 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, at $\lambda = 3.3\%$ 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 (see Supplement 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. Figure 2a shows the relationship between the length of a delay in emissions and the number of tons delayed required to be economically equivalent to a permanent sequestration.
Figure 2a: The number of tons of emissions delayed for \( \tau \) 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. Figure 2b: 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, \( \lambda \).

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

Critically, 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.

6. Conclusions

Our analysis shows how to derive a simple closed-form solution for the number of tons N of CO\textsubscript{2} that must be stored temporarily to equate their value with the value of a ton of CO\textsubscript{2} emitted permanently. N is derived by properly valuing the carbon asset and recognizing that the value of short-term storage results from the benefits of delaying a release to the atmosphere. The benefit of delay only exists 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 and economically efficient ton-year metric that is consistent with economic valuation and integrated assessment modeling approaches. This means the approach can be used for carbon trading applications directly.

For instance, given the time preference embodied in the widely-accepted 100 year GWP, if \( \lambda = 3.3\% \), a one-ton “permanent” sequestration of carbon has a present value of 18.69 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, provides a present value benefit of \( 18.69 - 18.07 = 0.62 \) ton-years. The ratio 18.69/0.62 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. This result means that if a firm buys 30.1 tons of additional carbon stored for 1 year, these tons offset the impact of 1-ton of carbon emissions when \( \lambda = 3.3\% \).

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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. 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.

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