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Any integration of carbon dioxide removal (CDR) via enhancement of terrestrial or marine sinks into climate policy requires accounting for the provided climate benefits. We discuss different accounting methods to determine the climate benefits of potential temporary CDR projects. We show that, depending on the time profile of carbon storage, the application of methods which involve discounting, which are based on economic considerations, lead to more conservative climate benefits estimates than the net method which does not values time within the permanence period. However, determining the climate benefits of removal should not be confused with a crediting scheme, although ideally crediting should reflect the climate benefits. Issuing permanent credits based on the realised climate benefit through time results in low initial issuance of carbon credits and does not necessarily provide appropriate incentives for investors. An alternative would be to issue temporary carbon credits that expire after a certain period of time, allowing market forces to resolve various valuation issues. However, accounting methods cannot be assessed in isolation without considering the liability and governance framework in place.

Keywords: Carbon Dioxide Removal, Temporary Carbon Storage, Carbon Sinks, Carbon Accounting

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Accounting for terrestrial and marine carbon sink enhancement

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Abstract

Any integration of carbon dioxide removal (CDR) via enhancement of terrestrial or marine sinks into climate policy requires accounting for the provided climate benefits. We discuss different accounting methods to determine the climate benefits of potential temporary CDR projects. We show that, depending on the time profile of carbon storage, the application of methods which involve discounting, which are based on economic considerations, lead to more conservative climate benefits estimates than the net method which does not values time within the permanence period. However, determining the climate benefits of removal should not be confused with a crediting scheme, although ideally crediting should reflect the climate benefits. Issuing permanent credits based on the realised climate benefit through time results in low initial issuance of carbon credits and does not necessarily provide appropriate incentives for investors. An alternative would be to issue temporary carbon credits that expire after a certain period of time, allowing market forces to resolve various valuation issues. However, accounting methods cannot be assessed in isolation without considering the liability and governance framework in place.

1 Introduction

CO_2 emissions scenarios in line with ambitious temperature targets as set out in the Paris Agreement require to achieve net-zero emissions by the middle of the century, followed by a period of net-negative emissions (e.g., Rogelji et al., 2021). These emissions scenarios are projected to require a considerable amount of atmospheric carbon dioxide removal (CDR) to offset hard to abate CO_2 emissions of which a large share is supposed to be provided by nature-based solutions like ecosystem restoration and reforestation (IPCC 2022). However, enhancing carbon removal of terrestrial or marine ecosystems might only translate into temporary carbon storage since carbon cycle feedbacks, ecosystem degradation, events like fires and further natural and human disturbances could release part of the stored carbon back to atmosphere (Brander et al., 2021; Parisa et al., 2022). In turn, the question arises what is the value of temporary storage and corresponding offsets compared to avoided emissions (e.g., Groom and Venmans, 2023) and failing to properly resolve this question is considered a major obstacle for the required implementation of nature-based solutions to enhance atmospheric carbon removal (Parisa et al., 2022). This applies in particular to terrestrial, biological CDR, since about 99 percent of current, annual, intentional CDR of 2 $GtCO_2$ is achieved by the creation of new forests, restoration of previously deforested areas, increase in soil carbon, and use of durable wood products, such as panels and sawnwood used in construction (Smith et al., 2023).

To address the problems of potentially, temporary storage, various accounting methods have been proposed in the literature to assess the value of such CDR projects, i.e. the climate benefit or mitigation value of the removals. Note that carbon accounting to determine the climate benefit (or the mitigation value) of removal should not be confused with approaches to organize the crediting of carbon removal activities. Ideally, the former informs the latter about the number of credits, however, depending on the liability and governance framework, the organization of carbon credit issuance can differ from the derived climate benefit value assessment. The accounting methods to determine the climate benefit of removals differ how they assess the value of time (either explicitly by using a discount rate or implicitly by using a finite time period or a combination) and the climate benefit (either by restricting the comparison to physical properties or including also socio-economic aspects like avoided damages). These methods then provide information about the climate benefit of the storage project, usually expressed in units of CO_2.

As mentioned above, the CO_2 credit issuance might differ from the time profile of the carbon removal of the project. Certain credit issuance schemes foresee to assign only temporary credits, i.e. credits which have to be replaced at certain point in time, irrespective if the storage project is still in place or not (e.g., Sedjo and Marland, 2003; Marechal and Hecq, 2006). This would imply that despite a potential positive value, i.e. a positive amount of total carbon credits assignable, no permanent carbon credits are supplied. Another alternative is to withhold a certain amount of credits in some kind of buffer account which is suppose to compensate for carbon release from storage. Accordingly, different accounting methods and credit flow designs are appropriate for different policy constellations, in dependence of the liability framework, whether the liability is transferred with credit issuance, remains with the storage operator, or is provided by some third-party actor.

Here, we explain prominent accounting methods, accompanied with an implementation of the methods in R, apply these to removal time profiles of three ocean-based CDR methods obtained from model runs, and discuss credit issuance schemes.

2 Accounting methods to determine the climate benefit of temporary carbon storage

All accounting methods assign a value to time, either by explicit and continuous valuation like discounting or implicitly and discontinuously by considering a finite time horizon, i.e. a permanence period. Note that different permanence periods, such as 100 years, 30-100 years, 20-60 years, and 10-20 years, have been applied in different methodologies. For example, California's Global Warming Solutions Act requires a 100-year maintenance period, while the Voluntary Carbon Standard typically uses a cutting cycle of 30-100 years; the American Carbon Registry has a 20-year crediting period, which can be followed by another 20-year period, while the Family Forest Carbon Program has options with commitments of 10 or 20 years; additionally, there is an emerging approach offered by the Natural Capital Exchange that utilizes single-year deferral harvests, with commitment periods defined in 1-year increments (Galik et al., 2022). Note that these time or permanence periods are usually embedded in some kind of CO_2 credit issuance scheme; while for assessing the climate benefit usually a permanence period of 100 years is applied (UNFCCC, 1997).

We compare the different accounting methods by the climate benefit provided. Since the climate benefit is measured in physical units, we refer to this property as the "cap", i.e., the maximum number of carbon credits which "should" be designed to the project. The cap guarantees that the release of carbon in later periods is taken into account when calculating the maximum amount of carbon credits that can be generated according to the different accounting methods.

2.1 Net method

The net method does not distinguish between time with the 100 years. Let $carbon\ uptake\ stock_t$ be the stock of carbon uptake of a specific marine or terrestrial sink enhancement project at time point t belonging to the permanence period of 100 years. Thus, the last time point of that permanence period is $T = 100$. Moreover, $\Delta carbon uptake stock_t = carbon uptake stock_t - carbon\ uptake\ stock_{t-1}$ is the respective first difference i.e. the change of the carbon uptake stock over time.

$$Cap\_Net = \sum_{t=1}^{T} \Delta\ carbon\ uptake\ stock_t \tag{1}$$

The carbon cap referring to the net method is then the sum of the uptake change over time over the whole permanence period of 100 years (flow summation method, cf. Richard and Stokes (2004)). Under a strong liability scheme, credits can be awarded when carbon is stored (positive change) and required when carbon is released (negative change) (Rickels et al., 2010). Even though not CDR, the EU imlicitly applies this method in its CCS directive (EU, 2009) which requires that for physical leakage of CO_2 from a storage side, a corresponding amount of credits (i.e., in the case of the EU ETS called allowances) must be surrendered (i.e. without explicit reference to a permanence period).

