Ocean-based Negative Emission Technologies

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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 and translating this information into the amount of carbon credits (to be used in official and voluntary emission trading schemes). Here, we assess accounting schemes in their appropriateness of assigning carbon credits. We discuss the role of temporary carbon storage and present the various accounting methods for carbon credit assignment. We explain how we have implemented the methods numerically and analyse carbon assignments across the different accounting schemes, using stylized, model-based ocean sink enhancement experiments.

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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 and translating this information into the amount of carbon credits (to be used in official and voluntary emission trading schemes). Here, we assess accounting schemes in their appropriateness of assigning carbon credits. We discuss the role of temporary carbon storage and present the various accounting methods for carbon credit assignment. We explain how we have implemented the methods numerically and analyse carbon assignments across the different accounting schemes, using stylized, model-based ocean sink enhancement experiments.

1 Introduction

Storing carbon in non-atmospheric reservoirs is an important option in managing and limiting atmospheric carbon concentration, because it allows to decouple the problematic link between carbon extraction and carbon accumulation in the atmosphere (Sinn, 2008). Non-atmospheric reservoirs include underground geologic formations, trees, soils, and the deep ocean (Herzog et al., 2003). Carbon is stored by either directly injecting it into these reservoirs or by enhancing the corresponding sinks. Enhancing carbon sinks allows to reduce directly atmospheric carbon concentrations by removing past emissions and, thereby, extending the remaining carbon emission budget.

Carbon stored in non-atmospheric reservoirs may be released intendedly or unintendedly and leak back to the atmosphere. Due to this potential non-permanent characteristic of the reservoirs, both the storage as well as the carbon emission offsets generated are perceived as temporary or at least partially temporary. This means that only a fraction of the storage is permanent. Therefore, temporary carbon storage, although providing climate benefits in the short run, could lead to higher atmospheric carbon concentration in the future and might aggravate climate damages in the long run. For that reason some authors argue that temporary storage has no value at all (e.g., Meinshausen and Hare, 2000; Kirschbaum, 2006) whereas other authors point out that under several conditions temporary storage has a significant value and does not aggravate climate change and can under certain circumstances even be equated to avoided emissions (e.g., Noble et al., 2000; Herzog et al., 2003; Dornburg and Marland, 2008). The rather mixed assessment originates from different assumptions about the influence of the storage project on atmospheric carbon concentration, the value of time, and the future path of carbon prices. The latter depends on the evolution of marginal abatement costs and the damage measure applied. These assumptions are crucially for the assessment, however, are seldomly made explicit but only implicitly included in the analysis of temporary storage (Herzog et al., 2003).

The assessment of carbon storage and in particular of temporary carbon storage in the literature is rather mixed results. Meinshausen and Hare (2000) shows that the release of stored carbon leads to higher atmospheric peak concentration at some point in time and concludes that temporary storage might provide short-term benefits, but increases long-term damages. Kirschbaum (2006) applies three different damage measures to hypothetical temporary storage projects and concludes that there is no climate-change mitigation value in temporary carbon storage. Dornburg and Marland (2008) replies to this analysis by pointing out, that two damage measures focus just on the impact in a single year and are therefore not just correlated but as well just appropriate ex-post damage measures. Concentrating on Kirschbaum's third damage measure, Dornburg and Marland conclude that temporary storage always decreases the cumulative impact of raised temperature and allows to buy time by reducing climate changes in the short time while developing further mitigation options for the long term. The development of further mitigation options can significantly decrease carbon prices. Consequently, when carbon is released back to the atmosphere when prices are low, while being removed from it when prices were high, temporary carbon storage can have a net economic benefit (Herzog et al., 2003). Comparing temporary carbon storage to other mitigation options, Sinn (2008) argues that the resource owners own more or less the atmosphere as well. Consequently, all fossil fuels carbon will be released to the atmosphere at some point in time and only the time profile of this release will determine climate change. The development of backstop technologies will only accelerate the release of fossil fuel carbon into the atmosphere, because resource owners react to the expected fall in resource prices in the future by extending the supply before the backstop technology is in place. Therefore, carbon storage allows to manage the time profile of carbon release to the atmosphere without affecting the resource extraction strategy of resource owners (Sinn, 2008; Edenhofer and Kalkuhl, 2009).

