Ocean-based Negative Emission Technologies

OCEAN NETs

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Abstract: Any integration of extra carbon dioxide removal (CDR) via terrestrial or marine sink enhancement into climate policies requires accounting for their effectiveness in reducing atmospheric carbon concentration. Different accounting methods have been introduced to quantify the impacts of sink enhancements. Here, we provide a manual for the different accounting methods, accompanying the implementation of the accounting methods in a R-file which is free for download. Hence, the material allows applying the different accounting methods and for demonstration purposes we provide a numerical example.

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1. Introduction

1.1 Context

OceanNETs is a European Union project funded by the Commission's Horizon 2020 program under the topic of Negative emissions and land-use based mitigation assessment (LC-CLA-02-2019), coordinated by GEOMAR | Helmholtz Center for Ocean Research Kiel (GEOMAR), Germany.
OceanNETs responds to the societal need to rapidly provide a scientifically rigorous and comprehensive assessment of negative emission technologies (NETs). The project focuses on analyzing and quantifying the environmental, social, and political feasibility and impacts of ocean-based NETs. OceanNETs will close fundamental knowledge gaps on specific ocean-based NETs and provide more in-depth investigations of NETs that have already been suggested to have a high CDR potential, levels of sustainability, or potential co-benefits. It will identify to what extent, and how, ocean-based NETs can play a role in keeping climate change within the limits set by the Paris Agreement.

1.2 Purpose and scope of the deliverable

The Deliverable is part of Task 1.1: Assessing carbon accounting schemes (which leads to D1.1 and D1.2) with the aim to quantify possible amount of carbon credits obtained by the various ocean NETs analyzed in WP4 by implementing them in a common numerical modelling framework (D1.1). As specified in the Grant Agreement D1.1 is intended to be a "Working paper on the numerical modelling framework to compare different accounting schemes". Thus, in practice this is a technical description of the modelling framework. D1.1 is supposed to assist other WPs in quantifying their output in terms of carbon credits and the working paper is supposed to explain the implemented accounting methods, implemented in R.

1.3 Relation to other deliverables

D1.1 is leading to D1.2., which is a "Report on appropriateness of accounting schemes to assign carbon credits to ocean NETs".

2. Technical part of the deliverable

For the numerical comparison of the different accounting methods in assigning carbon credits, we have implemented the methods into R. The R file is available here: https://www.oceannets.eu/milestones/

3. Conclusion

The review of existing accounting methods clearly shows that so far, the focus has been on projects with temporary storage since the majority of projects involved afforestation. For ocean CDR projects, and in particular ocean alkalinity enhancement, a major obstacle will be the verification of storage. Currently, there are no accounting methods available properly dealing with this issue.

Accounting for terrestrial and marine carbon sink enhancement

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Abstract

Any integration of extra carbon dioxide removal (CDR) via terrestrial or marine sink enhancement into climate policies requires accounting for their effectiveness in reducing atmospheric carbon concentration. Different accounting methods have been introduced to quantify the impacts of sink enhancements. Here, we provide a manual for the different accounting methods, accompanying the implementation of the accounting methods in a R-file which is free for download. Hence, the material allows applying the different accounting methods and for demonstration purposes we provide a numerical example.

1 Introduction

CO2 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 (Rogelji et al., 2021). These emissions scenarios are projected to require a considerable amount of atmospheric carbon dioxide removal to offset hard to abate CO2 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 2021) and failing to properly resolve this question is consider a major obstacle for the required implementation of nature-based solutions to enhance atmospheric carbon removal (Parisa et al., 2022).

To address the problem of temporary storage, various accounting methods have been proposed in the literature (Dutschke, 2002; Fearnside et al., 2000; Fearnside, 2002; Dornburg and Marland, 2008; Brãndao et al., 2019; Barker et al., 2007). They can be grouped into three categories: permanent credits, temporary credits, and a mixture of permanent and temporary credits. Here, we focus on methods which provide permanent credits.