2.2 Average method

The carbon cap referring to the average method is the sum of the stock change over time over the whole permanence period weighted by an average factor such that the uptake changes are decreasing over time compared to the net method. These time-averaged carbon stocks smooth out temporal carbon fluctuations (Kirschbaum et al., 2001). Thus, this cap reaches the average amount of carbon stored over the permanence period (Marland et al., 2001) and can be seen as a specific weighted flow summation method. This method implicitly assigns a further value to time within the time horizon of 100 years and therefore to avoided damage. While with the net method, a ton of carbon would need to be stored for 100 years, to have a positive carbon credit; the average method starts assigning a fraction of a full carbon credits if the storage period (of one ton of carbon) exceeds 50 years and starts increasing, though achieving a full credit also only for storage over 100 years.

$$Cap\_Average = \sum_{t=1}^{T} \left(\Delta\, carbon\ uptake\ stock_t \times \frac{T-(t-1)}{T} \right) \tag{2}$$

This cap is functionally equivalent to the one calculated with the Carbon Balance Indicator method described by Pingoud et al. (2016) when the permanence period is 100 years long.

2.3 Discount method

The carbon cap of the discount method is also a weighted sum of the uptake changes over time, but weighted by a discount factor referring to the social rate of time preference (*srtp*) such that future carbon fluxes is discounted to the present. As a result the respective uptake changes are also decreasing over time compared to the net method (Richard and Stokes, 2004; Thompson et al., 2009). This economic concept of explicitly including a time preference into an environmental assessment was introduced by O'Hare et al. (2009) and is discussed controversially in the literature. This cap again is a specific weighted (or discounted) flow summation.

$$Cap\_Discount = \sum_{t=1}^{T} \left(\frac{\Delta \; carbon \; uptake \; stock_t}{(1 + srtp)^{t-1}} \right) \tag{3}$$

The implicit damage assessment underlying the discount method can be related to the scientific impacts of CO_2 emissions. Sarofim and Giordano (2018) show that calculating global warming potentials (GWPs) of a time-scale of 100 years (which is the permanence period we consider) is consistent with a discount rate of 3.3 % (interquartile range of 2.7% to 4.1% in a sensitivity analysis). With such a discount rate, one tonne of CO_2 would need to be stored for 165 (200 to 133) years to earn a full credit (searching for the shortest permanence period to get the full credit defined as $Cap\_Discount = 0.995$).

2.4 Ton-year accounting methods

Ton-year accounting methods take the equivalence time into account when calculating carbon caps. Following Costa and Wilson (2000) the equivalence time is the storage time required to offset the global warming potential of one ton of carbon emitted into the atmosphere. Therefore, one ton of permanently stored carbon should be stored for this fix equivalence time. In other words the equivalence time is the sum (or the integral when considering continuous time steps) of all atmospheric carbon decay over the whole permanence period after a pulse of one ton carbon emitted into the atmosphere.

$$equivalence\, time = \int_{t=0}^{T} (carbon\, decay_t) dt \tag{4}$$

The full credit amount is offered when the carbon (measured in tons) is stored for the whole equivalence time (measured in years). Therefore, these methods are called ton-year accounting methods. The equivalence time depends on the behavior of atmospheric carbon decay over time. There are different suggestions in the literature of functional forms describing the atmospheric carbon decay pattern. One important model is the Revised Bern Model of Fearnside et al. (2000) which describes the carbon decay decreasing over time in a non-linear way. When applying this model the equivalence time takes about 46 years.

$$\begin{aligned} carbon\, decay_t^{(1)} = {} & 0.175602 + 0.258868 * e^{-0.292794t} + 0.242302 * e^{-0.0466817t} + \\ & 0.185762 * e^{-0.014165t} + 0.137467 * e^{-0.00237477t} \end{aligned} \tag{5}$$

An alternative model suggested by Joos et al. (2013) describes also a non-linear carbon decay decreasing over time, but yields a moderate longer equivalence time of about 52 years.

$$carbon\, decay_t^{(2)} = 0.2173 + 0.224 * e^{\frac{-t}{394.4}} + 0.2824 * e^{\frac{-t}{36.54}} + 0.2763 * e^{\frac{-t}{4.304}} \tag{6}$$

2.4.1 Moura-Costa-Wilson method

The carbon cap referring to the Moura-Costa-Wilson (MCW) method is the sum of the uptake stock in relation to the equivalence time, but only of that remaining permanence period fraction when the equivalence time is reached (cf. Costa and Wilson (2000)) because the permanence period exceeds the equivalence time. In other words the uptake stock is weighted by the fix equivalence factor, the reciprocal of the fix equivalence time. Using the MCW method the amount of carbon in the biosphere is tracked (cf. Rickels et al. (2010)).

$$Cap\_MCW^{(1)} = \frac{\sum_{t=T-equivalence\,time+1}^{T} carbon\ uptake\ stock_t}{equivalence\ time} \tag{7}$$

Alternatively the equivalence factor declines linearly over time to zero when the equivalence time is reached (by subtracting the amount of the equivalence factor at each time step) in order to treat all carbon fluxes consistently as suggested by Brãndao et al. (2013). Here, the change in carbon stock in the storage side over time is used. Using this alternative the uptake stock change is now weighted by a time-dependent equivalence factor. However, using this alternative the whole permanence period must be taken into account.

$$\begin{aligned} Cap\_MCW^{(2)} &= \sum_{t=1}^{T} \left(\Delta carbon\ uptake\ stock_t \times w_t\right) , \\ w_t &= \begin{cases} 1 - \frac{t}{equivalence\,time} , & \frac{t}{equivalence\,time} < 1 \\ 0 , & \frac{t}{equivalence\,time} \geq 1 \end{cases} \end{aligned} \tag{8}$$

An another alternative deals with a permanence period of 500 years in case that the respective carbon could be stored over this time period as suggested by Müller-Wenk and Brãndao (2010). Respectively the equivalence time must be adapted. Depending on the carbon decay pattern the equivalence time is about 147 years (cf. Fearnside et al. (2000)) or about 184 years (cf. Joos et al. (2013)) long. In any case the corresponding carbon cap takes again only into account the remaining permanence period fraction when the equivalence time is reached because of exceeding the equivalence time.

$$Cap\_MCW^{(3)} = \frac{\sum_{t=T-equivalence\,time+1}^{T=500} carbon\ uptake\ stock_t}{equivalence\ time} \tag{9}$$

2.4.2 Lashof method

Another ton-year accounting method is the Lashof method and was introduced by Fearnside et al. (2000) which assigns carbon credits dealing with the sum of all carbon decay after a carbon impulse (i.e. the integral of the respective carbon decay pattern) shifted beyond the permanence period. Thus, the full carbon credit amount can only be earned if carbon storage is successful until the end of the permanence period. There is the possibility of approximating the carbon decay pattern linearly. However, in this case the decay pattern is not accurately represented. Using the Lashof method the amount of carbon in the atmosphere is tracked (cf. Rickels et al. (2010)).

