

# Optimal global carbon management with ocean sequestration

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## Motivation and outline

The increasing anthropogenic disturbance of the Earth's radiation balance with the corresponding change in the Earth's climate system can be expected to become one of the most challenging global problems for mankind. In contrast to other global problems, the specific difficulty of the climate problem arises from the long delay between anthropogenic actions and climate response. Already today, the net radiative disturbance due to anthropogenic activities is estimated to be about  $1.6 \text{ Wm}^{-2}$  with increased atmospheric carbon concentration as the main single contributor (IPCC, 2007; Raupach and Canadell, 2010). However, mankind has so far only partially experienced the consequences of this disturbance because of the inertia of the climate system and, in particular, the thermal capacity of the oceans which cause a delay in the corresponding temperature reaction (Cess and Goldenberg, 1981; Knutti and Hegerl, 2008). From this inertia, it follows in turn that already induced changes can only be reversed on very long time scales. Consequently, once the effects of climate change have started to seriously affect the well-being of society and ecological systems, possible conventional response options are not effective for mitigating these effects on a short time scale. Furthermore, it is already not possible to regard today's atmospheric greenhouse gas (GHG) - and in particular carbon concentrations - as safe with respect to potential tipping points in the climate system, which are expected to trigger non-linear and probably dramatic climate change (e.g., Lenton et al., 2008; Zickfeld et al., 2010). Therefore, a profound mitigation strategy requires taking into account the different time scales of changes and effects and also the various anthropogenic influences on the climate system.

So far, society has failed to control the main anthropogenic source of the radiation balance disturbance: the emission of carbon dioxide. Neither emission reductions in the Kyoto Protocol nor announced emission reductions in the Copenhagen Accord have been or are sufficient to result in a significant change in the emission trend. After a short reduction in carbon emissions from fossil fuel burning by 1.3 percent in 2009 due to the financial crisis, carbon emissions have increased to a new record level of about 30.6 Gt CO<sub>2</sub> in 2010 (Friedlingstein et al., 2010; IEA, 2011). To emphasize the necessity of significant emission cuts in the near future, one can look at the chances for complying with the goal of the United Nations Framework Convention on Climate Change (UNFCCC) to restrict temperature increase to 2°C in order to prevent dangerous climate change (UNFCCC, 2010). A compliance probability of 50 percent requires cumulative carbon emissions to be below 1000 Gt C (Allen et al., 2009; Meinshausen et al., 2009; Raupach et al., 2011). However, cumulative carbon emissions by the end of 2008 were about 530 Gt C, so that more than half of this emission budget has already been used (Raupach and Canadell, 2010).

Current efforts to mitigate climate change fail not just with respect to absolute emission reductions on a global scale, but also with respect to considering the various anthropogenic influences on the climate system and the role of natural carbon sinks. First, the anthropogenic influence on the Earth's radiation balance does not just contain GHG emissions, which increase their concentration in the atmosphere and, therefore, the fraction of absorbed thermal radiation, but also contains land-use changes and aerosol emissions, which affect the fraction of solar radiation reflected to space (albedo). The latter influences have a negative radiative forcing and, therefore, a cooling effect, reducing the GHG-induced radiative forcing effect of about  $2.6 \text{ Wm}^{-2}$  to the above mentioned net radiative forcing of  $1.6 \text{ Wm}^{-2}$  (IPCC, 2007; Raupach and Canadell, 2010). Second, the atmospheric carbon concentration is not just influenced by corresponding emission, but also by the natural uptake of the terrestrial and oceanic carbon sink. The increase in atmospheric carbon in a given year relative to that year's total carbon emissions constitutes the airborne fraction (AF). This fraction is currently substantially lower than 1, which indicates that the natural sinks are removing anthropogenic carbon from the atmosphere. Canadell et al. (2007) and Raupach and Canadell (2010) estimate the average AF to be about 0.45 for the period 1960 to 2008. However, the AF is estimated to have increased at an annual rate of 0.24 percent (Raupach and Canadell, 2010), indicating that the natural sinks cannot keep pace with increasing carbon emissions and are showing the first signs of saturation.

Taking into account the various possible influences on the radiation balance and the role of natural carbon sinks, possible response strategies to climate change could also be to apply technologies which allow the increase of negative radiative forcing, or technologies which allow the enhancement or mimicking of the natural uptake of carbon. The former group contains technologies such as the modification of crops or injecting sulphur into the stratosphere to increase the fraction of reflected solar radiation, and can be summarized as radiation management (RM). The latter group contains technologies such as ocean iron fertilization or afforestation to increase the fraction of carbon uptake, and can be summarized as carbon dioxide removal (CDR). Both groups of technologies are summarized as climate engineering and can be defined as the large-scale deliberate intervention in the Earth's climate system in order to mitigate climate change (e.g., Royal Society, 2009). In particular, certain RM technologies seem to provide a quick and cheap response option to climate change as these technologies are expected to allow exerting a quick, significant negative radiative forcing at low cost to compensate for a doubling or even quadrupling of atmospheric carbon concentration compared to preindustrial levels (e.g., Barrett, 2008; Lenton and Vaughan, 2009; Royal Society, 2009). However, this is a preliminary and probably biased assessment as it is restricted to operational cost estimates, without taking into account possible price effects or external effects. In addition, dynamic efficiency is not appropriately considered (Klepper and Rickels, 2011). Even though RM seems to allow rather good global compensation of a GHG-induced temperature increase, it does not allow compensation for the change in all climate variables such as ice coverage or, in particular, precipitation (e.g., Feichter and Leisner, 2009; Ricke et al., 2010). Therefore, it is still unresolved if an application of RM will



result in an increase of welfare in all regions of the world (Klepper and Rickels, 2011). Additionally, it could be necessary to maintain those compensating RM technologies for several 100 to 1000 years, depending on the emission path and level of compensation (e.g., Brovkin et al., 2009) so that, in a dynamic perspective, their possible operational cost advantage can turn around. Furthermore, interrupting such compensating RM technologies due to unforeseen side effects will result in a rapid climate change if GHG-induced radiative forcing is still present so that the social costs of such an interruption could even exceed those of unmitigated climate change (Goes et al., 2011). Consequently, one could argue that, first of all, CDR technologies should be developed, or at least that their operational readiness is a precondition for the application of RM technologies (Klepper and Rickels, 2011).

Even though both CDR and RM measures are summarized as climate engineering, they have very different characteristics. CDR measures are currently assessed as being too limited in their potential to allow a quick change in the radiation balance at feasible costs (e.g., Lenton and Vaughan, 2009; Klepper and Rickels, 2011). In contrast to RM measures, they take effect much more slowly and have higher operational costs, but they address the root of the problem by directly affecting atmospheric carbon concentration and have, therefore, more similarities to conventional emission control measures. Besides, as they allow removing past carbon emissions, they can extend the remaining emission budget for complying with the 2°C ceiling and probably constitute a supplementary measure to emission control (Klepper and Rickels, 2011). This has been acknowledged to some extent by policy makers, as CDR measures are included in the Kyoto Protocol. Yet, these CDR measures are restricted to the terrestrial carbon sink, because in the present climate agreement only Land-Use, Land-Use Change and Forestation (LULUCF) projects are included (UNFCCC, 2001). Also, these measures are restricted in total volume (UNFCCC, 2001, Art. 3.4). Even though the current carbon uptake of the terrestrial sink is estimated to be slightly larger than that of the ocean sink, the former is subject to strong fluctuations that are not yet well understood. By looking at the change in the atmospheric, terrestrial and oceanic carbon reservoirs from 1800 to 1994, Sabine et al. (2004) show that the terrestrial biosphere has been a total net source of about 39 Gt C. They conclude that 'the ocean has constituted the only true net sink for anthropogenic CO<sub>2</sub> over the past 200 years' (p. 370).

The ocean contains about 65 times more carbon than the atmosphere. This difference is explained not only by the size of these two reservoirs, but also by the chemical reactivity of CO<sub>2</sub> in water and the various carbon pumps in the ocean. Most of the CO<sub>2</sub> dissolves in water, forming carbon acid first and then bicarbonate (HCO<sub>3</sub><sup>-</sup>) and carbonate ions (CO<sub>3</sub><sup>2-</sup>). The sum of these three elements describes the total amount of carbon in the ocean, called dissolved inorganic carbon (DIC). The amount of DIC in the ocean consists of bicarbonate ions (c. 89 percent), carbonate ions (c. 10 percent) and CO<sub>2</sub> (< 1 percent) (Najjar, 1992). Regarding the last figure, the atmosphere "sees" only a tiny fraction of the carbon present in ocean surface water within the chemical process of pCO<sub>2</sub> equilibration between the atmosphere and the ocean. Without this chemical reaction, about 70 percent of the anthropogenic carbon would remain in the

atmosphere (Sarmiento and Gruber, 2006). The chemical reactivity of  $\text{CO}_2$  constitutes a chemical sink for  $\text{CO}_2$  in the ocean. The effectiveness of this chemical sink can be quantified by the buffer factor, which measures the fractional change in atmospheric  $\text{CO}_2$  relative to the fractional change in DIC:  $\zeta = \frac{\partial[\text{CO}_2]/[\text{CO}_2]}{\partial[\text{DIC}]/[\text{DIC}]}$  for a given release of  $\text{CO}_2$  into the atmosphere. A low buffer factor, therefore, indicates that a large fraction of the atmospheric  $\text{CO}_2$  perturbation can be taken up by the ocean. The value of the buffer factor is proportional to the ratio between DIC and alkalinity (Sabine et al., 2004).<sup>1</sup>

The buffer factor measures the ability of the ocean to take up carbon from the atmosphere, but not the speed of this uptake. Compared to the total size of the ocean, only a small fraction of it is in direct exchange with the atmosphere. Whereas it takes around one year for the upper layer of the ocean to equilibrate with the atmosphere, the uptake bottleneck is the transport of anthropogenic  $\text{CO}_2$  to the deeper parts of the ocean, which is effected by the biological pump and the solubility pump. The biological pump is driven by two cycles: the organic matter cycle and the calcium carbonate cycle. Within the first cycle, phytoplankton captures  $\text{CO}_2$  through photosynthesis and produces its organic tissue by utilizing the inorganic nutrients that are dissolved in seawater. The reverse process is respiration and mineralization of this organic matter. Whereas photosynthetic production is restricted to the euphotic zone, remineralization is not and, as a consequence, occurs on average deeper in the water column.<sup>2</sup> The organic matter cycle causes surface depletion and deep enrichment of DIC, but causes slight surface enrichment and deep depletion of alkalinity in the top layer. Therefore, the organic matter pump decreases surface ocean  $\text{pCO}_2$  and hence,  $\text{pCO}_2$  in the atmosphere (Najjar, 1992). The second cycle works in the opposite direction. Its driving forces are plants and animals that build their  $\text{CaCO}_3$  skeletons in the euphotic zone from dissolved calcium and carbonate ions. When these skeletons sink in the water column, they dissolve back into calcium and carbonate ions. Ocean circulation transports these ions back to the surface layer. This cycle creates a surface depletion and deep enrichment in DIC and alkalinity. The effect of the calcium carbonate cycle on alkalinity is about twice as strong as its effect on DIC. As a consequence, it increases  $\text{pCO}_2$  in the upper layer and, therefore, increases atmospheric  $\text{CO}_2$ . Both cycles are present mainly in the upper layer of the ocean. The term "biological pump" designates the small fraction of organic matter and skeletons that survives remineralization in the euphotic zone and sinks to deeper layers. Due to their influence on DIC and alkalinity, and hence  $\text{pCO}_2$ , both cycles, the organic matter cycle and the calcium carbonate cycle, are important factors for the chemical equilibration of carbon between the atmosphere and the upper layer of the ocean. For overall equilibration, however, the transport of carbon into the deep ocean, which is especially effected by the solubility pump, is more important. The solubility pump is driven by two phenomena: thermohaline circulation and the

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<sup>1</sup>Alkalinity measures the ability of seawater to maintain its pH value when carbon acids are added. The pH value determines the distribution of DIC between the three different carbon forms, but is itself affected by the additional uptake of carbon.

<sup>2</sup>The euphotic zone is the layer that receives enough light for photosynthesis to occur. The depth of this layer is determined by the amount of incoming sunlight and the activity of the water (Sarmiento and Gruber (2006) p. 111). The aphotic zone is the layer below the euphotic zone.

solubility of  $\text{CO}_2$ . Surface water in equilibrium with atmospheric  $\text{CO}_2$  takes up additional  $\text{CO}_2$  on its way to the poles, as the solubility of  $\text{CO}_2$  increases with decreasing temperature. The formation of deep seawater is driven by thermohaline circulation, which transports cold and high-solubility high-latitude surface waters into the deep ocean. These two phenomena act together to pump carbon from the atmosphere into the ocean's deeper layers. However, for increasing atmospheric  $\text{CO}_2$ , this uptake process is limited mainly by the turnover speed, and the total ocean will still be undersaturated for a long time (in the order of  $10^3$  years) (Körtzinger and Wallace, 2002).