2 Conceptually aspects of assessing temporary carbon storage

Next to storing carbon in non-atmospheric reservoirs, avoiding carbon emissions by not burning a unit of fossil fuels can be perceived as temporary carbon emission reduction as well. This unit can be mined and burned in the future and would increase carbon emissions then (Noble et al., 2000). Without an absolute global quantity constraint through time and without a perfect backstop technology[1] in place, an avoided unit of carbon emission today implies lower carbon emissions now but higher carbon emissions in the future (Herzog et al., 2003; Sinn, 2008). Consequently, temporary carbon storage is one option to postpone carbon emissions. Its assessment requires to consider how the evolution of atmospheric carbon concentration is changed, to consider how climate damage is affected by this change, and how carbon accounting methods can appropriately address these issues.

2.1 Implications of temporary carbon storage for atmospheric carbon concentration

Consider the Situation A, where removal and release of carbon within a storage project are separate event and the stored amount of carbon does not affect the sink potential of other carbon reservoirs, e.g. the oceanic carbon sink. If a permanent liability for the owner of the carbon storage project can be established, which implies that removal and release provide and require carbon credits, temporary carbon storage can be compared to avoided carbon emissions (Noble et al., 2000). The reason is, that the atmosphere is indifferent between avoided and stored carbon emissions as long as the path of carbon emissions through time is not changed. This is assured if on the one hand at the point in time when carbon is stored, an equivalent amount of carbon is released by other sources and if on the other hand at the point in time when stored carbon is released, an equivalent amount of carbon emission is saved by other sources. The carbon concentration gradient between the atmosphere and the terrestrial and oceanic sink does not change compared to the situation without temporary storage.

Consider now Situation B, where in contrast to Situation A no permanent liability can be established. Therefore it is possible, that on the one hand at the point in time when carbon is stored, an equivalent amount of carbon is released by other sources, but on the other hand at the point in time when

[1] The concept of a backstop technology was introduced by Nordhaus (1973), referring to an alternative technology which substitutes the old technology by providing the same output, e.g., electricity. In the energy sector such technologies are nuclear, solar, wind, geothermal, and biomass, providing a backstop for fossil fuels (Liski and Murto, 2006).

stored carbon is released, no equivalent amount of carbon emissions are saved. Obviously, the future path of carbon emissions increases compared to the situation without temporary storage due to extra carbon emissions. Even if temporary storage does not result in extra carbon emission, the atmospheric carbon concentration is changed if the time profile of the carbon emission path changes. Consider therefore Situation C, where at the point in time when carbon is stored, no additional carbon is released and at the point in time when stored carbon is released, no additional carbon is saved. The carbon concentration gradient between the atmosphere and the terrestrial and oceanic sink is changed compared to the situation without temporary storage. As a consequence, the atmospheric carbon content is reduced by less than the stored amount. When the stored carbon is released, the atmospheric carbon concentration is higher compared to the situation without temporary storage (Kirschbaum, 2006). Postponing carbon emissions in time, implies as well postponing the natural transfers in non-atmospheric carbon reservoirs, no matter if carbon emissions are postponed by temporary storage or delayed carbon emissions.

In Situation C we considered the implications of the changed concentration on atmospheric carbon concentration, but we neglected the interaction between the other two active carbon reservoirs, the oceanic and the terrestrial one. If carbon is stored by enhancing the corresponding sinks, e.g., forestation measures to enhance the terrestrial sink, the atmospheric carbon concentration gradient does change with respect to both carbon sinks. Consider Situation D, where carbon is stored by a large-scale sink enhancement project. As a result, the atmospheric carbon concentration gradient decreases as well with respect to the non-enhanced carbon sink, which takes up less carbon than without the sink enhancement project. Oschlies et al. (2010) shows for a hypothetical large-scale Southern Ocean iron fertilization experiment for the duration of 100 years that of the total carbon sequestered in the ocean, more than 90 percent come from the atmosphere, but the remainder is derived from the terrestrial biosphere. Enhancing non-atmospheric carbon reservoirs implies that always a small part of the stored carbon is sequestered from the other non-atmospheric carbon reservoir and not from the atmosphere. Consequently, the stored amount of carbon can not just be equated to atmospheric carbon draw-down.