The respective carbon cap is the difference between the shifted and non-shifted integral because the respective initial portion within the permanence period without a shift falls now out of the permanence period and is excluded (cf. Brãndao et al. (2019)). In other words this cap is the sum of carbon uptake changes weighted by the inverse cumulative integrals of carbon decay in relation to the fix equivalence time.

$$Cap\_Lashof = \frac{\sum_{t=1}^{T} \left(\Delta carbon\ uptake\ stock_t * \int_{i=0}^{T-(t-1)} (carbon\ decay_i) di \right)}{equivalence\ time} \tag{10}$$

2.4.3 Combining ton-year accounting and discounting

The approach of Parisa et al. (2022) is to combine ton-year accounting methods and the discount method. They argue that accounting for stored carbon and the corresponding delayed emissions over time using the equivalence time should be also weighted by a discount factor. The discount factor values the delayed emissions economically because society has a time preference for the environmental impacts caused by emissions according to the social rate of time preference (cf. section 2.3). Due to the urgency in addressing climate change storing carbon today or in the near future should result in a higher value than storing carbon in the far future, even if the carbon is (partly) not permanently stored. Introducing discounting into ton-year accounting allows to drop the artificial permanence period of 100 years since postponing carbon emissions or leakage from storage has a lower valued fate in the atmosphere due to discounting. This can be seen in Table 1 which shows the benefits of delaying the emission of ton of CO_2 by 50 years in dependence of the permanence period. The example and the considered time horizons are based on Levasseur et al. (2012). The second column shows the climate benefits based on ton-year accounting with the Lashof method and the third column on discounted ton-year accounting following Parisa (2021) with a discount rate of 3 percent. The table shows that with "simple" ton-year accounting the climate benefit steeply drops if the permanence period is longer than the storage project and the climate benefits almost vanishes for a permanence period of 1000 years. In contrast, with discounted ton-year accounting the drop in climate benefit is smooth and even for a permanence period of 100 years a temporary storage project has a climate benefit.

Permanence period (year)	**ton-year (tCO_2**	**discounted ton-year (tCO_2**
20	1	1
50	1	1
100	0.3972	0.8000
250	0.1484	0.7721
500	0.0747	0.7719
1000	0.0382	0.7719

Table 1: Benefits of storing 1 tCO_2 over a period of 50 years calculated with ton-year accounting based on the Lashof method and with discounted ton-year accounting based on the Parisa appraoch for different choices of time horizon.

We apply the Parisa et al. (2022) approach in its basic specification; even though it does not differ in this specification from the discount method since in UNFCCC (2023) this approach is also discussed in detail with different combinations of discount rates, permanence periods and storage periods. Note that the authors also suggest to include in addition to the value of time the possibility to include an economic value assessment with the social cost of carbon.

2.4.4 Ecosystem-dynamics specific extensions

The above mentioned ton-year approaches can be supplemented with ecosystem dynamics to track the fate of carbon in the stored ecosystem. Sierra et al. (2021) propose an approach where the age and residence time of carbon in ecosystems is explicitly considered and modelled in the case of stored carbon, i.e. sequestration, as opposed to approaches using global warming potentials or tonne-year accounting methods, which use, for example, some sort of delayed release of carbon into the atmosphere. Without modelling the ecosystem and its characteristics in which the carbon is stored, the respective dynamics and respiration of the stored carbon back into the atmosphere are ignored (or abstracted) when developing a carbon accounting metric. Sierra et al. (2021) applies this in combination with the terrestrial ecosystem model (TECO) for the Duke Forest in North Carolina. Their ecosystem-specific treatment is discussed in the Appendix.

3 Implementation into R

For the numerical comparison of the different accounting methods in assigning the climate benefit of temporary carbon storage, we have implemented the methods for calculating the corresponding carbon caps into R.

First, the respective raw data i.e. time series of first differences of carbon uptake stock data (.csv file, information of carbon changes in columns, headers in first row of every time series) must be imported into R. Here, one data point is the carbon uptake stock change in one specific year of the permanence period. In this implementation one column of carbon uptake stock change with a permanence period of 100 years is used, except for the discounted ton-year approach. The filepath as well as the filename of the input data have to be adjusted accordingly such that the input data can be imported into R. While data manipulation such as carbon uptake stock data is necessary other data manipulation can be useful such as creating time indices (counted in yearly time steps).

The carbon caps, i.e. the climate benefit or mitigation value, are explained below. The carbon cap of the net method is simply given by the carbon uptake stock in the last year of the permanence period i.e. the accumulated carbon uptake. Alternatively, one could also sum up the carbon uptake first difference time series as described in equation (1).

The carbon cap of the average method is the sum of carbon uptake first differences weighted by the average factor as described in equation (2).

The carbon cap of the discount method is the sum of carbon uptake first differences now weighted by the discount factor as described in equation (3). Furthermore, the value of the social rate of time preference has to be specified by choosing a respective parameter. In this implementation a rate of 3 % is used.

When using ton-year accounting methods first the functional forms of the carbon decay pattern must be calculated. In order to do so the corresponding carbon decay equations as described in equations (5) and (6) could be implemented into R by creating functions with yearly time steps as the independent variables. Furthermore, the respective fix equivalence times could then be created as parameters by calculating the integrals of these two decay functions over the whole permanence period. In this implementation the carbon decay pattern suggested by the Revised Bern Model of Fearnside et al. (2000) is used leading to an equivalence time of about 46 years; with discounting the equivalence time shrinks to about 19 years.

The carbon cap of the MCW-1 method is now the sum of the respective fraction of the carbon uptake stock data divided by the equivalence time as described in equation (7). Alternatively, one could create new time series by computing uptake stock data multiplied by the fix equivalence factor and sum then up the corresponding fraction of these time series in order to calculate the carbon cap.

The carbon cap of the MCW-2 method is the sum of the carbon uptake first differences weighted by the time-dependent equivalence factor as described in equation (8). Therefore, additional time series describing the time-dependent weights as stated in equation (8) have to be created. Afterwards the uptake stock first differences have to be multiplied by these weight time series leading to the respective carbon cap by summing up these combined time series.

The carbon cap of the MCW-3 method is nearly the same as the one of the MCW-1 method. The only difference is the longer permanence period of 500 years. Thus, applicable carbon uptake stock data is needed and the equivalence times have to be adapted accordingly (cf. equation (9)).

When creating the carbon cap of the Lashof method the cumulative integrals of the carbon decay function as described in equation (10) are needed first by creating corresponding additional time series. Afterwards, carbon uptake stock first differences multiplied by these time series in reversed order have to be computed. The carbon cap of the Lashof method is then the sum of these combined time series divided by the equivalence time.