The absolute value of the long-term atmospheric carbon stabilization level and the time pattern of its achievement will depend crucially on the marine carbon cycle. For a given impulse emission of anthropogenic carbon it is estimated that, on time scales of several hundred years, between 70 and 80 percent of anthropogenic carbon will be taken up by the chemical buffering of the ocean. The range indicates the saturation dependent on the total amount of anthropogenic carbon impulse (Archer et al., 1997).<sup>3</sup> Therefore, the marine carbon cycle is perceived to be the most important cycle with regard to the climate (Najjar, 1992), and any approach to mitigate global warming that ignores the ocean ignores optimization potential. Accordingly, several questions arise for economic analyses related to climate change. First, what is an appropriate description of the global carbon cycle, in particular with respect to the oceanic carbon sink in economic models? Second, since natural forces transport carbon into the deep ocean where it affects society less adversely than in the atmosphere, the logical question is: Which carbon removal measures can be applied to accelerate the process of downward carbon transfer? Third, to integrate these measures into economic optimization, how can the carbon uptake be measured and verified, how can carbon credits be assigned, and how to deal with carbon that it is only temporarily stored and expected to leak back into the atmosphere at some point in the future? Fourth, what are the critical costs and critical carbon amounts to be removed from the atmosphere in order to provide an option for climate change mitigation in comparison to existing options? Fifth, what is the dynamic optimal application of such measures in climate change policy?

The papers in this cumulative thesis provide answers to these questions by investigating the role of CDR measures in relation to RM measures, by considering accounting and market requirements to one specific oceanic CDR measure, ocean iron fertilization, and by deriving the dynamic optimal carbon sequestration strategy for various climate policies.

The first paper, entitled “The real economics of climate engineering”, written together with my coauthor, Gernot Klepper, seeks to frame the discussion on climate engineering by providing an overview of current knowledge on the feasibility and costs of the various technologies. It explains the differences between the

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<sup>3</sup>On time scales of several thousand years, this fraction increases to about 90 percent due to the chemical sedimentary  $\text{CaCO}_3$  buffer, whereas on time scales of several ten to hundred thousand years, the remaining anthropogenic carbon will be taken up by terrestrial  $\text{CaCO}_3$  and silicate weathering (Archer et al., 1997).

various radiation management and carbon dioxide removal technologies using a simple representation of the Earth's radiation balance. The cost overview contains both operational and social costs by also discussing potential external effects. Given this overview, and based on the economic studies existing so far that analyze the implications of climate engineering, the paper then discusses the economic consequences of considering such technologies for the climate change reaction portfolio. Furthermore, with respect to the uncertainties about the impacts resulting from side-effects and the termination effect, an application of radiation management can result in a lock-in effect. Consequently, the paper argues that further economic research should focus more strongly on portfolios of climate engineering measures and put more emphasis on carbon dioxide removal measures. Own contribution: In this paper, I explained the simple representation of the Earth's radiation balance, provided the cost estimates of the various technologies, and reviewed and discussed the various existing economic studies related to climate engineering.

The second paper, entitled "Methods for greenhouse gas offsets accounting: A case study of ocean iron fertilization", written together with my coauthors, Katrin Rehdanz and Andreas Oschlies, addresses one main characteristic of most carbon dioxide removal technologies: the partly temporary storage of carbon. The paper assesses the impact of various accounting methods applied to large-scale carbon dioxide removal projects. The various accounting methods are applied to hypothetical large-scale Southern Ocean iron fertilization (OIF) projects for different durations. Ocean iron fertilization (OIF) is especially suitable for comparing the outcomes of different approaches, since fluctuations in oceanic carbon uptake during and after OIF and additional releases of other greenhouse gases such as  $N_2O$  have to be accounted for. Therefore, the paper discusses how to deal with these fluctuations and the release of other greenhouse gases (leakage), and calculates deduction rates to address the latter issue. Own contribution: In this paper, I did the majority of the work, covering all relevant aspects of the article. I explained the various accounting methods and applied them to the modeled data of various hypothetical Southern Ocean iron fertilization experiments for different periods of time. The data for the carbon uptake in the various experiments as well as data on  $N_2O$  emissions was provided by Andreas Oschlies. Based on the latter, I calculated appropriate deduction rates and compared the various accounting methods with respect to their economic and environmental effects.

The third paper, entitled "Economic prospects of ocean iron fertilization in an international carbon market", written with my coauthors, Katrin Rehdanz and Andreas Oschlies, addresses the economic prospects of ocean iron fertilization (OIF) within a climate agreement such as the Kyoto Protocol. It considers hypothetical, short-term, but large-scale OIF in the Southern Ocean for the duration of 1, 7 and 10 years in a post-Kyoto agreement and derives criteria for assessing the efficiency of OIF as a climate engineering option. The paper models a static compliance problem for various countries with a basic global  $CO_2$  market for the next commitment period (2012-2020), including domestic carbon emission reductions and emission trading. The paper provides information on critical unit costs and critical amounts for OIF and compares these to other mitigation options. Including OIF in a post-Kyoto agreement is expected to have implications for the

distribution of welfare. Accordingly, the paper also attempts to determine the distributional aspects arising from including carbon credits from OIF. Own contribution: In this paper, I did the majority of the work, covering all relevant aspects of the article. I derived and calibrated the basic static compliance problem and incorporated a forestry sector. Based on the results of the previous paper, I calculated the critical unit costs and critical amounts for OIF. Furthermore, I derived the change in welfare for the various groups of countries due to the inclusion of OIF in such a market.

The fourth paper, entitled “Optimal global carbon management with ocean sequestration”, written with my coauthor, Thomas Lontzek, investigates the dynamic socially optimal intervention in the global carbon cycle. The paper introduces a two-box model description of the global carbon cycle into economic models to explicitly include the largest non-atmospheric carbon reservoir, the ocean. This enables the achievement of a better representation of the global carbon cycle than the proportional-decay assumption usually resorted to in economic models. The paper analyzes the optimal amount of extraction and consumption of fossil fuels whereby the related emissions can be released into the atmosphere and injected into the deep ocean for the purpose of ocean sequestration in a microeconomic partial analysis framework. The paper clarifies the implications of the non-renewable description of the carbon cycle and, therefore, also for the partial non-renewable description of the atmospheric carbon stock for optimal tax paths. Own contribution: In this paper, I did the majority of the work, covering all relevant aspects of the article. I investigated the optimal properties of ocean sequestration embedded in the decision about global optimal energy consumption. I derived the optimal tax paths and clarified the influence of the non-renewable description of the global carbon cycle on these tax paths with respect to the literature. I calculated a numerical example to discuss the potential role of ocean sequestration in an optimal global carbon management strategy.

The fifth paper, entitled “The role of sequestration costs with a ceiling on atmospheric carbon concentration”, investigates the dynamic global optimal carbon sequestration decision in the presence of a ceiling on atmospheric carbon concentration. It considers aspects which have so far only been analyzed in the context of a damage function to measure the consequences of climate change for society. The paper clarifies the implications of four relevant aspects in the presence of a ceiling in a microeconomic partial analysis framework: the implications of stock-dependent extraction costs, the implications of modeling the global carbon cycle by a two-box model instead of proportional decay, the implications of modeling sequestration costs convexly rather than linearly, and the implications of oceanic instead of geologic carbon storage. Again, using a two-box model allows the non-renewable aspects of the global carbon cycle to be accounted for and implies that carbon emissions have to decline at the ceiling due to the ongoing saturation of the ocean with respect to anthropogenic carbon. The paper shows that there is a distinct difference in policy recommendations with respect to carbon sequestration according to the underlying assumptions of sequestration costs.

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# Part I

## The real economics of climate engineering

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# The real economics of climate engineering<sup>☆</sup>

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## Abstract

In 2008 Scott Barrett wrote a paper on “The incredible economics of geoengineering” in which he argued that the potential extremely low cost of climate engineering (CE) measures together with their quick response of the earth’s temperature to such interventions will change the whole debate about the mitigation of climate change. In his paper he did rely on very preliminary published results on the working of the different CE-options and of the cost of their introduction. We argue that more recent insights into the impact of CE-techniques and their associated costs change the prospect and the evaluation of the different options for manipulating the climate system of the earth. Whereas Barrett was mostly focusing on the cost of running CE-measures, we argue that the overall economic cost are quite different from those that were estimated a few years ago. On this basis, we point out that in particular uncertainties about side-effects suggest that economic research should shift its focus to portfolios of CE-measures and put more emphasis on measures to control atmospheric carbon concentration in order to deal with the lock-in effect implied by the high social costs of a truncation of measures which directly influence the radiation balance.

*Keywords:* climate engineering, emission control substitution, reaction advantage, lock-in effect

*JEL:* Q52, Q54, Q55

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## 1. Introduction

The international consensus about limiting the average temperature increase to 2°C was confirmed once again at the recent meeting of the parties to the United Nations Framework Convention (UNFCCC) in Cancun (UNFCCC, 2010). But greenhouse gas emission (GHG) trends and the corresponding reduction announcements challenge the credibility of this target. Estimates in the World Energy Outlook (2010) show that while it is indeed still possible to meet this target via conventional emission control measures, dramatic emission cuts will be imperative in the near future (IEA, 2010). A postponement of these emission reductions would involve a drastic increase in mitigation costs and would seriously undermine the probability of staying within the 2°C target. In comparison with a more efficient mitigation course, the fairly moderate emission reductions in the Copenhagen Accord up to 2020 are estimated to involve an additional \$US 1 trillion in investment costs in the period from 2010 to 2035 (IEA, 2010). Expanding the cumulative emission budget for the period 2000 to 2049 from 1000 Gt CO<sub>2</sub> to 1437 Gt CO<sub>2</sub> would be sufficient to increase the maximum probability of exceeding the 2°C target from 42 percent to 70 percent (Meinshausen et al., 2009). Furthermore, even today's atmospheric GHG - notably carbon concentrations - cannot be regarded as safe with respect to potential tipping points in the climate system with dramatic climate change as a consequence (e.g., Lenton et al., 2008; Zickfeld et al., 2010). In the light of this development, it is not surprising that scientists have started discussing alternative technical measures for counteracting climate change. Climate engineering is the blanket term used to refer to such measures.

Climate engineering (CE) is defined as the large-scale manipulation of the earth's radiation balance for the purpose of mitigating anthropogenic climate change (e.g., Royal Society, 2009). The measures can be distinguished according to whether they influence the carbon concentration in the atmosphere (Carbon Dioxide Removal - CDR) or directly affect the earth's radiation balance (Radiation Management - RM). CDR measures address the root of the problem, but their limited potential means that it will take decades before they have an influence on temperature. On the face of it, a number of RM measures apparently hold out prospects of influencing temperature within a matter of years, but their actual application might lead to a new, artificial climate with various characteristics that are hitherto unknown. While at first sight CDR measures seem to be very similar to existing emission reduction measures, RM measures definitely provide a distinctive new option in the bid for climate change mitigation. This assessment is bolstered by initial estimates suggesting that the operational costs for these measures would be much lower than conventional emission control, implying that the global problem of climate change could be solved now by a single or small group of countries (Schelling, 1996; Barrett, 2008)

Accordingly, two central pillars in the debate about CE are discussed by economists: (1) What would be the optimal level of CE in an optimal climate change reaction portfolio, and (2) How is conventional emission control affected by the use of CE or possibly even mere research into CE? The assessment of these

issues is essential for decisions on whether and how the various CE measures might be applied and how their application might affect the future of international climate mitigation negotiations. This paper seeks to outline a framework for the discussion by providing an overview on the current knowledge we have about the feasibility and the costs of the various CE options. With a discussion of potential external effects, the cost overview encompasses not only operational but also social costs. On the basis of this overview and existing economic studies analyzing the implications of CE, the paper then investigates the insights available on the economic consequences of considering such technologies for the climate change reaction portfolio.

Attempts at engineering the climate for the modification of weather variables reach back to the 19th century (Fleming, 2010). As early as 1965, advisors of US President Johnson suggested counteracting the warming of the earth by spreading out reflective particles on the ocean. In the following decades, the debate focused more on the enhancement of natural carbon sinks. While the possibility of enhancing oceanic carbon uptake by iron fertilization has so far only been tested in small-scale field experiments, the possibility of enhancing terrestrial carbon uptake by land-use change and afforestation measures (LULUCF) was written into the Kyoto Protocol. Ideas about directly influencing the radiation balance (e.g., Budyko, 1977, 1982; Teller et al., 1996, 2002) regained a place in the climate change debate through the work of Crutzen in the year 2006. Based on the measurement of the effects of the Pinatubo eruption in 1991, he calculated the amount of sulfur that would need to be injected into the stratosphere to counteract the global warming resulting not only from continuously increasing greenhouse gas emissions but also from the expected loss of cooling due to reduced industrial sulfur emissions.<sup>1</sup> Since then, an increasing number of scientific publications have investigated the various options and their side-effects. In 2009, the Royal Society Report published an overview report of this kind that also discusses related political, ethical, and governance issues.