2 Accounting Methods

Only methods with regard to stored carbon using a specific permanence period will be considered. A permanence period of 100 years is in line with the IPCC's definition of permanence (cf. UNFCCC (1997)). In implementing the accounting methods we assume that a cap on the cumulative amount of carbon credits is calculated because no permanent liability can be established. 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

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.

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)). Credits are awarded when carbon is stored (positive change) and required when carbon is released (negative change) (Rickels et al. (2010)).

$$Cap\_Net = \sum_{t=1}^{T} \Delta\, carbon\ uptake\ stock_t \quad (1)$$

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. 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.

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

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 is discounted to the present. As a result the respective uptake changes are also decreasing over time compared to the net method (cf. Thompson et al. (2009), Richard and Stokes (2004)). This economic concept of explicitly including a time preference into an environmental assesment 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.

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

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.

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

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.

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

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.

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

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)).

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

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 uptake stock change 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.

$$Cap\_MCW^{(2)} = \sum_{t=1}^{T} (\Delta carbon\ uptake\ stock_t \times w_t) \ ,$$

$$w_t = \begin{cases} 1 - \frac{t}{equivalence\ time} \ , & \frac{t}{equivalence\ time} < 1 \\ 0 \ , & \frac{t}{equivalence\ time} \geq 1 \end{cases} \tag{8}$$

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.

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

3 Implementation into R

For the numerical comparison of the different accounting methods in assigning carbon credits, we have implemented the methods into R.

First, the respective raw data i.e. time series of carbon uptake stock data (.csv file, information of carbon stocks in columns relative to benchmark, headers in first row of every stock) must be imported into R. Here, one data point is the carbon uptake stock in one specific year of the permanence period. In this implementation one row of carbon uptake stock with a permanence period of 100 years is used. 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 creating first differences of the 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 cumulative amount of carbon credits, 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.

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 functions 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

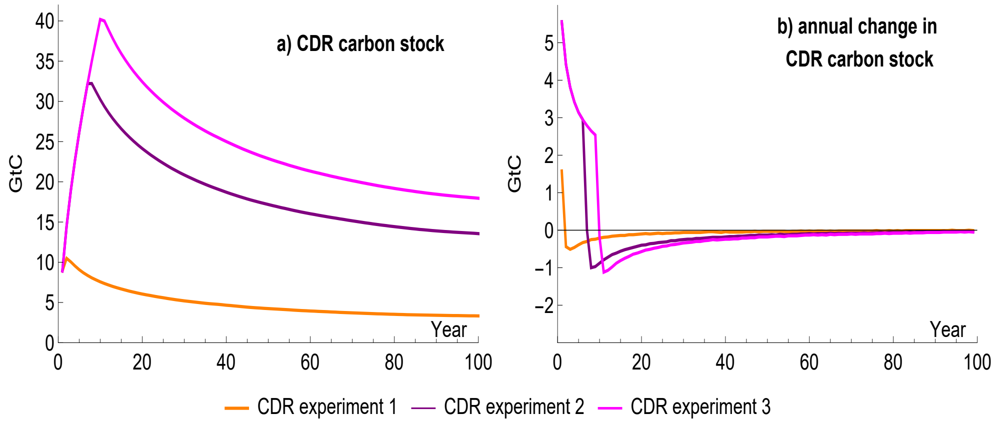

Figure 1: Carbon stock and change in carbon stock of sink enhancement project

of these combined time series divided by the 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 Numerical example of carbon credit assignment

We use three stylized sink enhancement projects, to demonstrate the application of the numerical framework. Figure 1 shows the carbon stock of the CDR project through time (Panel a) and the change in the carbon stock (Panel b). Note that such a profile could arise under short-term marine sink enhancement like with ocean iron fertilization but also for a terrestrial afforestation project with fast growing crops which subsequent harvesting.

Figure 2 shows the maximum uptake and the net uptake for the different experiments and how this translates into cumulative carbon credits across those methods which assign permanent carbon credits.