In addition we created the carbon cap of the combined ton-year accounting and discounting approach. First, a matrix containing the carbon decay over time (in each row) caused by a pulse of emission is created. Each column represents the delayed starting decay depending on when (after how many years) carbon is released i.e. when carbon decay starts. Before starting zeros are given. The first column assumes initial release i.e. no delay. Thus, the first element in this column represents initial carbon release in year zero i.e. no decay i.e. a factor of one. Here, a permanence period of 1000 years (must be equal to the number of rows) is used. In the last year (last row) the carbon decay in year 999 is given when carbon is initially released (first column). When using this matrix structure the number of columns must be equal to the number of carbon uptakes each year (here 100). The last column of this matrix contains zeros for years zero to 98. In year 99 the carbon release starts (factor of one). After creating this matrix each decay structure (delayed or not delayed) is multiplied by the corresponding discount factor over time. Therefore, each column of the matrix is multiplied by the discount factor at each point in time i.e. in each row (same discount factor for each column at the same point in time). Again a discount rate of 3 % is used. Now, a new time series containing the product of the sum of each discounted carbon decay structure (the sum of each column of the matrix stated above starting with initial carbon release i.e. first column) multiplied by the corresponding carbon uptake first differences over time is created. The cap referring to the ton-year-discounting approach is then the sum of this created time series divided by the sum of the discounted carbon decay structure with initial release as a reference scenario (i.e. the sum of the first column of the stated matrix which is the discounted equivalence time).

Given input data file, describing the carbon stocks in the targeted reservoir due to the enhancement activity, the R file calculates the various Caps (.xlsx output file). The R package "writexl" must be installed and loaded before exporting the output file. The filepath as well as the filename of the output file have to be adjusted such that the file is saved into the desired folder.

4 Comparsion of assigned climate benefits by different accounting methods

To show the implications of the different accounting methods we consider three ocean CDR projects with different time profiles: i) short-term ocean iron fertilization (OIF) in the Southern Ocean for one year as described in Oschlies et al. (2010), ii) continuous open-ocean magroalgae mariculture and sinking (MOS) as described in Wu et al. (2023), and iii) continuous ocean alkalinity enhancement (OAE) of the European coast obtained from David Keller[1]. For all three ocean CDR projects we track the change in the carbon stock of 100 years, i.e. implicitly assuming that there are no further changes in the carbon stock beyond the time horizon. Certainly, the discounted ton-year approach with a time horizon of 1000 years would allow tracking further changes in the carbon storage stocks, however, preventing comparison to the other accounting methods. The considered OIF scenario is interesting since its time profile is similar for afforestation projects for which the accounting methods were designed in the first place, but with as faster ramp up of the carbon storage than in afforestation projects. The considered MOS scenario is interesting since the project initially starts with a carbon deficit, i.e., the stock change is initially negative. This can be explained as follows. First,

[1]obtained via personal communication

macroalgae is seeded everywhere (for model mass balance purposes the C,N, and P in the biomass is taken from the ocean stocks), but cannot grow everywhere; thus, in the initial years there is a lot of C uptake that is rapidly turned back into dissolved inorganic C and can leave the ocean again as the unsuccessful macroalgae dies and is not replaced. Second, when macroalgae is planted everywhere it shades natural phytoplankton populations and competes with them for nutrients, leading to a decrease in the biological pump and ocean C uptake. Only after macroalgae has established itself in regions where it will be successful does it start to sequester a lot of C via artificial sinking. By this time natural phytoplankton populations have also recovered, although the amount of C they sequester continues to be different due to the large-scale macroalgae farms. The OAE experiment is then a continious and permanent increase in the carbon stock. Note that the OSM scenario exceeds the other scenarios by a factor of 10 since Wu et al. (2023) investigated maximum sink potential of this method. For our comparison the time-profile matters but not the level of the uptake, accordingly we scale the OSM scenario by a factor of 10 to have straightforward comparison of the scenarios. Figure 1 shows in the left panel the carbon storage stock over time for the three ocean CDR scenarios and in the right panel the corresponding climate benefits resulting from these storage profiles according to the different accounting methods.

The net method does not assign any value to temporay storage and in turn, the carbon benefit is restricted as expected to the net removal. The other methods assign value to temporarily removing carbon from the atmosphere and in turn their removal benefit is higher than with the net method for time-profiles with initial high carbon uptake. However, for time profiles where initially uptake is low or even negative, it is the other way around. While the net method accounts by definition only for the net change over 100 years, i.e. negative removal in initial years can be compensated by higher uptake later, the other methods account for these kind of “foregone” benefits in early years. Accordingly, while methods like the discount method have been criticized in particular based on storage profiles as realized with OIF, the comparison with other storage profiles show that then these methods