Economic matters related to CE were first addressed by Schelling (1996) in a special issue on the topic in *Climatic Change*. He points out that the CE option might turn the climate change problem upside down by reducing the global problem of emission control to a problem where a single state or a small group of states alone can decide on how to counteract climate change. Similar issues are explored by Barrett Barrett (2008), who concludes that the economics of CE present a very different set of incentives from mitigation. He argues that CE shifts the challenge from the payment issue that has hitherto been central to the climate change debate to a governance issue. Victor (2008) argues that, with respect to governance, we need to create major initial incentives for intensive research into, and assessment of, the various measures with a view to determining which measures qualify for inclusion in a CE portfolio. In his assessment he suggests that in the event of deployment, CE would probably not be restricted to a single measure but take the

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<sup>1</sup>Crutzen points out that industrial sulfur emissions counteract an ill-defined fraction of global warming from increased greenhouse gas emissions by reflecting solar radiation back into space. However, these sulfur emissions have severe impacts on human health and ecosystems so that political declarations were announced to reduce them. The cooling effect could be approximated by injecting a much smaller amount of sulfur not into the troposphere (like industrial emissions) but into the stratosphere, where the measure could also be extended to compensate for a doubling of atmospheric CO<sub>2</sub> concentration.

form of a portfolio of various CE measures, including compensation mechanisms. Kousky et al. (2009) also discuss a portfolio approach, concentrating on the risk of catastrophic climate change and arguing that a well-designed portfolio would comprise mitigation, adaptation, and CE measures.

This overview of the literature sets out to challenge two important aspects that have been taken for granted. One central assumption about CE is that it costs much less than conventional emission control. However, this assumption derives from scientific modeling studies and engineering feasibility studies that do not contain detailed cost estimates. Furthermore, research is advancing so fast that for several measures the cost estimates in the Royal Society (2009) are already outdated. Accordingly, the present article summarizes the most recent available information about the operational costs, discusses factors neglected in these estimates (like price effects), and explains why it is important to take a closer look at dynamic efficiency in comparing RM measures with CDR or emission control measures. Second, while a number of important economic issues related to CE have been addressed in the overviews referred to above, others have been largely ignored. A small number of papers have been published that analyze the economic aspects of CE from a theoretical or qualitative perspective in greater detail and with a special emphasis on incentives and strategic interactions. Accordingly, we review these papers and draw conclusions with respect to the new insights we can gain from them with respect to the impact that the consideration of CE measures might have and the economic consequences of actual CE implementation.

The paper is structured as follows. Section 2 briefly explains the climate system and the existing CE options that can influence it. Section 3 presents an overview of the currently available information related to the operational and social cost of various CE technologies. Section 4 reviews studies that analyze the implications of CE for the existing climate policy portfolio. A distinction is made between models which take a central planner's perspective (Section 4.1) and models which investigate the issue from a decentralized perspective (Section 4.2). Section 5 discusses and concludes.

## 2. Classification of climate engineering

For the classification of the various CE measures we consider a simplified representation of the earth's radiation balance based on Feichter and Leisner (2009) and Heintzenberg (2011). Short-wave solar irradiation on the atmosphere is determined by the solar constant  $S_0$ . About 70 percent of this irradiation is absorbed (51 percent by the earth's surface, 17 percent by aerosols and clouds in the troposphere, and 2 percent by ozone in the stratosphere). Accordingly, about 30 percent is reflected back into space by the atmosphere and the surface of the Earth. The relation of reflection to irradiation is called albedo,  $A$ . These two variables  $S_0$  and  $A$ , determine the earth's overall short-wave solar radiation energy input,  $F_{SW} = S_0(1 - A)$ . The irradiation absorbed is converted into latent heat and is returned to space as long-wave thermal radiation. Fraction  $\alpha$  of the long-wave thermal radiation is absorbed in the atmosphere mainly by water vapor and other

greenhouse gases (GHG). From there it is emitted back to the earth’s surface and out into space. Without this absorption, the average temperature on earth would be  $-18^{\circ}\text{C}$  instead of  $15^{\circ}\text{C}$ . On balance, solar irradiation  $F_{SW}$  is equivalent to thermal radiation,  $F_{LW}$ , the latter being determined by the temperature on the ground and in the atmosphere. From this simplified representation temperature  $T$  at ground level can be expressed as

$$T = \sqrt[4]{\frac{S_0(1 - A)}{2\sigma(2 - \alpha)}} \quad (1)$$

where  $\sigma$  is the Stefan Boltzmann constant (Feichter and Leisner, 2009). So far, anthropogenic intervention influences the albedo  $A$  and the absorption fraction  $\alpha$ . The former is mainly influenced by changes in land use and aerosol emissions, the latter by emissions of GHGs. Change in land use and aerosol emissions lead to an increase of  $A$  and hence produce a cooling effect compared to preindustrial levels. Overall, this cooling effect is outweighed by the warming effect from GHG emissions, which represent an increase of  $\alpha$  over and against its preindustrial level. The IPCC (2007) estimates that in sum the average net anthropogenic effect amounts to about  $+1.6$  ( $+0.6$  to  $+2.4$ )  $\text{Wm}^{-2}$ . Consequently, since the radiation budget is in a state of imbalance, the temperature of the earth is bound to increase. The reason why the radiative forcing induced so far has not been fully translated into a temperature increase has to do with the inertia of the earth’s climate system and in particular the thermal capacity of the ocean (e.g., Cess and Goldenberg, 1981; Knutti and Hegerl, 2008). The temperature reaction induced by the existing disturbance of the radiation balance is expected to take several more decades before it comes to full fruition (Hansen et al., 2005).

All variables in (1) can be influenced by RM measures. Accordingly, RM can be further distinguished according to whether it influences solar irradiation by changing  $S_0$  or  $A$  (Solar Radiation Management) or influences thermal radiation by changing  $\alpha$  (Thermal Radiation Management). CDR measures only influence  $\alpha$  by affecting the atmospheric carbon concentration. CDR measures can be further distinguished according to whether carbon removal is dominated by biological, chemical, or physical processes. Table 1 gives an overview of the various CE measures.

Table 1: Classification of various CE measures

|                              |   |                             |
|------------------------------|---|-----------------------------|
|                              | Reducing solar irradiation (lower $S_0$ ; SRM)                    | Space measures              |
| Radiation Management (RM)    |   | Stratospheric measures      |
|                              | Increasing albedo (higher $A$ ; SRM)                              | Cloud measures              |
|                              |   | Surface measures            |
|                              | Increasing $F_{LW}$ radiation (lower $\alpha$ ; TRM)              | Cloud measures              |
| Carbon Dioxide Removal (CDR) | Reducing $F_{LW}$ -absorbing atmospheric carbon (lower $\alpha$ ) | Biologically based measures |
|                              |   | Chemically based measures   |
|                              |   | Physically based measures   |

Source: Stephens and Keith (2008); Feichter and Leisner (2009); Heintzenberg (2011)

The classification in Table 1 is not entirely correct because feedback mechanisms mean that RM measures also influence carbon uptake, while changes on the Earth's surface mean that CDR measures can also influence the planetary albedo. The comparison between RM and CDR measures is anything but straightforward given that RM potential is usually measured in  $\text{Wm}^{-2}$  whereas the CDR is measured in carbon units (C), e.g. gigatons (Gt) C or atmospheric carbon concentration units (ppm). Neither of these units of measurement is readily translatable, since the influence of atmospheric carbon concentration on the radiation balance is non-linear. An increasing atmospheric carbon concentration implies that also increasing amounts of carbon have to be removed to observe the same change in the radiation balance.<sup>2</sup> Consequently, comparison between these two measures must take the prevailing atmospheric carbon concentration into account. In economic terms, we could say that the higher the atmospheric carbon concentration is, the less costly RM measures become relative to CDR measures as a way of changing the radiation balance. However, the higher the atmospheric carbon concentration already is, the longer RM measures have to be maintained until natural processes have reduced the atmospheric carbon concentration to a level where the RM measure can be discontinued. Accordingly, RM measures become more expensive in terms of accumulated costs. This issue is addressed in the next section.

### 3. Operational and social Cost

We can think of the cost of CE activities in three ways. The first (and most common one at present) looks at the cost of setting up and running a particular CE technology at current prices for capital goods and material inputs. The second perspective takes account of the fact that large-scale implementation of a certain CE technology will raise demand for certain materials and goods, so that their prices may rise significantly. Substantial expansion of certain industries may even be necessary to meet the demand for products required by a CE activity. Thirdly, the appropriate cost perspective for an analysis of the overall economic effects of a CE activity involves determining the social cost of the activity, i.e. looking at the operational costs plus the external costs - net, of course, of potential external benefits. At present, knowledge about the price effects and the social cost of CE is more or less non-existent.

Currently available information about the operational costs of CE activities allows only a rough estimate. The published cost estimates are based on modeling studies of the CE technologies and engineering feasibility studies, not on empirical tests. New modeling results about the necessary amounts of iron, lime, or sulfur to be spread out on the oceans or injected into the stratosphere will likely change the current cost estimates substantially. For example, the requisite amount of sulfur injected into the stratosphere to offset a warming corresponding to a doubling of atmospheric carbon concentration was estimated in the Royal Society Report

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<sup>2</sup>Given the atmospheric carbon concentration is 450 ppm, the necessary amount of carbon to be removed for a change of 1  $\text{Wm}^{-2}$  in the radiation balance is estimated to be about 178 Gt C; given the atmospheric carbon concentration is 750 ppm, this amount increases to 297 Gt C.

(2009) to be between 1 and 5 Mt S. More recent estimates suggest that between 9 and 10 Mt S is probably nearer the mark, provided it is spread out as sulfur trioxide or sulfuric acid over an area  $30^{\circ}\text{S}$  and  $30^{\circ}\text{N}$ . Otherwise the amount required could be as high as 75 Mt S (Heckendorn et al., 2009; Pierce et al., 2010). Consequently, the estimated operational costs for changing the radiation balance by  $1 \text{ Wm}^{-2}$  with this CE technology could go up to \$US 67 B (using existing airplanes) (Klepper and Rickels, 2011). In the Royal Society Report they were estimated to be about \$US 200 M.

Alongside the imponderables always inherent in theoretical modeling studies, one major uncertainty besetting estimates of operational costs from an economic perspective arises from price effects. Many CE technologies require large investments or complicated infrastructures and major material inputs in order to be effective from a global perspective. So they may have a strong impact on those markets representing the sources of such goods and materials. In the cost studies we have, these effects have been neglected. For example, measures like spreading out lime on the ocean or injecting salt aerosols into marine stratus clouds would require a huge number of ships, which in its turn would lead to a substantial demand shift on the global ship market. Similar effects can be expected for the global airplane market if measures like sulfur injection into the stratosphere were to be realized on a large scale. Price effects may also occur on the supply side of CE activities. Afforestation may increase the supply of wood once the trees mature; carbon capture may lead to the creation of  $\text{CO}_2$  certificates changing the market price of carbon. These effects may also lead to a change in relative prices in the world economy.

Scientific studies on the different CE technologies have shown that the use of CE may have unintentional side-effects, referred to in economics as “external effects”. It is essential to take these potential side-effects into account and include them in the analysis of the social cost of CE. They can take the form of external costs or external benefits. Side-effects can be related to the material in use or the spreading mechanism. They could also materialize as impacts on certain ecosystems or overall changes in the climate system.

Global side-effects may arise in the climate system if the greenhouse gas-induced change in the absorption of thermal radiation is compensated for by changing, say, the reflection of solar irradiation. The reason is that the greenhouse gas-induced radiative forcing is more or less equal across regions, whereas the negative radiative forcing of RM measures is strongest at places with high irradiation. Consequently, using RM measures to compensate for GHG-induced radiative forcing can be expected to result in effects that differ from region to region (e.g., Ricke et al., 2010). This regionally uneven change implies that other climate variables will also react to RM in a regionally differentiated way. For example, RM activities may successfully reduce the global temperature, but as a side-effect they may also lower precipitation in some regions of the world (Trenberth and Dai, 2007; Feichter and Leisner, 2009). However, these effects are not well understood yet, and current simulation models disagree on the impacts for various regions (e.g., Robock et al., 2008; Rasch et al., 2009; Jones et al., 2009; Ricke et al., 2010).

Given these uncertainties about the reaction of the earth system at both the local and the global level,

it is not surprising that we have no assessment studies that attempt to place an economic value on regional side-effects and in particular the side-effects related to the reaction of the climate system to RM activities. Since this is also true of the price effects of a large-scale deployment of RM and CDR, the currently available information consists merely of estimates relating to operational costs.

Table 2 gives an overview of the published estimates for CDR measures, including information on their potential, the expected investment requirements, and the major uncertainties related to these estimates. The table also indicates the side-effects that may arise, both positive and negative.

Table 2 does not include physical carbon removal techniques because the currently proposed methods are either not covered by our definition of climate engineering (carbon injection into the deep ocean) or cannot be considered effective CDR technologies (enhancing downwelling currents) (Keith, 2000; Zhou and Flynn, 2005, respectively). Also excluded are continental afforestation and oceanic macro-nutrient fertilization measures, which could be realized either by nutrient supply from land via pipelines or from the deep ocean via artificially enhanced upwelling. These biological carbon removal measures are omitted from the discussion because they are either inefficient or ineffective (Lampitt et al., 2008; Bathiany et al., 2010; Oschlies et al., 2010).