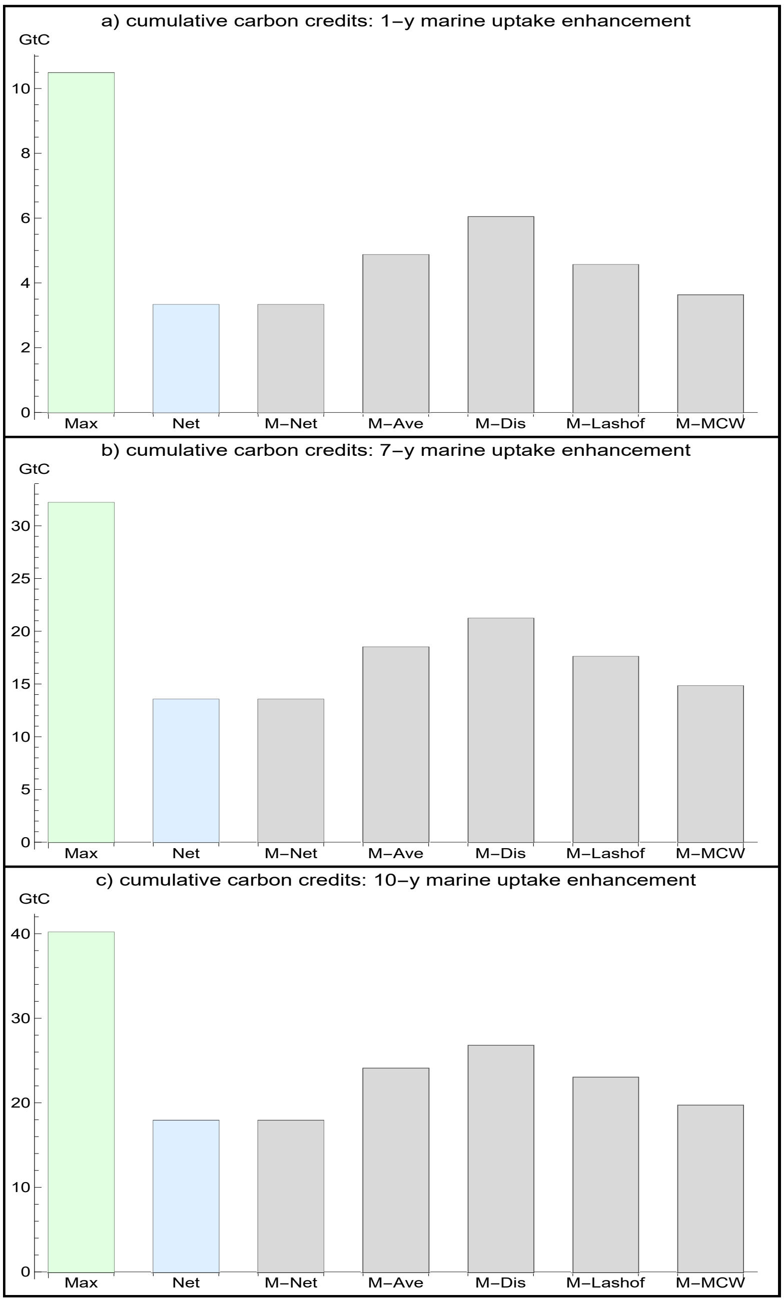

Figure 2: Physical carbon uptake, maximum and in net terms over a permanence time period over 100 years (max and net, respectively) and the cumulative amount of carbon credits for the different methods which assign permanent carbon credits, net method, average method, discount method, equivalence based on Lashof method, and equivalence based on MCW (MCW-1).

The difference between maximum and net uptake (over the assessment period of 100 years) show that part of initial removal is only temporary storage. As explained above, also temporary storage provides benefits and different accounting methods assign a different value in terms of cumulative credits to this temporary storage. The exemption is the net method which by construction assigns cumulative carbon credits only up to the net amount of storage while the other methods exceed this amount.

The information about the cumulative amount of carbon credits is not indicative on the path of credit issuance for the net, the average, and the discount methods. For these methods further assumptions are necessary, e.g., how much credits will be hold back. Here, with model-based assessment without uncertainty one could issue credits based on removal up until the cumulative cap is achieved. For all three experiments it would imply that carbon credits are issued in the first years.