2.2 Implications of temporary storage for climate change damages

Except from Situation A, the path of carbon emissions and evolution of atmospheric carbon concentration is affected. However, this does not necessarily mean, that temporary storage aggravated climate damages, as it can be explained by the IPCC SRES scenarios. The SRES scenarios were constructed by the IPCC to analyze future trends in the production of GHGs. Based on 4 different storylines, 4 scenarios families were derived, A1, A2, B1, and B2, describing the evolution of GHGs during the 21st century (see Figure 1).

If temporary storage is evaluated on changes in temperature for single years all depends on the emission scenario chosen. In this situation, storing carbon and releasing it shortly before the maximum change in temperature occurs would be the worst thing to do (Dornburg and Marland, 2008). On the contrary, based on a given emission path, temporary storage could also be used beneficially. Under the SRES A2 Scenario[2], the maximum impact would occur at the end of the artificially truncated time horizon in 2100 and the release of stored carbon should take place after 2100. Applying the SRES B1 Scenario[3] would imply implementing storage such that the release takes place after 2050.

The possibility to apply temporary storage in such a way is limited because it would require knowing in advance when the maximum impact would occur. Additionally, this kind of damage measure implies a discontinuous value of time, because no value is assigned to postponing climate impacts within the 100 year time horizon. Only postponing climate impacts beyond

[2]The A2 Scenario assumes a very heterogenous world with increasing global population and regional oriented economic growth (Nakicenovic et al., 2000).

[3]The B1 Scenario assumes a convergent world with global population growth peaking in mid-century and declining thereafter, accomplished with rapid changes in economic structures towards a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies (Nakicenovic et al., 2000).

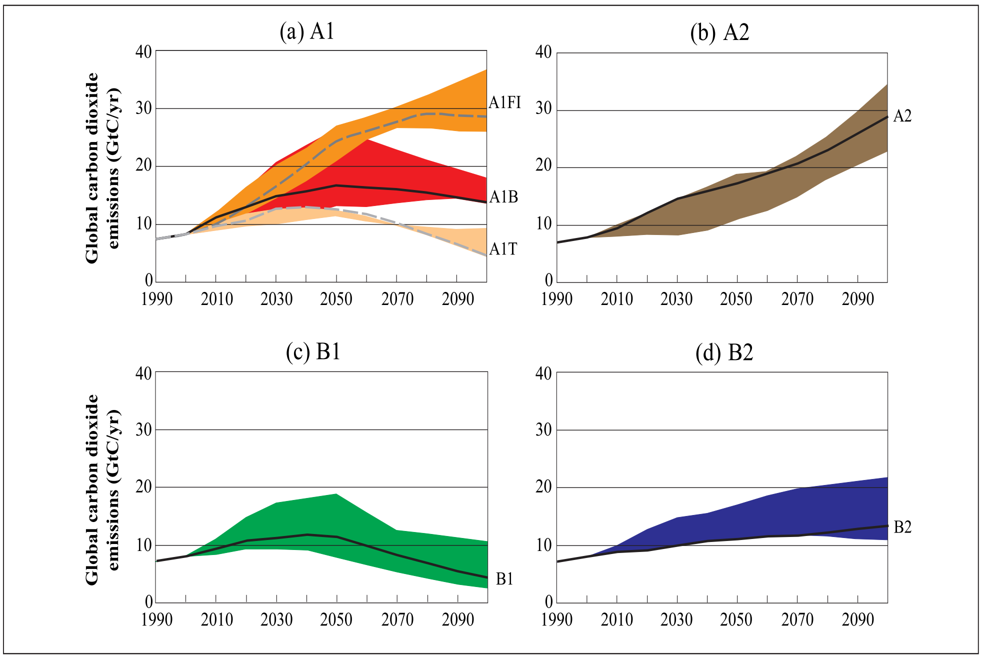

Figure 1: Total global annual CO_2 emissions from all sources (energy, industry, and land-use change) from 1990 to 2100 (in gigatonnes of carbon (GtC/yr)) for the families and six scenario groups. The 40 SRES scenarios are presented by the four families (A1, A2, B1, and B2) and six scenario groups: the fossil-intensive A1FI (comprising the high-coal and high-oil-and gas scenarios), the predominantly non-fossil fuel A1T, the balanced A1B in Figure 3a; A2 in Figure 3b; B1 in Figure 3c, and B2 in Figure 3d. Each colored emission band shows the range of harmonized and non-harmonized scenarios within each group (Source Nakicenovic et al. (2000)).