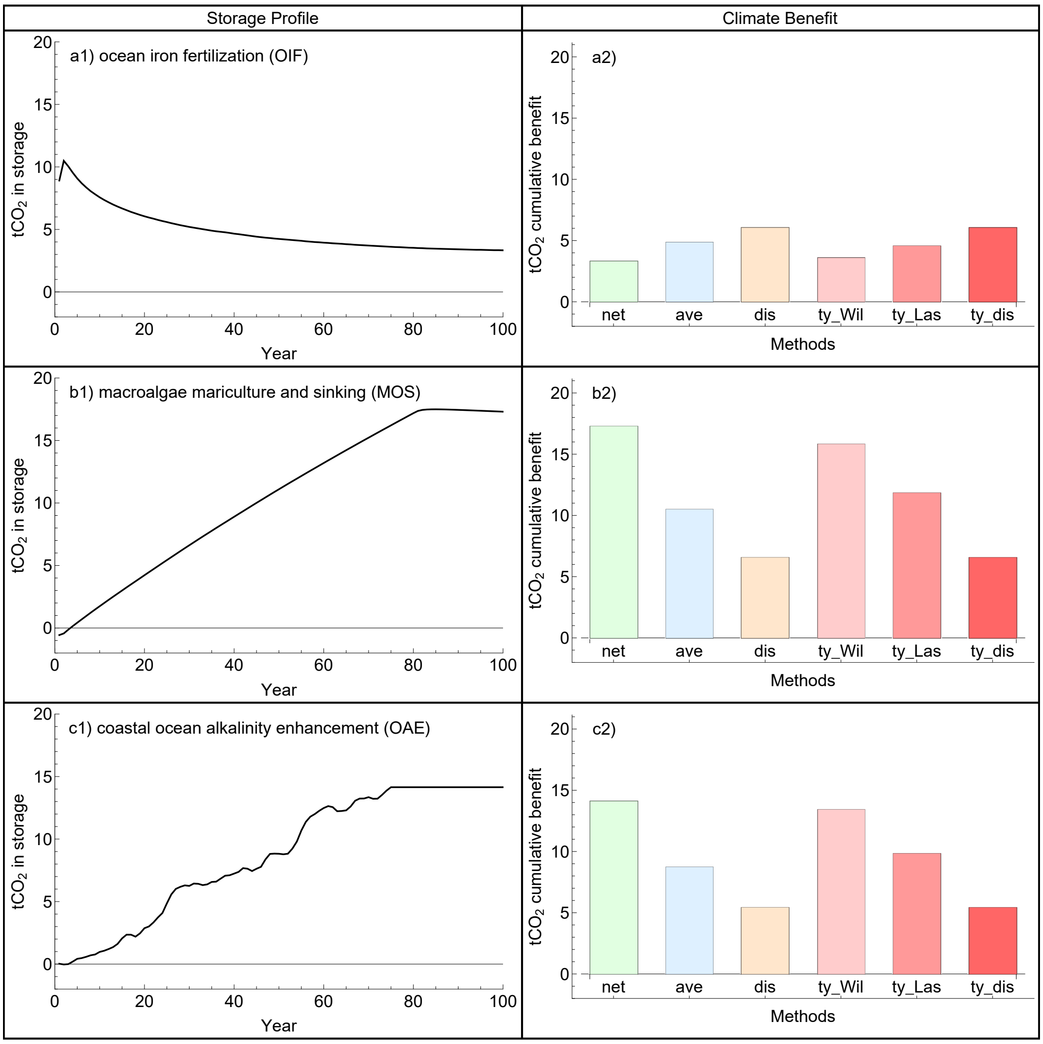

Figure 1: Carbon storage profile and cumulative climate benefits. The left panel shows the stoarge profile for three ocean-based CDR methods and the right panel the cumulative climateb benefit for the net method, the average (ave) method, the discount (dis) method, and for ton-year accounting (ty), with the Wilson (Wil) method, the Lashof (Las) method, and the discounted (dis) ton-year method.

become more conservative compared to the net method.

5 Organizing credit issuance

For potential temporary storage projects, the credit issuance should be restricted to provided climate benefits and credits can be issued depending on how the climate benefit develops over time in case the storage is still in place. Accordingly, to derive the amount of credits, one assumes that storage has only taken place up to the current time period. To demonstrate the credit issuance across the different accounting methods, we consider an artificial storage project which stores $10tCO_2$ for 100 years (i.e., the permanence period). Figure 2 shows the credit issuance over time for the different methods, indicating that credit issuance is increasing slowly and full credit issuance of $10tCO_2$ is not achieved before the end of the permanence period. For the net method, this means that no credits would be issued before the end of the permanence period.

Such kind of ex-post crediting provides only small incentives for commercial removal projects and in turn ex-ante crediting, where credit issuance is based on the expected climate benefits, provides an alternative. With a perfect liability regime in place, the credits representing the expected climate benefits could be issued in advance; any leakage of the stored carbon would require to surrender an equivalent amount of other carbon credits. Consider the previous example with $10tCO_2$ storage. With the net method, carbon credits equivalent to $10tCO2_2$ would be issued in exchange for removing the $10MtCO_2$ (in the example in the first year), subsequent leakage of some or all of the stored carbon would require to surrender an equivalent amount of credits. Obviously, such a liability regime is difficult to establish, in particular under international carbon credit trading. Accordingly, different schemes are possible for credit issuance to manage liability for leakage of stored carbon.

One scheme involves to address leakage with some kind of insurance. The insurance operates either financially, i.e. a certain amount of the revenues are set aside to allow buying other carbon credits in case of carbon leakage or physically, i.e., a certain amount of the credits from the project are

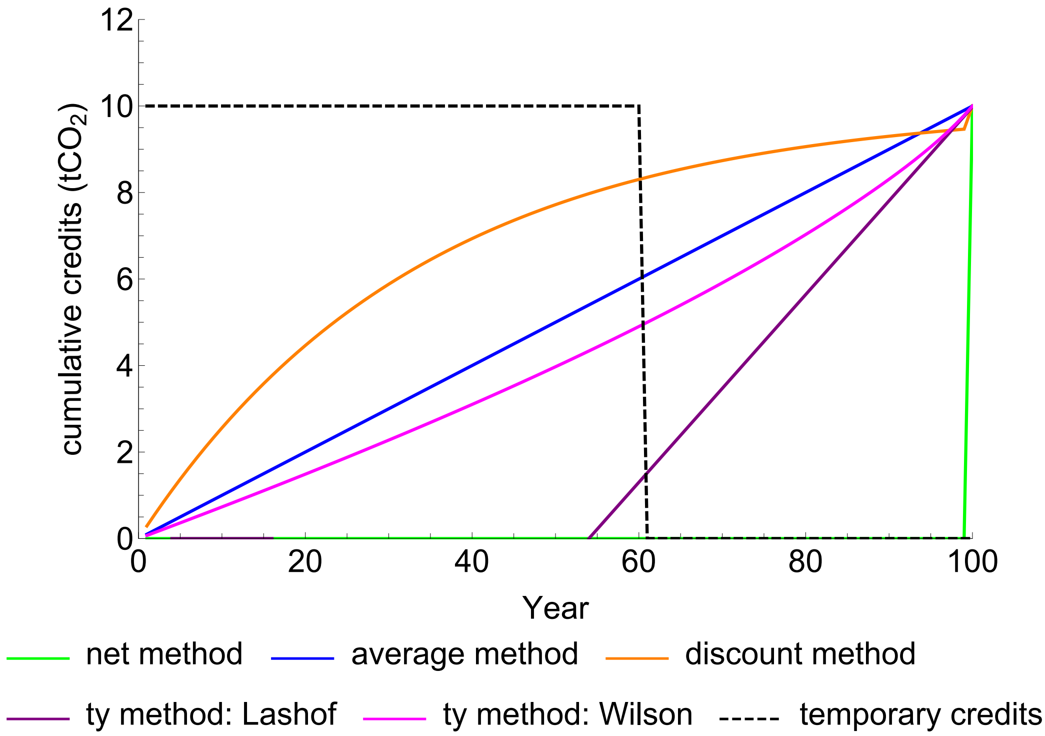

Figure 2: Cumulative amount of CO_2 credit issuance through time for idealized storage project

transferred to a reserve and released in case of leakage (Subak, 2003). Note that reserve or buffer pools are not intended to compensate for planned leakage since these are supposed to be considered in the accounting method but for unintended leakage. Having a joint buffer account for various projects allows for risk management, i.e. reducing the overall default risk by properly picking projects and minimizing therefore the size of the buffer account. The latter is in the interest of the operator (either the removal provider or a market intermediary) since the credits in the buffer account are not sold and reduce the revenues. However, missing proper portfolio management can result in cluster risk. Apparently, this is the case for buffer accounts for the California cap-and-trade program which allows for removal credits achieved via afforestation (Badgley et al., 2022). Currently, there appears to exist no active portfolio management for the buffer account and the possibility to reduce overall leakage risk by including for example ocean-based removals which is not correlated in its leakage risk with land-based removal methods is not yet exploited.

Insurance schemes and buffer accounts become active upon leakage, issuance of temporary credits consider carbon leakage as default. Hence, the credits have to replaced. However, issuance of temporary carbon credits is not a fixed scheme and various design options are possible. Temporary carbon credits can be mixed with permanent credit issuance: only those carbon credits which exceed the net amount of storage have to replaced or temporary credits can be turned into permanent credits upon approval that the stored amount of carbon is still in place.