The cost estimates in Table 2 show that the operational costs of the CDR techniques are within the range of the costs that have been projected for conventional emission control for the year 2035, for example by the IEA (2010). However, such a comparison is not entirely above criticism, one reason being that it significantly underestimates the total cost of CDR. Various CDR technologies are expected to require large investments in installations and logistic infrastructures, and these investments are frequently omitted from the estimates of the operational costs in Table 2. In addition, the operational cost of a CDR technology refers to the outlays for input, labor, and capital, whereas the marginal abatement cost of emission control is defined as the amount of social product (GDP) lost if the emissions of a ton of CO<sub>2</sub> are avoided. Accordingly, emission control costs take into account the processes of adjustment with which an economy responds to the increasing demand for resources and the accompanying price effects. Those processes are ignored in the operational cost computations for CE measures. Another economic source of expenditure left out of account both in the operational cost of CDR and in the abatement cost of emissions is associated with the external effects of CDR and emission control respectively. The external costs of CDR tend to be negative, thus prompting underestimation of the overall economic cost. There is only one aspect that can contribute to a lower estimate of the cost of CDR, namely technological progress and the scale effects possibly occurring in conjunction with the large-scale deployment of CDR measures.

Table 2: Overview of current operational cost estimates and potential side-effects for various CDR technologies

| Measure  | Potential                                    | Operational costs in \$US/tCO <sub>2</sub> | Main investment requirements   | Uncertainties   | Side-effects  | Sources  |
|--|--|--|--|---|---|--|
| <b>Biological based carbon dioxide removal</b>                       |  |  |  |   |   |  |
| Bio-char production  | 5 Gt CO <sub>2</sub> /year                   | 45 (15-76)                                 | Bio-char production units  | Net carbon storage potential due to use as energy source; use as fertilizer may reduce costs  | Use as fertilizer increases net primary production; residuals from pyrolysis process might limit application for food production                                      | Chan et al. (2008); Asai et al. (2009); van Zwieten et al. (2009); McCarl et al. (2009); Washington State University (2009); Woolf et al. (2010); Roberts et al. (2010); de Gryze et al. (2010); Major et al. (2010)     |
| Southern Ocean iron fertilization                                    | 5 Gt CO <sub>2</sub> /year                   | 45 (8-82)                                  | Iron sulphate production and treatment, ship fleet for spreading (20-500 ships)  | Necessary amount of iron sulphate; coagulation of iron sulphate; increase in export production; leakage (even though accounted for in the estimate for potential) | Impacts on marine biogeochemistry, ecology, and biodiversity; increases nutrient supply for fish stocks, change in OMZ, temporary acceleration of ocean acidification | Chisholm and Morel (1991); de Baar et al. (2005); Zeebe (2005); Aumont and Bopp (2006); Boyd et al. (2007); Boyd (2008); Smetacek and Naqvi (2008); Oschlies et al. (2010); Rickels et al. (2010); Wallace et al. (2010) |
| Afforestation  | 4 Gt CO <sub>2</sub> /year                   | 60 (19-101)                                |  | Measurement of carbon uptake and leakage varies between studies; unintended carbon release due to fire, storms; impact on albedo                                  | Ecological effects and implication for biodiversity; land requirements  | Ellis (2001); Murray (2003); van Kooten and Sohngen (2007); Royal Society (2009)   |
| <b>Chemical based carbon dioxide removal</b>                         |  |  |  |   |   |  |
| Spreading pulverized olivine   | 4 Gt CO <sub>2</sub> /year                   | 42 (27-57)                                 | Exploitation, transport, pulverization, and spreading infrastructure   | Access to target area (tropical catchment areas of large rivers) for spreading  | Increase in soil and oceanic pH value; ecological impacts (e.g. input of silicic acid into oceans)  | Schuiling and Krijgsman (2006) Hangx and Spiers (2009) Köhler et al. (2010)  |
| Spreading pulverized calcium hydroxide                               | 1.5 Gt CO <sub>2</sub> /Gt CaCO <sub>3</sub> | 50 (45-54)                                 | Exploitation, transport, thermal treatment, storage for separated CO <sub>2</sub> , fleet for spreading (about 3000 ships) | Exploitation and spreading logistics, uptake limited due to ocean circulation, storage of separated CO <sub>2</sub>   | CCS-related side-effects; reduced ocean acidification   | Kheshgi (1995); Harvey (2008); Cquestrate (2008)   |
| Spreading pulverized lime  | 0.3 Gt CO <sub>2</sub> /Gt CaCO <sub>3</sub> | 65 (57-72)                                 | Exploitation, transport, pulverization infrastructure, fleet for spreading (between 4000 and 6000 ships)                   | Exploitation and spreading logistics, uptake limited due to ocean circulation   | reduced ocean acidification   | Harvey (2008)  |
| Air Capture (sodium hydroxide)                                       | 1.0-1.2 Mt CO <sub>2</sub> /unit/year        | 250 (69-430)                               | \$US 247-480 M/unit  | Storage of captured carbon, energy provision  | CCS related side-effects  | Pielke Jr (2009); Keith (2009); Lackner (2009, 2010); Dai et al. (2010); Socolow et al. (2011)   |
| <b>Comparison to existing abatement technologies</b>                 |  |  |  |   |   |  |
| Conventional emission control for limitation to 2°C increase by 2050 | 21 Gt CO <sub>2</sub> (in 2035)              | 90-120 (in 2035)                           | \$US 940 B/year (2020-2035) \$US 1280 B/year (2030-2035)   | Simulation results  | Side-effects associated with nuclear power, CCS, and biofuel production   | IEA (2010)   |

Detailed derivation of estimates can be found in Klepper and Rickels (2011).



Table 3: Overview of current operational cost estimates and potential side-effects for various RM technologies

| Measure   | Annual potential in $\text{Wm}^{-2}$ | Operational costs in B $\text{\$/Wm}^{-2}$  | Main investment requirements   | Uncertainties   | Side-effects   | Sources   |
|---|--------------------------------------|---|--|---|--|---|
| <b>SRM surface measures</b>   |                                      |   |  |   |  |   |
| Modification of crop and forest albedo  | -1                                   | No quantitative assessment available, but operational costs and investment requirements are expected to be relatively low   |  | Genetic modifications; replacement of existing plants   | Increases effectiveness of afforestation; side-effects due to genetic modifications  | Ridgwell et al. (2009); Royal Society (2009)  |
| <b>SRM cloud measures</b>   |                                      |   |  |   |  |   |
| Modification of marine stratus clouds by injection of salt aerosols from Flettner ships | -4                                   | 0.135   | R&D $\text{\$US 27 M}$ ; Setting-up $\text{\$US 30 M}$ ; Ship fleet $\text{\$US 1.7 B}$ ; additional logistic and maintenance costs (e.g. ports) | Automatic operation of ships; replacement and maintenance requirements; Flettner rotors   | Salt is non-toxic and residence time is low (< 2 weeks); climatic side-effects   | Latham et al. (2008); Salter et al. (2008); Jones et al. (2009); Rasch et al. (2009)  |
| <b>TRM cloud measures</b>   |                                      |   |  |   |  |   |
| Modification of cirrus clouds by injection of bismuth (III)-iodide                      | -1 to -4                             | No quantitative assessment available. Spreading is suggested to be done from airplanes on scheduled flights, implying cost in the order of magnitude or even lower as for modification of marine stratus clouds; otherwise cost estimates from sulfur injection can be applied; understanding of cloud dynamics low and in turn necessary spreading amounts are highly uncertain. |  |   | Bismuth (III) iodide is non-toxic and residence time is low (<2 weeks); climatic side-effects  | Sanderson et al. (2008); Mitchell and Finnegan (2009); Mitchell (09.02.2011)  |
| <b>SRM stratospheric measures</b>   |                                      |   |  |   |  |   |
| Sulfur injection; existing airplanes (>18km)  | Unlimited                            | 16-67   | Airplane fleet $\text{\$US 18-56 B}$ ; base station $\text{\$US 1 B}$ per unit   | Coagulation between already existing and newly injected particles and therefore spreading amount; estimation of fuel costs; sulfur logistics; existing airships would only allow spreading height of 6 km | Recovery of ozone layer slows down; increase of anthropogenic sulfur emissions by 10 to 17 percent; ratio of diffuse irradiation to direct irradiation increases resulting in higher net primary production and lower solar power generation; perception of sky changes (less blue skies, more red sunsets); space observation affected; climatic side-effects | Rasch et al. (2008a,b); Robock (2008); Robock et al. (2008); Tilmes et al. (2008); Robock et al. (2009); Kravitz et al. (2009, 2010); Heckendorn et al. (2009); Murphy (2009); Mercado et al. (2009); Pierce et al. (2010); Keith (2010); McClellan et al. (2010); Ricke et al. (2010); Jones et al. (2010) |
| Sulfur injection; newly designed airplanes (>18km)                                      | Unlimited                            | 2-12  | Airplane fleet $\text{\$US 6-36 B}$ ; base station $\text{\$US 1 B}$ per unit  |   |  |   |
| Sulfur injection; newly designed airships (>18km)                                       | Unlimited                            | 5-18  | Airship fleet $\text{\$US 19-66 B}$ ; base station $\text{\$US 1 B}$ per unit  |   |  |   |
| Injection of engineered nanoparticles   | Unlimited                            | No quantitative assessment available; prototypes do not exist; irrespective of construction costs, spreading amount estimated to be 0.1 Mt implying cost reductions up to the order of 200 in comparison to sulfur injection  |  |   | Residence time of nanoparticles; climatic side-effects   | Keith (2010)  |
| <b>Comparison to existing abatement technologies</b>                                    |                                      |   |  |   |  |   |
| Conventional emission control (450 to 550 ppm $\text{CO}_2$ by 2100)                    | -2 to -5                             | 200   | $\text{\$US 940 B/year}$ (2020-2035) $\text{\$US 1280 B/year}$ (2030-2035)   | Time period for comparison; based on annual share of GDP (0.5 to 1 percent); simulation results   | Side-effects associated with nuclear power, CCS, and biofuel production  | Royal Society (2009); IEA (2010)  |

Detailed derivation of estimates can be found in Klepper and Rickels (2011).

We turn now to the different RM technologies that have been proposed. As in the case of CDR, knowledge about the cost of RM is confined mostly to the operational side, whereas little attention has been paid so far to market and price effects or external costs. Table 3 provides an overview of the available estimates on operational costs for potential RM measures on an annual basis, including information on the potential, the investment requirements, the main uncertainties involved in these estimates, and the potential side-effects. Again, the potential effects of demand on markets for inputs in RM technologies do not figure in the operational costs. The table also shows the positive and negative side-effects that could potentially influence the social cost of RM.

Table 3 does not show measures for modifications in space designed to change solar irradiation. Such measures, e.g. placing mirrors in the earth's orbit, are highly inefficient and exceed the Royal Society estimate based on conventional measures by a factor of between 8 and 9 (Klepper and Rickels, 2011). Nor does the table feature surface measures addressing the albedo of urban areas (e.g. roofs and streets), deserts, and the ocean surface, because these measures are either ineffective on a global scale, inefficient, or based on a technology that is as yet non-existent (Klepper and Rickels, 2011). The technology for the modification of marine stratus clouds refers only to Flettner ships. Technically speaking, the modification could also be performed by airplanes, but there are no studies available on such an approach.

The overview of the various RM technologies shows that in particular marine stratus and potentially cirrus cloud modification are relatively cheap in terms of operational costs. Bearing in mind the cost development of stratospheric sulfur injection since the publication of the Royal Society report referred to earlier, it seems likely that the estimated costs for these technologies will also increase. Nevertheless, the estimated costs for sulfur injection into the stratosphere with existing airplanes would seem to be affordable for a rich country or a small group of rich countries. However, all measures that look to be capable of reducing the radiative forcing associated with a doubling of atmospheric CO<sub>2</sub> concentration to pre-industrial levels potentially involve large external effects on the climate system. As we have said, these effects are not yet well understood, but they certainly have the potential to cause high social costs.

As set out in the previous section, a comparison between RM measures and CDR or conventional emission control measures is by no means straightforward. Alongside the non-linear relationship between atmospheric carbon concentration and changes in radiative forcing, the comparison is bedeviled by differences in the intertemporal features of RM over and against CDR and emission mitigation. Whereas CDR measures address the root of temperature increase by lowering atmospheric carbon concentration, RM measures have to be sustained until natural processes have sufficiently lowered atmospheric carbon concentration. Consequently, comparison between the cost of CDR and of RM activities depends crucially on the reference period chosen.

The Royal Society (2009) bases its comparison on the period up to 2100. The assumptions are that an unmitigated scenario will result in an atmospheric carbon concentration of 750 ppm in the year 2100,

which will be reduced to a stabilization scenario (450 to 550 ppm) by emission control. The accumulated cost of this emission control scenario is translated into cost per  $\text{Wm}^{-2}$  per year and is then compared to the cost of RM measures per  $\text{Wm}^{-2}$  per year. This approach ignores the fact that in 2100 emission control would result in a comparatively low  $\text{CO}_2$  concentration. By contrast, if the same temperature had been achieved via RM, the atmospheric concentration would still be about 750 ppm. As a consequence, the RM measures would have to be maintained until the concentration had declined by natural processes to levels that are not considered harmful. Consequently, the comparison of costs presented in the Royal Society (2009) overestimates the costs of conventional emission control, since it does not include the follow-up cost of maintaining RM activities for temperature control. A truly appropriate cost comparison would have to be based on a dynamic analysis in which the cost of achieving the effect on temperature obtained by the mitigation of a given emission - say one Gt  $\text{CO}_2$  - is compared to the cost of achieving this same temperature effect by means of an RM measure. To the best of our knowledge, a dynamic cost comparison of this kind has yet to be attempted, but it would be highly desirable for comparisons between RM, CDR, and emission control.