this time horizon has a value (Dornburg and Marland, 2008). If instead temporary storage is evaluated on cumulative changes in temperature, there is always a positive value no matter when and how long the carbon is stored (Dornburg and Marland, 2008). Considering cumulative changes in temperature addresses both the duration and the magnitude of climate change and takes into account consequences of a continuous increase in temperature such as sea-level rise (Kirschbaum, 2006). Consequently, even if temporary storage results in higher atmospheric carbon concentration in the future compared to the situation without temporary storage, it does not necessarily aggravate climate damages.

The example with temporary storage within different IPCC scenarios reveals that for the general assessment of temporarily avoided emissions, either by delayed fossil fuel burning or non-permanent storage, assumptions about the value of time and about the future path of carbon emissions (or rather of carbon prices) need to be well defined. In the following we briefly discuss the issue.

The assessment of temporary storage or permanence requires a positive value of time. Without this positive value, permanence would extend to near eternity (Fearnside, 2002) and would therefore prevent an empirical assessment of carbon storage. Various carbon accounting methodologies have been proposed to assess the value of different temporary storage projects (e.g., Dutschke, 2002; Fearnside et al., 2000; Fearnside, 2002; Marland et al., 2001; Costa and Wilson, 2000). A common assumption of these approaches is to assess permanence over the time period of 100 years, following the IPCCs definition of permanence for sequestration projects (UNFCCC, 1997).[4]. In general, the value of time is expressed by a discount rate, the social rate of time preference, which measures how society values future abatement costs and climate damage costs. The determination of an appropriate discount rate is a central issue within the climate change debate and beyond the scope of this paper. However, it should be noted, that an increasing consumption path in the future still implies a positive social rate of time preference, even if the pure rate of time preference has been set to zero due to ethical considerations.[5] For a recent discussion on this topic see Heal (2009) and Dasgupta (2008). Note, the choice of a finite time horizon includes a value of time, even if applied with a zero discount rate, as it is done when calculating the Global Warming Potentials (GWP) of different greenhouse gases. Fearnside et al. (2000) points out, that a 100 year time horizon with zero discount rate is equivalent to a 1000 year time horizon with 0.9 percent discount rate.

The future path of carbon prices reflects assumptions about the path of marginal costs of carbon emission abatement (marginal abatement costs) and

[4]The choice of 100 years is not based on scientific rationale but was rather a policy decision (Leinen, 2008)

[5]The social rate of time preference, r, depends on the pure rate of time preference, ρ, the growth rate of consumption, g, and the elasticity of marginal utility, η.

of marginal costs of climate change damages (marginal damage costs). This includes assumptions about technological progress and the development of backstop technologies as well as possible thresholds of climate change and carbon fluxes in the global carbon cycle.

As mentioned above, the atmosphere is indifferent between avoided and stored emissions, as long as a permanent liability is established. In this situation the future path of carbon emissions is not changed and therefore exogenous and the value of temporary storage projects is only determined by the development of the marginal abatement costs. Temporary carbon storage has a positive value, if marginal abatement costs at the point in time of carbon removal are larger than the present value of the marginal abatement costs at the point in time of carbon release. It requires that the rate of change in marginal abatement costs is below the discount rate. If carbon prices remain constant or if a backstop technology exists that caps the abatement costs in the near future, temporary storage with a permanent liability can achieve an almost equivalent value to permanent storage (Herzog et al., 2003). Without a permanent liability, temporary storage results in additional carbon emissions. In this situation the future path of carbon emissions is changed and therefore endogenous and the value of temporary projects is determined by the development of marginal damage costs as well. Temporary storage has a positive value, if marginal abatement costs at the point in time of carbon removal are larger than the present value of the marginal damage costs at the point in time of carbon release. Note, that the calculation of the present value of the marginal damage costs is not just based on the discount rate. Exchange fluxes with the oceanic and the terrestrial sink to which the stored amount of carbon has not been exposed before its release are relevant as well. A higher discount factor implies a lower present value of the marginal damage costs, higher exchange fluxes imply a higher present value of the marginal damage costs. The value of temporary storage without a permanent liability is based on the additional use of fossil fuels in the present, while delaying the associated additional damages into the future (Rickels and Lontzek, 2008). Irrespective of liability issues, the value of temporary storage, is therefore increasing in the value of time and consequently in duration of storage time (Herzog et al., 2003; Rickels and Lontzek, 2008).