Without the requirement of issuing permanent credits, i.e. having a liability regime which ensures that carbon credits have to be surrendered if the enhanced extra carbon stock decreases, temporary carbon credit or mixed regimes are possible. As explained in Section 3, the former requires that all credits are replaced at some point in time whereas the latter implies that only those carbon credits which exceed the net amount of storage (blue bar in Figure 2) have to replaced.

A special case arises for the equivalence methods as these already define a carbon credit issuance regime, namely in dependence how equivalence of permanent storage has been achieved. This is shown in Figure 3, indicating that with the Lashof method the assigment of credits is slower compared to the MCW (MCW-1) methods, however, assigning a larger amount of carbon credits in total.

5 Conclusion

We present four accounting methods for permanent carbon credit assignment whereby for the equivalence method two different realization of the method are shown. We explain how we have implemented the methods numerically

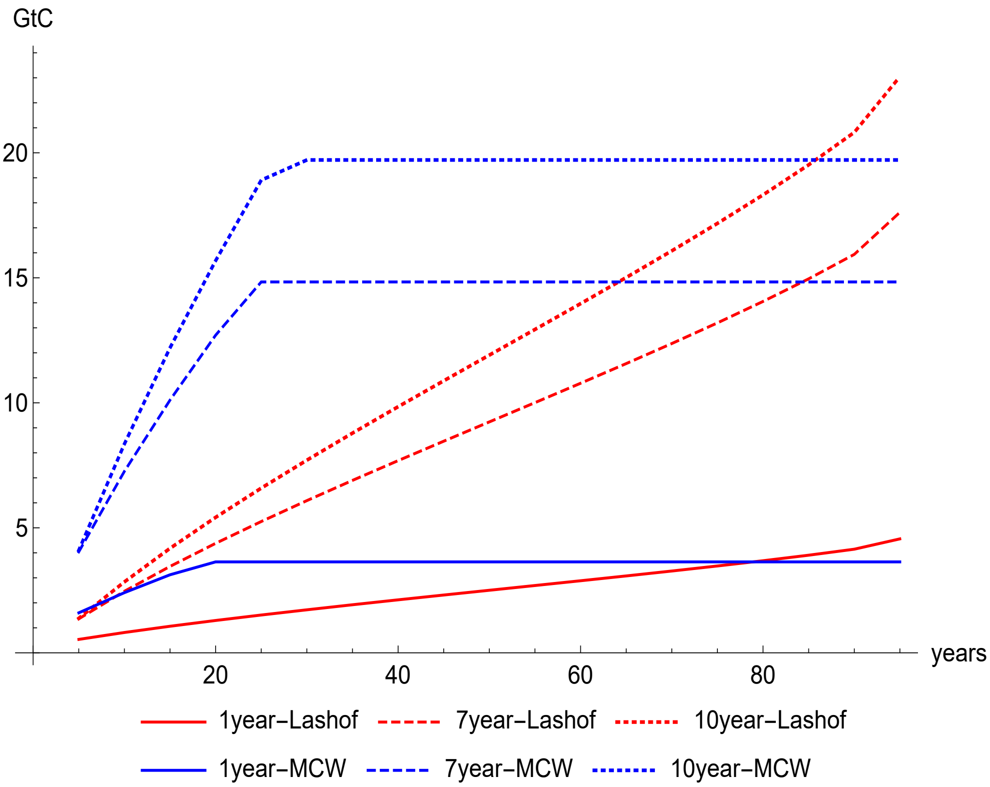

Figure 3: Cumulative carbon credits through time for the two equivalence methods and the three different experiments.

and analyse carbon assignments across the different accounting schemes, using stylized, sink enhancement experiments. The working paper is accompanied by an implementation of the various accounting methods in an R script, "Carbon Accounting Caps".[1]

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[1]The R-script can be assessed at https://git.geomar.de/open-source/carbon-accounting-caps

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