In principle temporary credits expire after a certain period and need to be replaced. Dutschke (2002) proposes a leasing approach where ton-year accounting methods and temporary credit methods are combined for crediting forest carbon sink. Temporary credits are issued for a commitment period but are also accounted for by using an underlying atmospheric carbon decay pattern and the corresponding equivalence time. After the commitment period the carbon is considered to be stored permanently. This approach has many advantages such as making carbon "sequestration and reduction by conservation an asset with a defined value and lifetime". Murray et al. (2007) discusses temporary credits considering the non-permanence issue (among other issues) of agricultural soil carbon sequestration activities. They state that this issue will reduce the value of temporary credits compared to the credit value for avoided emissions. However, under specific assumptions (such as relatively long time horizons of temporary credits and a rapid technology improvement) temporary credit prices can evolve in such a way that the temporary credit value can achieve a significant fraction of a full credit value.

Galik et al. (2022) investigate new approaches issuing temporary credits for forest carbon offsets with reduced commitment periods as well as reduced measurement, monitoring, and verification costs. These reduced costs should "improve participation rates among forest landowners and land managers". The time periods of these approaches for offsetting carbon range from 100 years to very small time lengths. The Natural Capital Exchange utilizes single-year deferral harvests. Galik et al. (2022) analyze the influence of accounting on net mitigation within these approaches using hypothetical offsets and accounting methods using three different annual factors: Decay factors referring to remaining emissions in the atmosphere following a pulse of removals, additional discount factors and factors referring to standard ton-year accounting methods (100 year time horizon). The decay and discount factors are taken from Parisa et al. (2022). Moreover, when using both decay and discount factors the methodological approach is similar to the combined ton-year accounting and discounting approach of Parisa et al. (2022) presented in section 2.4.3. The annual ton-year factors are taken from Parisa (2021). Galik et al. (2022) find that applying annual decay factors or these factors combined with additional discount factors provide the largest net reductions in the early years of the projects. However, the annual decay factors (without discounting) and the annual ton-year factors tend to be the most consistent approaches across varying parameters such as timelines, forest types or project configurations.

However, as mentioned above, it is possible to require that all credits from removal projects need to be replaced at some point in time (Dornburg and Marland, 2008). Such an approach ensures that no additional carbon emission will be released, because all credits have to be replaced at some point in time, even permanently stored carbon so that the application of temporary carbon credits provides extra climate benefits as the atmospheric carbon concentration is reduced compared to a situation with emission reductions only (Rickels et al., 2010). In principle, one could argue that under such a scheme the full liability for the carbon storage is transferred to the buyer, i.e. who needs to replace the removal irrespective of the fate of the stored carbon. However, from the perspective of the storage operator, knowing that the credits will be replaced anyway irrespective of the fate of the stored carbon does not result in appropriate incentives to maintain the carbon storage in place. This can be addressed by a limited possibility of renewing temporary carbon credits such that the storage operator has incentives for appropriate project maintance.

Under the Clean Development Mechanism (CDM) of the Kyoto Protocol, assignment of temporary credits was possible to afforestation projects: temporary or long-term certified emission reductions (tCERs or lCERs). Temporary certified emission reductions (tCER) are valid for a fixed period of time, until the commitment period after the commitment period they have been issued. However, they can be renewed if the carbon storage is still in place, limited to the length of the crediting period, i.e. 60 years. Long-term certified emission reductions (lCER) are also valid for a fixed period of time, the overall crediting period, but cannot be renewed, even in case of still stored carbon. These credits expire at the end of the crediting period (UNFCCC, 2003). These consideration already show various design options temporary credits are possible, in particular resulting from the possibilities regarding the length of the expiry period (Subak, 2003).

To demonstrate the implications of temporary crediting issuance scheme we consider again the stylized example with permanent removal of 10tCO_2. Assuming commitment periods of 5 years and total crediting period of 60 years, temporary credits would need to replaced in the commitment period after the crediting period. The dashed line in Figure 2 shows the credit issuance with temporary credits (assuming the tCER specification with a maximum period for renewing credits for 60 years). Obviously, here the full amount of credits are available up front and the valuation of temporary credits are resolved by the market. Since the temporary credits have to be replaced in the future, the owner or user of these credits can decide in dependence on the trajectory of CO_2 prices for emission reductions or permanent removals when to replace the temporary credits and it which price he would be willing to buy them in comparison to permanent removals.

6 Conclusion

We discuss various accounting methods which can be applied to determine the climate benefit of potential temporary carbon removal projects. The determination of the climate benefit of removal should not be confused with a credit issuance scheme, however, the credit issuance should ideally reflect the climate benefit. While on a first view, the net method seems to be appropriate to determine the climate benefit since it only assigns value to permanent storage, the application to ocean-based CDR with a slow or initially negative uptake reveals that the net method might overestimate the climate benefits. For the considered storage profiles observed under model-based ocean CDR methods like magroalgae mariculture and sinking or alkalinity enhancement, methods which explicitly account for the value of time, like the discount method, assign a lower climate benefit than the net method. Methods like the discount method account for the small or negative climate benefits in the early years. Accordingly, applying methods like the discount method which are based on economic considerations, result in more conservative climate benefits than the net-method.

Yet, credit issuance in dependence of the realized climate benefit results in low initial issuance of carbon credits and is not necessarily providing appropriate incentives for investors. An alternative would be the issuance of temporary carbon credits which expire at a certain amount of time. Including the option of renewal given that the stored carbon is still in place, provides appropriate incentives for storage operators for project maintenance. Furthermore, various valuation methods are transferred to the market participants who decide about the discount relative to the price for emissions reductions or permanent removals and at which point they want to replace the credits. While methods as discussed by Groom and Venmans (2023) require some assumptions about the trajectory of future emissions, temperatures and in turn the social cost of carbon (SCC), these valuation issues are resolved by market forces with temporary credits. Accordingly, a worsening of climate change (i.e. a stronger increase in the SCC) would result in an earlier replacement of temporary credits.

However, our analysis does not identify a specific accounting method which is suited best for assigned carbon credits to temporary storage projects since the accounting methods cannot be assessed in isolation without the liability and governance framework in place. For example, a strong liability framework as it is provided within the effort-sharing regulation of the EU where the states implicitly have the liability for the stored carbon allows for a more generous accounting of temporary carbon removal since impermanence (i.e. unintended leakage of stored carbon) would occur as debit in the land-use, land-use-change, and forestry (LULUCF) accounts (for the case of afforestation). On the other hand, with a transfer of the liability to the buyer of the credit, for example as part of the implementation of Article 6.4 of the Paris Agreement, a more cautious accounting method appears appropriate. This can also be addressed within the issuance of temporary carbon credits. While the analyzed accounting methods aim to determine the "value" of the storage project (in terms of total credits), the issuance of credits (i.e. the flow of credits) provides further means to deal with impermanence of carbon removal.

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Appendix

Ecosystem-specific estimation of climate benefits

Sierra et al. (2021) define carbon sequestration (CS) as the integral of an amount of carbon removed from the atmosphere stored over the time horizon it remains within an ecosystem. With this definition a metric regarding the climate benefit of sequestration (CBS) can be developed. This metric quantifies the radiative effect of temporary stored carbon in an ecosystem before carbon is released back into the atmosphere as a result of respiratory processes and disturbances. Thus,

$$CS(T, S_0, t_0) = \int_{t_0}^{t_0+T} M_s(t - t_0)dt \quad (11)$$

with $M_s(t-t_0)$ representing the fate over time t of stored carbon S_0 taken up by the corresponding ecosystem at time t_0 up to T. This fate leads now to the modelling of ecosystems. To do so Sierra et al. (2021) use the theory of compartmental dynamical systems. When modelling the ecosystem $r(t)$, carbon release at time t, is also modelled.