Since marginal damage costs are highly uncertain, the level of maximum tolerable global warming can be determined by limiting the increase in global average temperature, which requires a carbon emissions budget for a given period of time. The carbon emission budget is calculated, e.g. from 2000 until 2050, assuring that a defined change in global average temperature is not exceeded (Meinshausen et al., 2009). Once an overall budget is agreed, the time preference distributes the much more certain mitigation costs over time and not the more uncertain damages (Edenhofer and Kalkuhl, 2009). The budget framework requires that temporary carbon storage does not lead to additional carbon emissions. However, temporary carbon storage allows shifting of carbon emissions between various commitment periods. As stated above, this is beneficial, if marginal abatement costs at the point in time of carbon removal are larger than the present value of the marginal abatement costs at the point in time of carbon release. If the carbon budget in a given commitment period is almost exhausted, the prevailing carbon price is high. If the budget in a future commitment period is less tight, because the atmospheric carbon concentration is already decreasing or technological change has lead to lower fossil fuel demand, the discounted carbon price from that period may be lower than in the actual one. In this situation temporary storage is beneficial, because it allows lending of carbon emission from the future commitment period for usage in the actual commitment period, lowering thereby overall abatement costs.

2.3 Implications of temporary carbon storage for carbon accounting in non-global climate regimes

The various influences of temporary carbon storage on atmospheric carbon concentration (Situation A to D) and therefore the value of the temporary storage in the context of climate policy can be discussed under the framework of the Kyoto Protocol, i.e. a situation where some countries had binding emission reduction targets while others had not. The former are summarized as Annex I countries, the latter as Non-Annex I countries.

Situation A applies to carbon storage projects in Annex I countries. These are countries with binding emission reduction targets under the Kyoto-Protocol, so that the issue of permanence does not arise. Permanent Carbon credits (Emission Reduction Units) are awarded to activities which increase the stored amount of carbon and carbon credits (e.g. Assigned Amounts or Certified Emission Reductions) are required for activities which decrease the stored amount of carbon. The link between the National Inventories and the compliance with Assigned Amounts establishes a permanent liability for the owner of the carbon storage project, if the Protocol is prolonged.

Situation B and C apply to carbon storage projects in Non-Annex I countries. Non-Annex I countries have no binding emission reduction targets and will not compensate for any reduction in carbon stocks within storage projects, because they have no Assigned Amounts with which to comply (Phillips et al., 2001; Ellis, 2001). The non-permanence problem for projects within Non-Annex I countries is addressed by issuing temporary carbon credits, which transfer the permanent liability to the buyer of the carbon credits. They have to be replaced no matter if the storage turns out to be permanent or not (UNFCCC, 2003). This concept of temporary carbon credits provides “a suitable framework for awarding and trading carbon credits” (Dornburg and Marland, 2008, p.212). Issuing temporary carbon credits 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 (Rickels et al., 2010).

Situation D reveals a shortcoming of current carbon accounting methods, because they are so far solely applied to the stored amount of carbon. The influence of temporary carbon storage on the atmospheric carbon concentration gradient with respect to the two other active carbon reservoirs, the terrestrial and oceanic carbon sink, is currently not appropriately addressed. Oschlies et al. (2010) shows, that it is not sufficient to account for changes in only a single carbon pool to compare the effectiveness of different sink enhancement and therefore sequestration options. They show that within the hypothetical large-scale Southern Ocean iron fertilization experiment each ton sequestered in ocean is equivalent to an emission cut of about 1.2 tons of carbon on a 100 year timescale. The reason is the response to the lower atmospheric carbon concentration gradient in the situation of an equivalent cut in emissions. This example shows, that it is necessary to improve carbon accounting methods with respect to the underlying metric, changing this from the stored amount of carbon to a metric like canceled carbon emissions or global radiative forcing (Lenton and Vaughan, 2009). Furthermore, these conceptual considerations allow to assess accounting methods in terms how they change the emissions path in response to the issuance of carbon credits.