#### **4. Economic models of climate engineering**

As we saw in the previous section, the information about operational costs available at present only allows for a very limited comparison with existing mitigation measures. Economic adjustment processes to a large-scale deployment of climate engineering measures are not included in these estimates. Furthermore, no reliable cost estimates exist for the external effects. Accordingly, economic analyses on climate engineering have so far been restricted to analytical approaches deriving general implications of CE from theoretical models and (illustrative) quantitative results based on highly aggregated simulation models like DICE. The existing literature focuses on RM measures because on the face of it these represent a distinctive new option with respect to their effectiveness in influencing the radiation balance, their ostensibly low operational costs, and not least their novelty value in the climate change reaction portfolio. Research approaches can be divided into those that investigate CE from a central planner's perspective and those that adopt a decentralized perspective.

##### *4.1. Centralized climate engineering decisions*

We begin by discussing the research that investigates the globally optimal application of CE in a static framework. In such a framework there do not appear to be many new insights to be gained from analyzing CDR measures, as their economic impact would only differ from existing emission control with respect to cost. However, including both RM and CDR measures would allow for factoring in feedback mechanisms like the positive effect of a temperature decrease caused by the application of RM on carbon uptake by biologically based CDR measures.

Moreno-Cruz and Smulders (2010) consider these feedback mechanisms to some extent, although they only consider RM measures and conventional emission control. In their theoretical model, the sum of mitigation costs and global damage costs are minimized in a static framework, while mitigation costs are determined by the application of conventional emission control and RM measures. Social costs are determined by atmospheric carbon concentration, temperature increase, and side-effects of RM. The influence of the atmospheric carbon concentration on social costs is non-monotonic because the authors consider both external benefits with respect to a CO<sub>2</sub>-induced increase in plant productivity and external costs with respect to CO<sub>2</sub>-induced ocean acidification. The temperature is determined by the atmospheric CO<sub>2</sub> concentration and the application of RM measures, while temperature in its turn also affects natural CO<sub>2</sub> uptake. Consequently, the temperature feedback effect from RM measures on carbon uptake is included in the analysis but not the possibility of any complementary effects with CDR measures.<sup>3</sup> The influence of temperature and side-effects of RM on social costs is monotonic and convex, as is the influence of emission control and RM measures on mitigation costs.

The results of the model are straightforward. Given that it is possible to increase welfare by the application of RM, RM is used in such a way that marginal costs are equal to marginal benefits and conventional mitigation measures are to some extent substituted for by RM. The substitution effect depends on the curvature of cost functions for both measures. Additionally, the substitution effect is limited by the influence of CO<sub>2</sub> concentration on economic damages, which is negative once a certain concentration threshold has been exceeded. However, the important result that Moreno-Cruz and Smulders (2010) come up with is that the application of RM does not necessarily imply a higher atmospheric carbon concentration but may even produce a lower concentration compared to the situation where only mitigation measures are in use. This result depends on the magnitude of the substitution and the feedback effect on natural carbon uptake.

The authors show that it is possible to construct a situation where zero or even negative values for the optimal carbon emission tax occur. In this theoretically specified case, the effect of increased carbon concentration on the global temperature is controlled via RM measures. At the same time, the benefits of an increased fertilization effect are so high that the carbon concentration deriving from emission control measures would be too low.

The crucial assumption for the results in the paper by Moreno-Cruz and Smulders (2010) is that the application of RM makes it possible to increase global welfare, or, to put more explicitly, that the social benefits induced by the reduction of temperature will outweigh the social costs accruing from the side-effects. This central assumption is further investigated by Moreno-Cruz et al. (2010). They determine the optimal level of RM with respect to external effects in the climate system by drawing on the findings of the study

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<sup>3</sup>Beside the positive temperature effect, it would also be legitimate to consider the positive effect on carbon uptake deriving from the increase in diffuse irradiation over and against direct irradiation as a result of stratospheric sulfur injection (Mercado et al., 2009).

by Ricke et al. (2010).<sup>4</sup> While on a global average the application of RM does indeed make it possible to compensate for a greenhouse gas-induced temperature increase, the extent of this compensation will vary regionally. Moreover, other climate variables like precipitation or polar ice coverage may be either too large or too small compared with the original situation. To account for these effects, the authors use a residual vector model that measures the deviation in temperature and precipitation from the situation without climate change. As mentioned, the application of RM does not make it possible to reverse both variables to the situation without climate change. The residual vector model measures aggregated squared residuals of these two variables on an annual basis for various regions on the earth. The variables are normalized and measured in standard deviations obtained from the situation without climate change to account for regional variability. The authors determine the global optimal level of RM by minimizing the regional aggregated deviations weighted by population, economic output, or land area.

With this model they are able to show that while such a globally optimal level leads to a high degree of compensation for both temperature and precipitation, there are also regions where the deviation is larger than it would be with unmitigated climate change. These regions would suffer a reduction in welfare from the globally optimal policy. Therefore, instead of looking for a globally optimal RM level, the authors suggest going in search of find a Pareto-improving RM level. The Pareto-improving level is determined by increasing the RM level until an additional amount of RM would start to make a region worse off again with respect to the aggregated squared deviation in temperature and precipitation.

Based on the data by Ricke et al. (2010), the region determining the Pareto-improving RM level is Western Africa, with an RM level that is 78 percent of the global optimum. The authors argue that a Pareto-improving RM level would be possible, implying that every region or country would have an incentive to accept such an RM level. However, it should be noted that this conclusion is based on the deviation in physical units and not on a monetized and regionalized impact assessment. In addition, precipitation and temperature change is equally weighted, even though some regions might be more seriously affected by temperature, others by precipitation, and others again by the change in the variability of these variables. Finally, the analysis does not consider “climate change winners” because it measures the deviation from the situation without climate change without taking account of the fact that various regions stand to gain from climate change. In fact, from the “climate change winners” perspective, it seems doubtful whether a Pareto-improving RM level actually exists. Nevertheless, to our knowledge this paper is the first to address regional variation in side-effects and highlights the fact that the optimal level of RM is not necessarily the one that fully offsets greenhouse gas-induced temperature increase.

Adopting a dynamic perspective makes it possible to analyze one distinctive feature of RM measures: their reaction advantage over existing mitigation options in the presence of unforeseen climate change dy-

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<sup>4</sup>Ricke et al. (2010) use the general circulation model HadCM3L to investigate the regional change in temperature and precipitation caused by a doubling of CO<sub>2</sub> concentration with and without RM compensation.

namics. It also enables us to investigate the implications of controlling for the increase in global temperature while doing nothing to address the root of the problem. Moreno-Cruz and Keith (2009) analyze these features by considering two different decision-making stages with a time interval between them. In the first stage, uncertainty exists about the climate sensitivity revealed in the second stage. In the first period, the optimal level of emission control is determined, and once climate sensitivity is known, the optimal level of RM is chosen based on this new information. The economic damages are determined by the CO<sub>2</sub> concentration, the side-effects of RM, and the temperature increase, the influence of the three variables being additive-separable, monotonic, and convex. Consequently, in contrast to Moreno-Cruz and Smulders (2010), positive CO<sub>2</sub> fertilization effects are not considered. The temperature increase is determined by climate sensitivity. The mitigation costs are convex, while the costs of RM are linear, implying that the level of RM is determined by its effectiveness in decreasing temperature and its side-effects. The mitigation costs and social damages due to increased temperature are calibrated with Nordhaus' DICE model (2008), while the social damages due to the increase in CO<sub>2</sub> concentration are calibrated based on the analysis by Brander et al. (2009). With respect to the effectiveness of RM in decreasing temperature and the influence of its side-effects on social damages, various scenarios are considered.

This model set-up captures the uncertainty of climate change and with it the difficulty of determining the optimal mitigation level in advance. As pointed out by Solomon et al. (2009), it may be the case that even today's CO<sub>2</sub> concentration is already sufficient to trigger irreversible damage via sea-level rise or changes in precipitation patterns. As expected, the authors confirm the substitution effect between RM and mitigation. The higher the effectiveness of RM and the lower the impact of the side-effects of RM, the lower the mitigation effort at the first stage will be. However, the authors also show that even in the case of low effectiveness and high side-effect impact, RM will be used to some extent at the second stage if climate sensitivity turns out to be substantially high based on the convexity of the optimization problem.

The inter-temporal substitution effect illustrates the insurance character of RM measures. If there is a measure that is conducive to response if climate change turns out to be worse than expected, it will be optimal to choose a lower level of precaution. Moreno-Cruz and Keith (2009) also analyze the case where the benefit of an RM measure is in itself uncertain with respect to effectiveness in lowering temperature. As expected, this results in higher mitigation efforts at stage one compared to the case with complete knowledge about effectiveness. The authors argue that in a situation like this emission control and RM become risk complements.

These implications of CE and particularly RM are confirmed and extended in the articles by Gramstad and Tjøtta (2010) and Goes et al. (2011). Both apply the DICE model taken from Nordhaus (2008) and consider four scenarios: 1) business as usual (BAU), 2) optimal emission control, 3) optimal emission control and RM application, and 4) optimal application of RM only. Both articles show that the third scenario (emission control plus RM) is optimal with respect to social welfare and confirm the substitution effect

between emission control and mitigation in this scenario. Gramstad and Tjøtta also indirectly confirm the reaction advantage of RM by showing that in the optimal scenario (3) there are only minor welfare losses associated with postponing RM action for 20 or 30 years.

However, with respect to the insurance character of RM, Goes et al. (2011) show that welfare losses in the fourth scenario exceed even those in the BAU scenario (compared to the optimal scenario) if the application of RM is interrupted. Though this result is based on a modified damage function placing additional weight on the rate of temperature change, it shows that the insurance character of RM might be lost owing to the possibility of interruption, which would imply possible rapid climate change (e.g., Matthews and Caldeira, 2007; Brovkin et al., 2009; Ross and Matthews, 2009). Nevertheless, it should be noted that the results are derived from the scenario with only RM application to counteract climate change. As pointed out by Bickel and Agrawal (2011) assuming that the application of RM is still accompanied with some level of emission control or a least an sufficient increase in emission control is possible once RM application is truncated, increases the number of scenarios with RM application which pass cost-benefit tests.

The analysis of Bickel and Agrawal (2011) shows that more emphasis should be put on possible scenarios how to phase out RM application. Despite its advantage in responding to rapid climate change, the use of RM as an insurance might result in a lock-in effect. This idea is developed e.g. by Brovkin et al. (2009). In their analysis, the authors consider the application of various levels of RM to reduce the temperature increase associated with a cumulative emission of 5000 Gt C, where 90 percent of this amount is emitted in the period between 2000 and 2300.<sup>5</sup> Their emission scenario results in a peak temperature increase by 7 °C in 2350. The authors show that the application of RM allows for temperature reduction and results in a lower CO<sub>2</sub> concentration than the one modeled without RM compensation. However, they point out that the compensating effect of RM would need to be maintained for several thousand years because even in year 10000 there would still be 40 to 60 percent of the emitted carbon in the atmosphere. The results produced in Brovkin et al. (2009) underline the fact that an analysis of CE measures needs to consider CDR and RM measures simultaneously.

Rickels and Lontzek (2011) analyze the potential of CDR measures in a dynamic context by considering the possibility of increasing oceanic carbon uptake, but again in an isolated manner without the simultaneous consideration of RM measures. Their analysis follows in the footsteps of Marchetti (1977), who suggested injecting carbon directly into the ocean.<sup>6</sup> This measure may not be climate engineering in the strict sense of the term, as the measure would require capturing industrial CO<sub>2</sub> emissions and does not remove carbon from the atmosphere. But Rickels and Lontzek analyze this measure in a rather stylized way so that the

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<sup>5</sup>Though this amount seems to be rather high in absolute terms, it implies lower carbon emissions in the period from 2000 to 2100 than the SRES A2 Scenario of the IPCC. It also represents a rather conservative estimate for the earth's fossil fuel resources. The analyses by Sinn (2008) and Edenhofer and Kalkuhl (2009) show that there is good reason to believe that a large fraction of these resources will be used.

<sup>6</sup>Marchetti (1977) was the first author to use the term geo-engineering in the context of climate change mitigation.

results also apply to oceanic CDR measures like iron fertilization or chemical enhancement of alkalinity. The authors show that applying this measure extends the period in which fossil fuels can be extracted in reasonable amounts. Without this measure, extraction amounts of extraction would necessarily decline much earlier due to the inertia of the carbon cycle.