The stored carbon over time i.e. carbon sequestration is a form of negative emission and its fate in the atmosphere can be described as:

$$M_a'(t) = -h_a(t - t_0)S_0 + \int_{t_0}^{t} h_a(t - \tau)r(\tau)d\tau \tag{12}$$

where the prime symbol stands for a perturbed atmosphere i.e. negative fate. $h_a(t - t_0) = carbon\ decay^{(4)}_{t-t_0}$ is the impulse response function of atmospheric CO_2 released into the atmosphere (cf. section 2.4). Hence, the negative term in equation (12) represents the response of the atmosphere to a sequestration S_0 at t_0. The positive term in equation (12) represents the perturbation in the atmosphere of the carbon returning back from the ecosystem.

Sierra et al. (2021) define now the climate benefit of carbon sequestration as:

$$CBS(T, S_0, t_0) = \int_{t_0}^{t_0+T} k_{CO_2} M_a'(t)dt \tag{13}$$

where k_{CO_2} is the radiative efficiency or greenhouse effect of one unit of CO_2 in the atmosphere (assumed to be constant over time). The climate benefit of carbon sequestration can be interpreted as the whole atmospheric response to carbon sequestration during a specific time horizon taking both the carbon uptake out of the atmosphere as well as the carbon release back into the atmosphere over time into account.

Sierra et al. (2021) apply this climate benefit metric using a simple ecosystem carbon model, the terrestrial ecosystem model (TECO). This model is assumed to be linear reaching an equilibrium state (steady state) over time when sequestration takes place. Hence, it plays no role when the sequestered carbon enters the system. Thus, $a = t - t_0$ describes these arbitrary point in time. The TECO model describes the dynamics of carbon at a temperate forest dominated by loblolly pine. It contains eight carbon pools $x_i, i = 1, ..., 8$ implemented in the vector $\mathbf{x}$: foliage, woody biomass, fine roots, metabolic litter, structural litter, fast soil organic matter, slow soil organic matter and passive soil organic matter. Using the theory of compartmental dynamical systems the dynamics of the carbon pools due to sequestration can be described by the following linear differential equation system:

$$\frac{d\mathbf{x}(t)}{dt} = \mathbf{u} + \mathbf{B}\mathbf{x} \tag{14}$$

$\mathbf{u} = \mathbf{b}U$ is a vector of carbon inputs determining the annual constant input U (instantaneous uptake at any given time) to each carbon pool by using the vector of allocation coefficients $\mathbf{b}$.[2] The matrix $\mathbf{B} = \mathbf{AC}$ represents the dynamics and interrelations of the carbon pools by using the matrix $\mathbf{C}$, a diagonal matrix with cycling rates for each pool, and the matrix $\mathbf{A}$, a matrix of transfer coefficients among pools (constant cycling rates i.e. no other changes in the environment are assumed).

We illustrate the TECO application by recreating central results using Mathematica implemented in "Replication_TECO model".[3] Figure 3 shows the fate of a pulse of carbon input entering the TECO system at an arbitrary time when the ecosystem is in a steady state. The carbon fate can then be calculated as follows:

$$M_s(a) = ||\mathbf{e}^{a\mathbf{Bu}}|| \tag{15}$$

where $\mathbf{e}^{(.)}$ denotes the matrix exponential and $||(.)||$ denotes the sum of the absolute values of all elements in a vector. Using this ecosystem respired carbon can be calculated as follows:

$$r(a) = -\mathbf{1^T}\mathbf{B}\mathbf{e}^{a\mathbf{Bu}} \tag{16}$$

where $\mathbf{e}^{(.)}$ denotes again the matrix exponential and $\mathbf{1^T}$ is the transpose of a vector containing only 1s. Carbon enters the ecosystem through the foliage,

[2] Uptake of 12.3 Mg C per ha corresponding to the annual amount of photosynthetically fixed carbon predicted by the model in this forest (GPP).

[3] The Mathematica-script can be assessed at x.

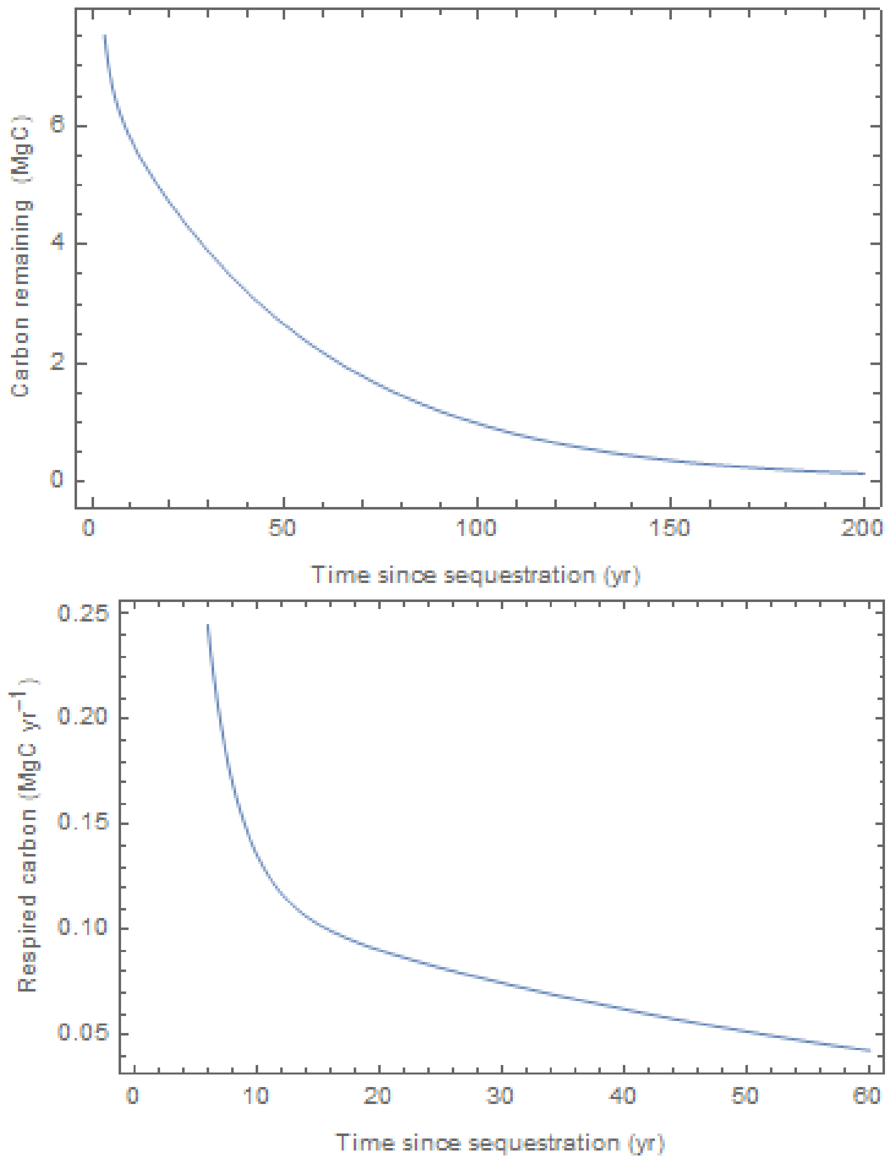

Figure 3: Fate of carbon $M_s(t)$ (upper panel) and respired carbon $r(t)$ (lower panel).

wood, and fineroot pools. Most carbon is quickly transferred to the fine and metabolic litter pools. Afterwards, the carbon moves to the remaining pools and during this transition lots of respiration losses take place. As a result most of the carbon is returned back to the atmosphere with a transit time of 30.4 years meaning that half of the sequestered carbon is returned back to the atmosphere in 7.6 years.