3 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 the following carbon caps using different accounting methods (i.e. carbon credits when considering the whole permanence period) are presented. These carbon accounting methods are applied when using land based negative emission technologies such as afforestation, but some of them are also already investigated regarding ocean based negative emission technologies such as ocean iron fertilization (cf. Rickels et al. (2010)).

3.1 Net method

Let $carbon\ uptake\ stock_t$ be the stock of carbon uptake of a specific ocean based negative emission technology 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)).

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

3.2 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.

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

3.3 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.

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

3.4 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.

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

3.4.1 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 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.

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

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.

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

3.4.2 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.

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

4 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 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.

5 Numerical example of carbon credit assignment

We use a stylized experiment for marine sink enhancement, ocean iron fertilization (OIF) (cf. Rickels et al. (2010)), to demonstrate the application of the numerical framework. The stylized experiment represents model-based OIF for 1, 7 and 10 years. 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.

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

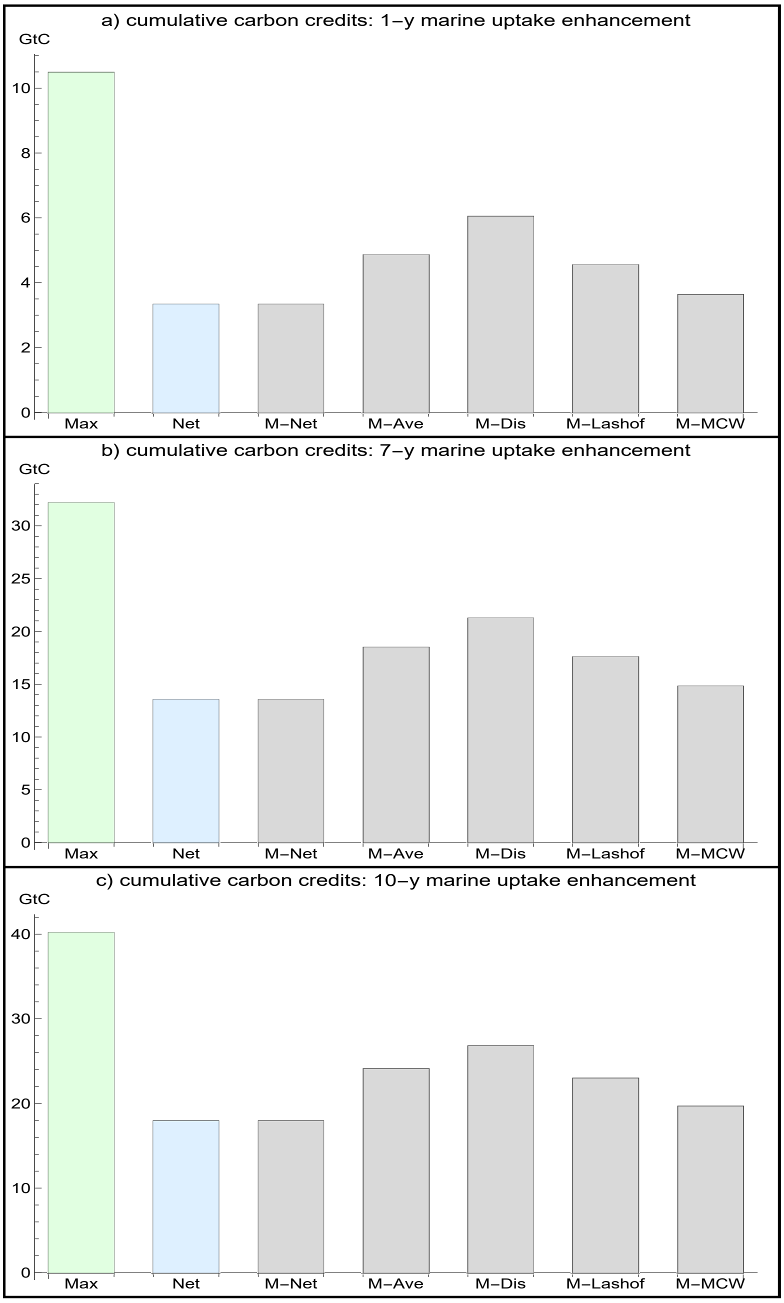

Figure 2: Physical carbon uptake, maximum and in net terms over a permanence time period over 100 years (max and net, respectively) and the cumulative amount of carbon credits for the different methods which assign permanent carbon credits, net method, average method, discount method, equivalence based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