Furthermore, they show that atmospheric carbon peak concentration is lower if the technology is applied but that the long-term atmospheric carbon stabilization level might increase due to the fact that the ocean becomes supersaturated with anthropogenic carbon resulting in carbon leaking back into the atmosphere in the long-run. This issue raises the question how to deal with CDR technologies that involve carbon leakage or temporary storage characteristics. The assessment of temporary versus permanent storage requires a positive value for time. The Kyoto-protocol defines the period of 100 years as basis for the assessment of permanence (UNFCCC, 1997), implying a discontinuous value of time. This decision was not based on scientific rationale but on a political will (Leinen, 2008).

Not just to this respect, discussion of the pros and cons of CE measures calls for an assessment of their potential impacts on climate change and potential side-effects that reaches well into the future. For such an assessment, the determination of appropriate social discount rates is crucial. This topic goes beyond the scope of this article, and we refer to e.g. Dasgupta (2008) and Heal (2009) for recent overviews of the aspects to be considered.

#### *4.2. Decentralized climate engineering decisions*

In analyses of centralized climate engineering decisions, one crucial assumption is that the application of CE - and in particular RM measures - will actually bring about an improvement of global welfare that still needs to be empirically validated. It is very unlikely that this assumption will be fulfilled for single regions or countries. If this is not the case, the question arises as to whether a small number of countries might choose to use RM measures without international consent. This is feasible for a number of measures if one considers the implementation costs and their effectiveness in controlling temperature (Schelling, 1996; Barrett, 2008, 2009). Consequently, the scientific community has a particular interest in papers that investigate the use of RM from a perspective where several actors may decide independently on the RM measure. The different actors do not necessarily need to represent different countries. They could also represent different generations.

In a static framework, this issue is addressed in the second part of the article by Moreno-Cruz and Smulders (2010). Again, social damages are determined by the CO<sub>2</sub> concentration, temperature increase, and side-effects caused by RM, as set out in the previous section. The authors consider  $n$  actors, e.g. countries, where one actor can unilaterally deploy RM. The remaining  $n-1$  actors can only determine their level of emission control. Each of the  $n-1$  countries minimizes its own social costs (the cost of emission control plus economic damages), taking into the account the emission control measures opted for by the other actors and the level of RM chosen by the one actor. The unilateral actor minimizes global social costs



by selecting the level of RM, taking the emission control opted for by the  $n-1$  actors as given.

In such a situation, the substitution effect between emission control and RM action is influenced by the free-rider problem. From a global perspective, countries would choose a lower level of emission control than is optimal even without the unilateral RM deployment. The possibility of using RM amplifies the free-rider effect, resulting in even lower emission control plus higher RM deployment than is globally optimal.

To our knowledge, there are no other analyses discussing the implications of RM deployment from a decentralized perspective, which is surprising. In particular, the static analysis by Moreno-Cruz et al. (2010) referred to in the previous chapter would be an interesting starting point for a decentralized optimization perspective, with respect not only to the optimal level of RM but also to new incentives with a bearing on climate change negotiations. Rickels et al. (2011) discuss the latter point with reference to CDR. They analyze the implications of integrating carbon credits from large-scale iron fertilization into a static compliance problem for the year 2020. Besides analyzing the market requirements (prices, amount of carbon credits) for iron fertilization to compete with emission control and afforestation, they also investigate the distributional impacts.

As expected, their results indicate that “carbon credit selling countries” (most of them developing countries) experience a reduction in profits whereas “carbon credit buying countries” are more or less indifferent between extending carbon credit supply from CDM activities and opting for carbon credit supply from iron fertilization instead. The authors argue that it might be possible to design a new option in which allocation of carbon credits from iron fertilization is conditional on accepting emission reduction targets. This would create new incentives for developing countries to join a global climate regime, while developed countries are more or less indifferent. Overall, the new option would require more ambitious emission reduction targets to ensure carbon price stability.

Such new incentives for mitigation of climate change by CDR measures might require modifications to the negotiation framework for international climate treaties. This question is addressed in an intertemporal framework by Barrett (2010), who analyzes possible international treaties about the level of emission control and air capture. He assumes the cost of emission control to be convex and that of air capture to be linear and relatively high. Furthermore, he assumes that applying air capture does not in itself imply social damages due to side-effects. Barrett posits a three-stage decision game. In stage one, countries decide on whether to participate in an international treaty, in stage two those participating decide on their level of emission control and/or air capture, while in stage three non-participants decide on their level of emission control/air capture. He argues that separate treaties for emission control and air capture are not cost-efficient due to the difference in marginal costs for the measures, while due to the relatively high constant marginal costs of air capture, a combined treaty based on cost-effectiveness might not be self-enforcing. Consequently, if new measures like air capture are integrated into international treaties, the preference for cost-effectiveness would need to be reassessed. Cost-effectiveness in second-best treaty arrangements might imply that air

capture would not be used, even though its usage would increase welfare. Barrett argues that, in such a situation, separate treaties covering the different technologies may be superior to cost-effectiveness.

Analyses of globally optimal CE measures have identified a fundamental substitution effect between emission control and CE. This may no longer be true if consideration extends to a large number of actors valuing the use of CE differently. This eventuality is investigated by Moreno-Cruz (2010). He uses the basic model set up by Moreno-Cruz and Keith (2009), but transfers it to a two-country decision problem where countries are differently affected by climate change and the side-effects of RM. In the two-stage decision problem, both countries decide simultaneously about emission control in stage one and about RM action in stage two. In stage two, the social damages due to climate change and the side-effects of RM are known, i.e. there is no uncertainty about climate sensitivity. Again, countries minimize social costs resulting from the expense of emission control/RM action plus economic damages. First, the author considers the case where both countries are similar in their perception of climate change and RM-related social damages. Once more, the outcome confirms the technical substitution effect between emission control and RM action, resulting in lower aggregate emission control in stage one. In contrast to Moreno-Cruz and Keith (2009), this result is based on cost-effectiveness only and not on the reaction advantage of RM action with respect to uncertain climate sensitivity. Alongside the substitution effect, the two-country decision problem is also affected by the free-riding factor. Both countries anticipate that a lower level of emission control will result in a higher level of RM action in the second stage and have an incentive to realize lower emission control in the first stage. However, the author argues that because the two countries are very similar, the influence on emission control is dominated by the substitution effect and not by the strategic effect.

Turning to a more interesting case, the author assumes that the countries are differently affected by climate change and RM-related side-effects. He demonstrates that a situation may arise in which one country does not take RM action in the second stage because it is strongly affected by these side-effects. Despite this, the other country will still take RM action conditional on the aggregate emission level observed in stage one. Accordingly, the country strongly affected by RM-related side-effects has an incentive to increase its emission control in stage one so that the other country will choose a lower level of RM in stage two. The author points out that this effect might result in a situation where aggregate emission controls exceed that in a situation where the option of RM action is not available. Such a situation could arise if one country is assumed to be “climate change winner” and the other country a “climate change loser”. The former would have little incentive for emission control. If it is also an “RM loser” it will have an incentive to increase emission control, taking into account that the “climate change loser” has a strong incentives to choose a high level of RM.

Note that the results in Moreno-Cruz (2010) do not necessarily require the countries to be differently affected in physical or economic terms. It would be sufficient for them to value RM-related side-effects differently, due, say, to ethical considerations. This idea is taken up in the analysis by Goeschl et al. (2010),

where the authors consider two generations which do not overlap. Effectively, they also use a two-stage decision problem in which uncertainty about climate sensitivity exists. It is assumed that climate sensitivity and hence the related climate change-induced social damages are either high or low. The uncertainty about climate sensitivity is revealed in stage two, and the economic damages are also only realized in stage two. The first generation decides on its level of emission control and whether or not it intends to invest in R&D for the development of RM measures. This latter decision determines the availability of the option of taking RM action in stage two. Consequently, the second generation decides about whether it will use RM or not, provided the necessary R&D has been done in stage one. RM action also causes side effect-related economic damages. The first generation behaves altruistically, minimizing the sum of emission control costs, R&D investment, and economic damages, where the latter are only realized in stage two. The costs for emission control are assumed to be convex, the R&D investment costs for the development of RM to be a fixed amount, and the cost of RM action in stage two to be zero. The social damages caused by RM-related side-effects are assumed to be linear and the social damages caused by climate change to be convex, implying convex benefits for RM action.

However, the distinctive feature of the model proposed by Goeschl et al. (2010) is that the economic damages are assessed differently between generations and that the first generation takes into account this possibility in its altruistic optimization decision. In the reference case without different assessment, the first generation invests in R&D, and the second generation takes RM action if climate sensitivity turns out to be high. Again the substitution effect is observed, implying a lower level of emission control in stage one than would have been chosen without the RM option. The authors then analyze the case where the second generation's assessment of the economic damages caused by RM-related side-effects is lower than that of the current generation. Consequently, the second generation might also have an incentive to take RM action if climate sensitivity turns out to be low, even though this was not intended by the first generation. As a result, the first generation deviates from optimal behavior in the reference case. Three strategic options are available for the first generation: (1) increasing emission control and investing in R&D so that the second generation has lower incentives for RM action; (2) increasing emission control but refraining from R&D investment so that the second generation cannot take RM action; (3) decreasing emission control and investing in R&D, accepting that RM will be used at stage two. The strategic option realized depends on the choice of parameters.

The authors also consider the case where the second generation assesses the economic damages caused by RM-related side-effects to be very large. Consequently, the second generation might have an incentive to refrain from RM action, even if climate sensitivity turns out to be high. Again, the first generation changes its behavior, having two potential options: (1) increasing emissions control and saving the investment for R&D and (2) reducing emission control substantially and investing in R&D so that the second generation is "forced" to take RM action. Both cases show that, in general, different assessments of RM or CE might

alter the substitution effect observed in the analyses discussed in the previous section. Furthermore, the authors emphasize that the current generation cannot take an isolated decision about CE research without considering the potential options for its application.

## 5. Discussion and conclusion

Two fundamental issues are considered in the economic analyses of CE: the determinants and the level of the social cost of CE, and the investigation of the incentives for the use of CE. With respect to the social cost of CE measures, very little information is available. It is mostly confined to the operational cost of CE measures. The cost figures published increase over time. However, these estimates include neither price effects nor any quantitative assessment of potential external costs. Consequently, it is obvious that current estimates strongly underestimate the true social cost of CE. Given current knowledge, it seems that the main restrictions on CDR measures are the ability to capture CO<sub>2</sub> and the potentially high operational costs. RM measures, on the other hand, are expected to be mainly limited by current uncertainty about their social cost. The very limited knowledge we have about the social cost of RM, notably with respect to regional variation in the extent of temperature increase control and the potential for reduced precipitation, may possibly stay the way it is, unless such measures are tested or applied on a large scale.

Furthermore, existing cost estimates for the various measures have been investigated in a rather piecemeal way. As pointed out by Victor (2008), the application of CE measures will probably take place in the form of a portfolio composed of various measures. Consequently, feedback and interaction effects have to be investigated further. For example, the effectiveness of afforestation measures could be raised if they were combined with genetic leaf modifications, so that not only carbon is removed but also the albedo of forest areas is improved. Also, measures that may seem ineffective on a global scale, like increasing the albedo in urban areas, might support emission control on a local scale via energy efficiency gains and temperature decrease.

These economic analyses should be seen as an initial theoretical exploration of a field where empirical assessments are still almost completely absent. But they have provided important new insights and indicate many directions for further research. Theoretical economic analyses have shown that from a centralized perspective it is rational to replace emission control by CE. This result is based on cost considerations and also, in the case of RM measures, on their reaction advantage. The substitution effect is supported by the positive interaction with natural carbon uptake, as pointed out by Moreno-Cruz and Smulders (2010). But as we have seen, an explicit assessment of the interaction effects between CDR and RM measures is still conspicuous by its absence.

In general, the results in from the centralized perspective are preconditioned by the assumption that CE action makes it possible to increase social welfare. With respect to the potential side-effects, this can

be considered a crucial assumption that needs to be further investigated. Nevertheless, the work of Moreno-Cruz et al. (2010) shows in principle that different globally optimal levels are possible, depending on the weighting given to the different climate variables. Furthermore, the work done by these authors shows that such a globally optimal level might not be the level agreed upon from the perspectives of different countries. This addresses the more realistic question of how decisions on CE could and should be taken. From a decentralized perspective, the substitution effect might be amplified over and against the first-best situation or else undermined by strategic effects. In the first case, different actors might further lower their already low emission reduction efforts if some countries indicate an intention to counteract dramatic climate change by RM action (moral hazard effect). In the second case, countries that suffer from RM action or simply dislike it might increase their emission control to reduce the incentives for RM action. As shown by Goeschl et al. (2010), such strategic incentives do not only exist between countries but also between generations. This study also provides theoretical confirmation that the decision about research on CE cannot be divorced from the decision on its application.