The carbon sequestration (CS) of this ecosystem is now the integral of the fate of the stored carbon depending on the time horizon i.e. the integral of $M_s(t)$ (upper panel) in figure 3 (cf. equation (11)). In this ecosystem where a steady state can be reached CS can be calculated as:

$$CS(T) = ||\mathbf{B}^{-1}(\mathbf{e}^{T\mathbf{B}} - \mathbf{I})\mathbf{u}|| \tag{17}$$

where $\mathbf{e}^{(\cdot)}$ denotes again the matrix exponential, $\mathbf{B}^{-1}$ is the inverse of $\mathbf{B}$, $\mathbf{I}$ is the identity matrix and $||(.)||$ denotes again the sum of the absolute values of all elements in a vector. The upper panel in figure 4 shows increasing ecosystem-level CS with increasing time horizon. For a time horzion of 200 years, where almost no carbon remains in the ecosystem (cf. (upper panel) in figure 3), ecosystem-level CS reaches almost the steady-state carbon stock (373.67 Mg C per ha when the time horizon goes to infinity).

The climate benefit of sequestration (CBS, lower panel in figure 4) integrates the fate in the atmosphere (cf. equation (12)) multiplied by the radiative efficiency (cf. equation (13)) depending on the time horizon. The impulse response function for atmospheric carbon $h_a(t - t_0)$ is taken from Joos et al. (2013) regarding the present-day curve (PD100) for illustration purposes:

$$\begin{aligned} carbon\ decay_a^{(3)} = h_a(a) = 0.2173 * e^{\frac{-a}{1.000.000}} + 0.224 * e^{\frac{-a}{394.4}} + \\ 0.2824 * e^{\frac{-a}{36.54}} + 0.2763 * e^{\frac{-a}{4.304}} \end{aligned} \tag{18}$$

Most carbon is in sum taken out of the atmosphere for a time horizon of about 100 years (i.e. highest benefit). For longer time horizons the sum of removed carbon decreases due to respired carbon out of the ecosystem over time. However, in the long run the sequestered carbon taken out of the atmosphere at an arbitrary starting point in time outweighs the effect of released carbon back into the atmosphere (i.e. overall benefit).

The CS and CBS metrics of Sierra et al. (2021) provide a new component

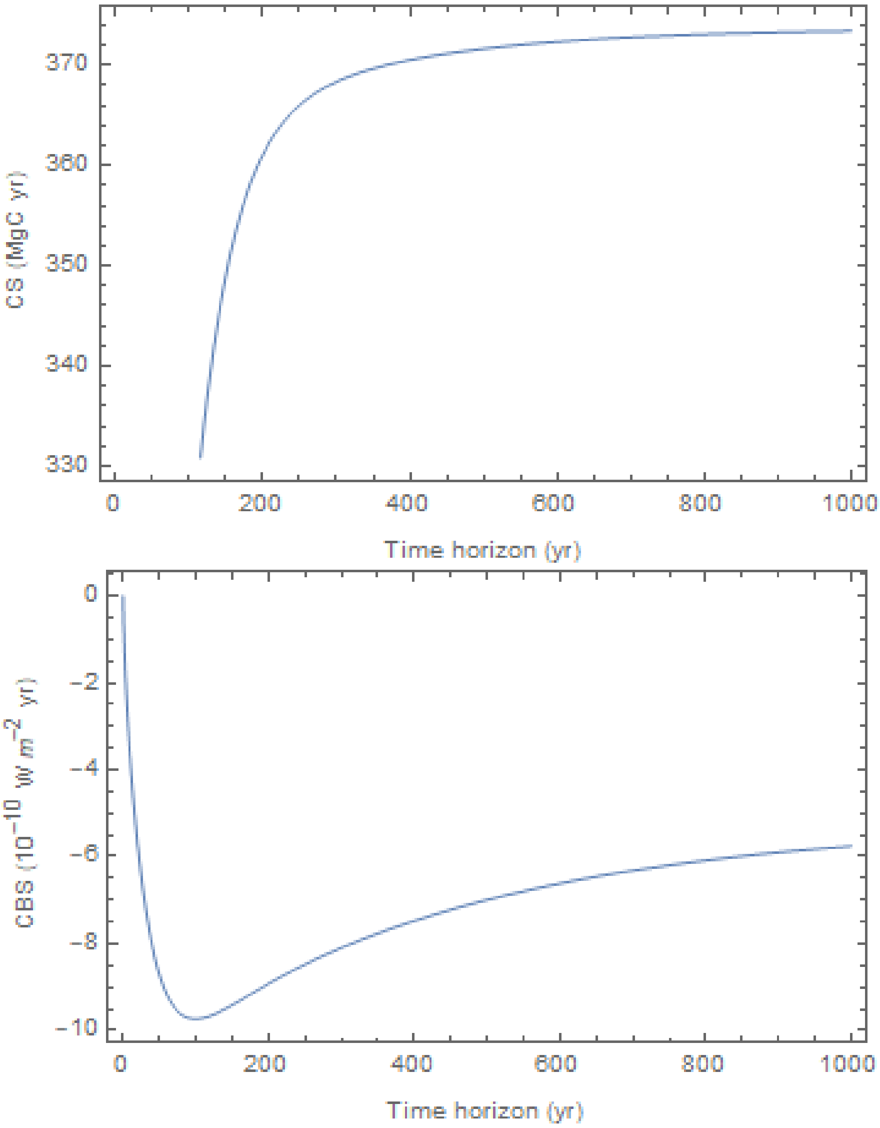

Figure 4: Carbon sequestration (CS) (upper panel) and climate benefit of sequestration (CBS) (lower panel) for instantaneous carbon uptake at any given time.

regarding carbon accounting by explicitly modelling the ecosystem and the transit time of carbon after a carbon impulse. Thus, these metrics are improvements in contrast to those treating all carbon removals equally (when not modelling the ecosystem). The CBS metric can directly compare quantified climate benefits of sequestration with climate impacts of emissions on a similar time horizon and, therefore, addresses the non-permanence issue more accurate. However, besides the problem of assuming an impulse response function for atmospheric carbon as in section 2.4 the CS and CBS metrics need also modelling assumptions about the ecosystem of interest.

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