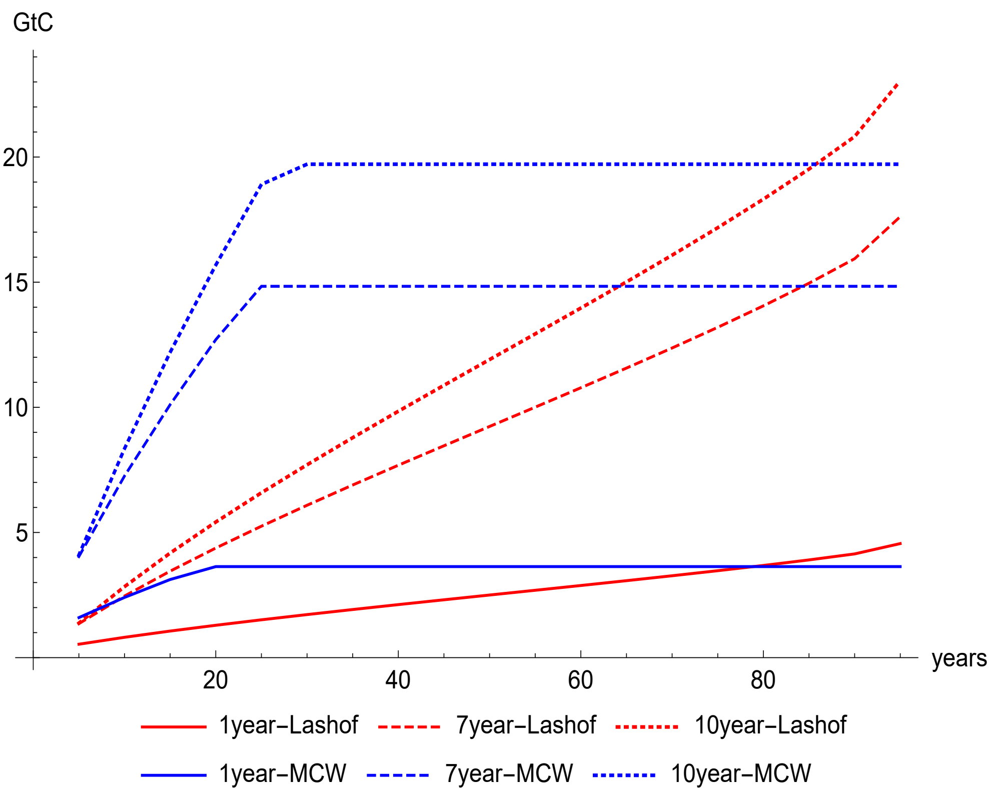

Figure 3: Cumulative carbon credits through time for the two equivalence methods and the three different experiments.

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.

6 Conclusion

Ambitious climate policies requires in addition to drastic reductions in anthropogenic greenhouse gas emissions also active removal of CO_2 from the atmosphere. Such kind of carbon dioxide removal can be achieved via technical methods, like Direct Air Capture with Carbon Capture and Storage (DACCS) or by enhancing the natural terrestrial or marine sinks. However, the carbon removed via enhanced carbon sinks is potentially in part temporary.

Any integration of extra carbon dioxide removal (CDR) via terrestrial or marine sink enhancement into climate policies requires therefore accounting for their effectiveness in reducing atmospheric carbon concentration and translating this information into the amount of carbon credits (to be used in official and voluntary emission trading schemes). In this version of the working paper, we discuss the role of temporary carbon storage and present the various accounting methods for carbon credit assignment. We explain how we have implemented the methods numerically and analyse carbon assignments across the different accounting schemes, using stylized, model-based ocean sink enhancement experiments. The working paper is accompanied by an implementation of the various accounting methods in an R script, "Carbon Accounting Caps".[6]

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[6]The R-script can be assessed at `https://bityl.co/A9xP`

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