Overall, it seems that CE-related economic research neglects CDR measures or considers them only indirectly. Moreno-Cruz and Keith (2009) argue that emission control and RM measures constitute risk complements but do not explicitly include CDR measures in their analysis. Even though political will might restrict RM action to climate change emergencies, societies could find themselves in a position where the social costs due to side-effects of the RM measures are higher than expected but would even be exceeded by rapid climate change as a result of a truncation of RM action. In such a situation, it would be necessary to reduce carbon concentrations quickly. But if this were restricted to the natural carbon sink processes, it would take decades, if not centuries. Taking into account the potential lock-in effect by RM application implied by combining the results of Brovkin et al. (2009) and Goes et al. (2011), one might argue that CDR measures should be ready for action if RM measures are applied. That holds in particular true, if economic analysis starts focusing more on the dynamic efficiency of RM measures, not just with respect to its reaction advantage, but also with respect to its possible long-term application and the problems associated with a possible necessary phase-out. Consequently, one could argue that research should focus more on CDR measures. Given the results obtained by Gramstad and Tjøtta (2010), who show that welfare losses from postponing RM action by 20 to 30 years would be rather modest, a priority for CDR research would appear to be reasonable. However, as pointed out by Barrett (2009), restricting research on CE or even on certain CE measures would be reckless in view of potentially disastrous and sudden climate change. Furthermore, as argued by Victor (2008), any ban or taboo on certain CE measures or CE in general would probably lead to the exploration of these measures by less responsible and scrupulous governments and individuals.

The quickly advancing theoretical insights into the incentives and the functioning of CE measures illustrate the complexity of the role of CE in the quest for avoiding dangerous climate change. They show that

CE may be able or even may need to play a role in controlling climate change. Yet, the models show that the balance of emission control and CE activities depends essentially on the relative cost of the different options for climate mitigation. These costs turn out to be extremely difficult to determine since they involve not only direct cost but also market effects and external costs. Hence, further work on the real cost of CE is urgently needed.

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## Part II

# Methods for greenhouse gas offsets accounting: A case study of ocean iron fertilization

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# Methods for greenhouse gas offsets accounting: A case study of ocean iron fertilization<sup>☆</sup>

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## Abstract

Reducing atmospheric carbon concentration by removing past emissions can extend our rapidly diminishing emission budgets corresponding to the target of limiting the temperature increase to 2° C above preindustrial levels. Forestation measures to offset carbon emissions have already entered the Kyoto Protocol. Other carbon offset options like ocean iron fertilization or chemically enhanced weathering are currently being analyzed. The analysis and comparison of such options requires determination of the amount of carbon credits generated that can be used for compliance. In our analysis we assess the impact of various accounting methods applied to large-scale sink enhancement projects, taking into account the partly temporary storage characteristics arising from such projects. We apply the various accounting methods to hypothetical large-scale Southern Ocean iron fertilization projects for different durations. From an economic perspective, issuing temporary carbon credits would provide the largest number of carbon credits at an early stage. This is equivalent to the existing tCER regulation under the Kyoto Protocol. Issuing temporary carbon credits for short-term ocean iron fertilization would also benefit the environment, as all credits would have to be replaced in the next commitment period. As some carbon will be stored permanently, this reduces atmospheric carbon concentration.

*Keywords:* climate change, ocean iron fertilization, permanence, carbon accounting

*JEL:* Q51, Q54, Q56

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## 1. Introduction

Today, most countries regard a 2°C temperature increase above preindustrial levels as the maximum tolerable limit for global warming (e.g., UNFCCC, 2010, 2/CP.15). An exceedance probability of below 20 percent for this limit implies an emission budget of less than 250 GtC from 2000 to 2049, of which more than one third has already been emitted. Extrapolating current global CO<sub>2</sub> emissions this budget will only last until 2024 (Meinshausen et al., 2009). These figures emphasize the necessity of considering all options for the mitigation of climate change, including large-scale sink enhancement projects (Buesseler et al., 2008). Such carbon sink enhancement projects would enable us to offset carbon emissions by reducing atmospheric carbon concentration through the removal of past emissions.

One main characteristic of all sink-enhancement projects is the partly temporary storage of carbon. This means that part of the storage is temporary, while the rest is permanent. For this reason, some authors have expressed general doubts about the potential efficacy of mitigating climate change by such projects (Meinshausen and Hare, 2000; Kirschbaum, 2006). Under the Kyoto Protocol, temporary storage issues arise only for Land-Use, Land-Use Change, and Forestation (LULUCF) projects in non-Annex I countries. In Annex I countries, the issue of permanence does not arise (Phillips et al., 2001; Ellis, 2001). These are countries with binding emission-reduction targets.<sup>1</sup> However, Non-Annex I countries have no binding emission reduction targets and will not compensate for any reduction in carbon stocks as 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 permanent liability to the buyer of carbon credits. The carbon credits have to be replaced at some point in time, whether the storage is permanent or not (UNFCCC, 2003). According to Dornburg and Marland (2008, p.212), this concept of temporary carbon credits provides “a suitable framework for awarding and trading carbon credits”.

Due to space limitations, increasing the effort to enhance the terrestrial carbon sink is unlikely to be cost-efficient for sufficient reductions of atmospheric carbon concentration at reasonable cost. For this reason other sink enhancement options are currently being discussed. Considering further sink enhancement projects, such as enhancing the oceanic carbon sink by means of iron fertilization or enhancing the mineral carbon sink by means of chemically accelerated weathering in a post-Kyoto agreement, will probably raise further questions about the appropriateness of accounting methods. These sink enhancement projects differ from LULUCF projects with regard to possibilities of intended or unintended release of stored carbon. Also, in the case of oceanic sink enhancement, they would partly take place in international territory.

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<sup>1</sup>Carbon credits (Emission Reduction Units) are awarded for activities that increase the stored amount of carbon, e.g., forestation, while carbon credits (e.g. Assigned Amounts or Certified Emission Reductions) are required for activities that decrease the stored amount of carbon, e.g., deforestation. If the Protocol is prolonged, the link between the National Inventories and the compliance with Assigned Amounts establishes a permanent liability for the owner of the carbon storage project.

Consequently, accounting methods other than those applied to LULUCF projects need to be discussed. This is particularly important because analysis of the economic potential of sink enhancement over and against other mitigation options is not feasible without information on the amount of credits generated to offset carbon emissions. This paper assesses the value of partly temporary storage arising within sink enhancement projects. It does so by providing an overview of the effect of the various accounting methods discussed in the literature on the number of credits that can be generated. The various accounting methods are applied to hypothetical large-scale Southern Ocean iron fertilization projects for different durations. Ocean iron fertilization (OIF) is especially suitable for comparing the outcomes of different approaches as fluctuations in oceanic carbon uptake during and after OIF and additional releases of other greenhouse gases like  $\text{N}_2\text{O}$  have to be accounted for.

To address the problem of temporary storage, various accounting methods have been proposed in the literature (see e.g., Dutschke, 2002; Fearnside et al., 2000; Fearnside, 2002; Marland et al., 2001; Costa and Wilson, 2000). They can be grouped into three categories: permanent credits, temporary credits, and a mixture of permanent and temporary credits. There are a number of publications on the various accounting methods, but studies providing a comprehensive overview of accounting methods from all three categories are rare. In particular, we have, as yet, no quantitative analyses comparing the number of carbon credits generated. One exception is the study by Phillips et al. (2001). It considers three accounting methods issuing permanent credits and one issuing temporary credits to an afforestation project and demonstrates that the number of carbon credits issued over time varies significantly for the various accounting methods.

Very few studies put large-scale sink enhancement projects like OIF into the context of an international climate agreement. To our knowledge, the rare exceptions are Sagarin et al. (2007), Leinen (2008), and Bertram (2010). These provide non-technical overviews of the scientific, legal, and economic issues related to OIF and summarize the requirements made by carbon markets on the generation of carbon credits by OIF. However, all three studies discuss OIF in general terms, without any explicit application of accounting methods to OIF. To our knowledge, our is the first paper to quantitatively assess all relevant accounting methods discussed in the literature for all three categories with reference to a large-scale sink enhancement project like OIF.

In Section 2 we provide an overview of the relevant accounting methods, taking into account the issue of permanence and leakage. “Leakage” refers to changes in carbon emissions outside the enhancement region and to changes in emissions of other GHGs than carbon. In Section 3 we apply the various accounting methods to the results of hypothetical large-scale Southern Ocean iron fertilization projects (Oschlies et al., 2010). Section 4 contains a discussion and our conclusions.

## 2. Carbon Accounting: Permanence and Leakage

The assignment of carbon credits to carbon sink enhancement projects for carbon storage requires the fulfillment of certain criteria. The Kyoto Protocol established such criteria for Clean Development Mechanism (CDM) and Joint Implementation (JI) projects.<sup>2</sup> These projects have to be measured by an approved methodology, the storage has to be additional, the credits have to be verified by a third party, the storage has to be permanent, and the number of carbon credits has to be corrected for leakage (Grubb et al., 1999). Leinen (2008) discusses the fulfillment of these criteria for large-scale sink enhancement projects like OIF, identifying the issues of permanence and leakage as the most critical. In our analysis, we focus on these two issues, referring to the literature for a discussion of the remaining criteria (Leinen, 2008; Bertram, 2010).

Carbon accounting methodologies can be divided into three categories. In the first category, permanent credits are issued. Once issued, these credits are equivalent to other carbon credits like Assigned Amounts, regardless of whether the stored carbon is released in future. In the second category, temporary credits are issued. These temporary credits can be used for compliance within a commitment period, but they have to be replaced in a later period. Temporary credits can be renewed if the carbon is still stored. The third category is a mixture of permanent and temporary credits. Temporary carbon credits are replaced by permanent carbon credits if the carbon is stored for a sufficient period of time.

In the following Subsections 2.1 to 2.3 we present existing accounting methods related to the three categories and assess their application to OIF. In line with the IPCC's definition of permanence, we regard a time period of 100 years as permanent (UNFCCC, 1997).<sup>3</sup> We refer to this time period as the permanence period. In Section 2.4 we explain how leakage related to large-scale carbon offset projects like OIF can be accounted for. To account for leakage, two issues need to be addressed. OIF might lead both to changes in carbon emissions outside the enhancement region and to changes in emissions of other GHGs than carbon. Both changes might result in a lower net reduction of greenhouse gas forcing than was initially assumed when considering only the gross effect of OIF. Evaluating the true potential of OIF requires accounting for such offsets, as called for by the recent London Convention (2007).

### 2.1. Carbon accounting methods with permanent carbon credits

There are four carbon accounting methods that assign permanent carbon credits: the *net* method, the *average* method, the *discount* method, and the *equivalence* method. With the first method, it makes no difference when the stored carbon is released within the permanence period of 100 years. As a consequence,

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<sup>2</sup>The Clean Development Mechanism (CDM) enables a country with an emission-reduction or emission-limitation commitment under the Kyoto Protocol (Annex B Party) to implement an emission-reduction project in developing countries. The Joint Implementation mechanism (JI) enables a country with an emission-reduction or emission-limitation commitment under the Kyoto Protocol (Annex B Party) to earn emission reduction units (ERUs) from an emission-reduction or emission-removal project in another Annex B Party (UNFCCC, 1997, 2003)

<sup>3</sup>The choice of 100 years was not based on any scientific rationale but was rather a political decision (Leinen, 2008).



the first method does not attach any importance to time within the permanence period. The other methods do. In applying the accounting methods to OIF we assume that a cap on the cumulative amount of carbon credits is implemented 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 by OIF.

### 2.1.1. *The net method*

In the literature this method is also referred to as the *flow summation* method (Richard and Stokes, 2004), the *carbon stocks change* method (Ellis, 2001) or the *ideal accounting system* (Cacho et al., 2003). It accounts for the annual changes in carbon storage stocks, no matter when they occur within the permanence period. Consequently, this method considers storage and removal as separate events, awarding carbon credits when carbon is stored and requiring carbon credits when carbon is released, presuming that a permanent liability exists. The overall amount of carbon credits will only be positive if carbon is stored beyond the permanence period. We refer to this amount as  $Cap_{net}$ . For a storage project storing one ton C in year 1 and releasing it in year 99,  $Cap_{net}$  would be 0 t C. For release in year 101,  $Cap_{net}$  would be 1. Applying the method to OIF, we assume that carbon credits are provided when carbon stocks increase, though only up to the  $Cap_{net}$  amount.

### 2.1.2. *The average method*

This method accounts for the annual changes in carbon stocks, though only up to the average amount of carbon stored over a defined period of time (Phillips et al., 2001; Marland et al., 2001; Ellis, 2001; Richard and Stokes, 2004). We refer to this amount as  $Cap_{avs}$ . For a storage project storing one ton carbon in year 1 and releasing it in year 99,  $Cap_{avs}$  would be 0.99 t C. Applying the method to OIF, we assume that carbon credits are provided when carbon stocks increase, though only up to the  $Cap_{avs}$  amount which is calculated over the permanence period.

### 2.1.3. *The discount method*

This method accounts for the annual changes in carbon stocks over a defined period of time, applying a social discount rate in discounting future carbon to the present. The result is called “present tons equivalents” (PTE) (Thompson et al., 2009; Richard and Stokes, 2004). Though the concept of discounting a physical unit is not intuitive, van Kooten and Sohngen (2007, p.244) point out that “the idea of weighting physical units accruing at different times is entrenched in the natural resource economics literature, going back to economists’ definition of conservation and depletion (Ciriacy-Wantrup, 1968)”. We refer to the present tons equivalents as  $Cap_{dis}$ . For a storage project storing one ton carbon in year 1 and releasing it in year 99, the  $Cap_{dis}$  would be 0.9448 t C for a discount rate of 3 percent. Applying the method to OIF, we assume that carbon credits are provided when carbon stocks increase, though only up to the  $Cap_{dis}$  amount.

#### 2.1.4. The equivalence method

This method accounts for annual carbon stocks, weighted by the equivalence factor. The method is based on the idea that to be regarded as permanently stored carbon should be stored for a fixed period of time, the equivalence time. If the amount of carbon is stored until the end of the equivalence time, the full amount of carbon is credited. For this reason the method is also called *ton-year accounting* (e.g., Costa and Wilson, 2000; Fearnside et al., 2000). To apply the method, the equivalence time needs to be determined. According to various studies, the equivalence time varies between 42 and 150 years (Marland et al., 2001; Ellis, 2001), suggesting a degree of arbitrariness that cannot be explained by scientific evidence but rather by political considerations (Dutschke, 2002; Cacho et al., 2003; Marland et al., 2001). For this reason, the *equivalence* method has aroused considerable controversy. Nevertheless, it has a certain appeal because it provides a pragmatic and simple accounting method for various carbon storage projects of different lengths (van Kooten and Sohngen, 2007; Murray, 2003).

Costa and Wilson (2000) and Fearnside et al. (2000) propose calculating the equivalence time in relation to the calculation of the GWP. The equivalence time in years calculated in this way yields the storage time required to offset the GWP of one ton of carbon released in year 1 and measured in ton-years. However, different approaches exist regarding the tracking of emissions. Costa and Wilson (2000) track the amount of carbon in the biosphere (MCW Approach), while Fearnside et al. (2000) and Fearnside (2002) track the amount of carbon in the atmosphere (Lashof Approach). The MCW Approach determines equivalence time by integrating over the time-decaying abundance of a ton of carbon over the permanence period, measured in ton-years. Storing one ton of carbon for this equivalence time is awarded one carbon credit. The amount of carbon stored is multiplied by the equivalence factor to obtain the annual amount of carbon credits. The equivalence factor is determined as the reciprocal of the equivalence time. The Lashof Approach assigns carbon credits according to the area of the integral over the time-decaying abundance of a ton of carbon shifted beyond the permanence period, again measured in ton-years. The full amount of carbon credits is therefore only obtained if the carbon is successfully stored until end of the permanence period. Two possibilities exist for determining the annual carbon credits for the Lashof Approach. The amount of annual carbon credits is obtained either via linear approximation of the decay pattern of atmospheric carbon, which would again allow for calculating an equivalence factor, or by calculating the amount of ton-years shifted beyond the permanence time horizon. We choose the second option, because the decay pattern of atmospheric carbon is not accurately represented by linear approximation until the end.

We refer to the total amount of carbon credits for the two approaches as  $Cap_{equ}^M$  (MCW Approach) and  $Cap_{equ}^L$  (Lashof Approach). Applying the Revised Bern model (Fearnside et al., 2000), we obtain an equivalence time of 46 years for the MCW Approach.<sup>4</sup> For a storage project storing one ton of carbon in

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<sup>4</sup>The derivation of equivalence time is explained in more detail in Section 3 below.

year 1 and releasing it in year 99,  $Cap_{equ}^M$  is 0.9782 and  $Cap_{equ}^L$  is 0.9596. Though the equivalence time is 46 years with the MCW Approach, implying that a storage time of 46 years would be sufficient to earn a full carbon credit,  $Cap_{equ}^M$  is below 1. Since we consider a permanence period of 100 years in our analysis, the positive carbon stock from year one can only be accounted for up to the equivalence time (46 years). At that point the stock is set to zero and remains zero until the year 99. In year 99 it turns negative so that it is subtracted from the full credit, again weighted with the equivalence factor and only for the remaining year within the permanence period.

### 2.1.5. Intermediate results

So far the analysis has shown the impact of assessing time for a permanence period of 100 years. While the *net* method does not assign credits to the idealized storage project (storage in year 1 and release in year 99), the remaining methods assign different amounts of credits (see Table 1). As for the remaining methods, the amount is highest with the *average* method and lowest with the *discount* method. However, applying a different discount rate would change the results. The *average* method is similar to the *equivalence* method, applying an equivalence time of 100 years. For this method, the amount of annual carbon credits can be obtained via multiplication by an equivalence factor of 1/100, if carbon credit issue within the average storage method were not based on carbon stocks change but on the carbon stocks. However, we make a distinction between the two methods because the *equivalence* method covers approaches that derive the equivalence time on the basis of the atmospheric carbon decay pattern. Note that if the release in the

Table 1: Numerical example for accounting methods assigning permanent carbon credits

| Method                             | Valuing time over the permanence period of 100 years | Carbon credits for storage of 1t C in year 1 and release in year 99 |
|------------------------------------|--|---|
| net method                         | no   | 0   |
| average method                     | yes  | 0.9900  |
| discount method (3 percent)        | yes  | 0.9448  |
| equivalence method-MCW Approach    | yes  | 0.9782  |
| equivalence method-Lashof Approach | yes  | 0.9596  |

idealized storage project took place in year 101, all methods would provide full carbon credits. For the last three methods, this would imply a modest increase in carbon credits, while for the *net* method we would observe an increase from zero to full crediting.

## 2.2. Carbon accounting methods with temporary carbon credits

Two carbon accounting methods that assign temporary carbon credits are discussed in the literature. Both of them are applied to account for LULUCF activities under the Kyoto Protocol. With the first method, temporary credits are valid for a fixed period of time but can be renewed if the carbon is still stored. With

the second method, temporary credits are valid for a fixed period of time and cannot be renewed, even if the carbon is still stored (Phillips et al., 2001). Decision 5/CMP.1 of the UNFCCC (2003) refers to the first method as temporary certified emission reductions (tCER) and to the second as long-term certified emission reductions (lCER). tCERs expire at the end of the commitment period following the period in which they were issued, while lCERs expire at the end of the crediting period of the project for which they were issued (UNFCCC, 2003; Olschewski et al., 2005). This is important as the crediting period is generally longer than the commitment period. Decision 5/CMP.1 regulates the modalities and procedures for afforestation and reforestation project activities under the CDM mechanism in the first commitment period of the Kyoto Protocol. It therefore serves as a guideline for the general modalities of temporary carbon credits for temporary storage projects. It is important to note that the maximum project duration is either 30 or 60 years<sup>5</sup> (UNFCCC, 2003). The maximum crediting period is shorter than the permanence period of 100 years and all temporary carbon credits (tCER and lCER) have to be replaced during that time, whether the storage is permanent or not.

Applying the concept of temporary carbon credits to OIF, we follow Decision 5/CMP.1 and distinguish between short-term temporary carbon credits and long-term temporary carbon credits. We refer to these two methods as the *shorttemp* and *longtemp* methods. We assume that short-term temporary carbon credits are issued on the basis of the carbon stocks at the end of a commitment period and have to be replaced in the next commitment period. For the *shorttemp* method no cap is required. We assume further that long-term temporary carbon credits are also issued on the basis of the carbon stocks at the end of a commitment period, but are valid until the end of the crediting period (60 years). Therefore the carbon stocks at the end of the crediting period constitute a cap for issuing carbon credits. This implies that the amount of long-term temporary carbon credits issued in the earlier commitment periods may be smaller than the actual change in carbon stocks observed during the first commitment period. We refer to the cap for the *longtemp* method as  $Cap_{ltemp}$ .

### 2.3. Carbon accounting methods with permanent and temporary credits

Carbon accounting methods that assign a mixture of permanent and temporary credits are rarely discussed in the literature. A carbon accounting method could assign permanent credits for the amount of carbon stored permanently (as discussed in Subsection 2.1) and also assign temporary carbon credits for the amount of carbon stored temporarily (as discussed above). However, there are other accounting methods that deserve consideration in connection with the renewal of temporary carbon credits. Dutschke (2002), for example, proposes that the underlying carbon stocks for the renewal of expired credits can only be taken as a basis at diminishing rates. The underlying amount of carbon depreciates in accordance with the atmospheric carbon

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<sup>5</sup>20 years with two renewable periods of 20 years, if certain requirements are fulfilled.

decay pattern, but only for a fixed period of time. Thereafter the remaining amount of carbon is considered to be stored permanently.

Applying this method to OIF, we assume that temporary carbon credits are issued on the basis of the carbon stocks at the end of a commitment period and have to be replaced in the next commitment period. Calculation of the underlying carbon stocks requires taking the time-decaying abundance of carbon in the atmosphere into account. Accordingly, the amount of carbon credits issued within a commitment period is smaller than the actual amount of carbon stored. Take, for example, a storage project where one ton of carbon is added to the stored carbon stocks each year. Assume further that the commitment period is five years. Applying the Revised Bern Model, the amount of carbon credits is not 5 but only 4.35502, because the one ton added in the first year has already decayed for four years, the one ton added in the second year has decayed for three years, and so on.

The UNFCCC framework does not provide any guidance on the application of this method. In our analysis we assume that the crediting period is equal to the permanence period of 100 years and that carbon credits issued in the final commitment period do not have to be replaced. We refer to this method as the *mixed* method.

#### *2.4. Leakage and the carbon accounting methods*

The leakage issue addresses all potential offsets that have to be taken into account to obtain the net amount of carbon credits in the various accounting methods. Potential offsets arise due (1) to carbon emissions outside the enhancement region (spatial leakage) and (2) to changes in emissions of other GHGs than carbon (GHG leakage). To account for carbon emissions outside the enhancement region of the OIF projects (spatial leakage), we apply the accounting methods to global data for oceanic carbon uptake rather than local data. To account for emissions of other GHGs than carbon (GHG leakage), we introduce a deduction rate.<sup>6</sup> The deduction rate reduces the gross amount of carbon credits to a net amount that then can be used for compliance. The deducted amount of carbon credits can be retained in a buffer account and can be released later if no leakage has been observed (Ellis, 2001).

### **3. Results**

#### *3.1. Accounting methods applied to OIF*

To demonstrate the effect of the various accounting methods, we apply the results of hypothetical large-scale Southern Ocean iron fertilization projects, realized as model experiments in Oschlies et al. (2010).<sup>7</sup>

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<sup>6</sup>Note that in the publication this deduction rate is misnamed as discount factor.

<sup>7</sup>The focus of our analysis is on OIF as a means of increasing oceanic carbon uptake. However, this is not the only reason to do OIF. OIF has also been discussed as a method of increasing primary and secondary productivity in the ocean for feeding fish stocks.

Within the model experiments, OIF is realized by increasing the phytoplankton growth rate in the Southern Ocean (south of 30°) for 1, 7, 10, 50, and 100 years, while the carbon emissions are represented by the IPCC SRES A2 Scenario (see Appendix A for a description of the model experiments).<sup>8</sup> We refer to these model experiments as Experiments 1 to 5. The maximum phytoplankton growth rate is increased from 0.13 per day at 0° C to either 0.26 per day, calibrated against the changes in export production observed for persistent natural iron fertilization on the Kerguelen Plateau and Crozet Islands in the Southern Ocean (Blain et al., 2007; Pollard et al., 2009), or to 10.0 per day to simulate an upper bound for OIF. We refer to the former growth rate as “low fertilization effectiveness” and to the latter growth rate as “high fertilization effectiveness”. Though the latter rate is beyond a physiologically sensible range, the intended effect in the model is a further drawdown of macronutrients than observed in the island-induced natural iron fertilization. As we do not know whether island-induced iron fertilization is sufficient to completely relieve phytoplankton from iron stress, the “high fertilization effectiveness” sensitivity growth rate explores a hypothetical scenario of a purposeful OIF impact being larger than that of island-induced natural OIF (Oschlies et al., 2010). Additionally, its inclusion emphasizes the differences between the various accounting methods because relative changes in carbon fluxes are larger. The model outcome is summarized by the annual global oceanic carbon uptake over 100 years for each model experiment and for both growth rates. Table B.1 in the Appendix shows the annual changes in carbon stocks for oceanic uptake measured in Gt C compared to the unfertilized control run (baseline) for each model experiment and for both growth rates. It indicates that in fertilization years the simulated carbon uptake is larger than in the baseline, but at annual rates diminishing with increasing duration of the fertilization. When fertilization stops, marine carbon uptake becomes smaller than in the baseline, but again at diminishing rates over time. For further details on the OIF model experiments, see Oschlies et al. (2010).

In applying the different accounting methods we assume that each model experiment starts in 2012, so the permanence period lasts until 2112. We further assume that the first commitment period is from 2012 to 2020, because 2012 is when the first commitment period of the Kyoto Protocol comes to an end. A second commitment period with new reduction targets is currently being negotiated and should cover the period from 2012 to 2020 (e.g., European Union, 2009). Following the literature, we assume further commitment periods of 5 years from 2020 to 2115 and a final commitment period of 7 years, ending in 2112. For the *discount* method we assume a social discount rate of 3 percent. For both the *equivalence* method and the *mixed* method, we use an impulse response function for the time-decaying abundance of CO<sub>2</sub>,  $F(CO_2(t))$ ,

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<sup>8</sup>The SRES A2 non-intervention scenario assumes high population growth and moderate, uneven economic growth, leading to an increase from today’s emissions of about 8 GtC/yr to about 29 GtC/yr in the year 2100. After 2100, annual emissions are assumed to decline by 1.45 GtC per year, reaching zero at year 2300.

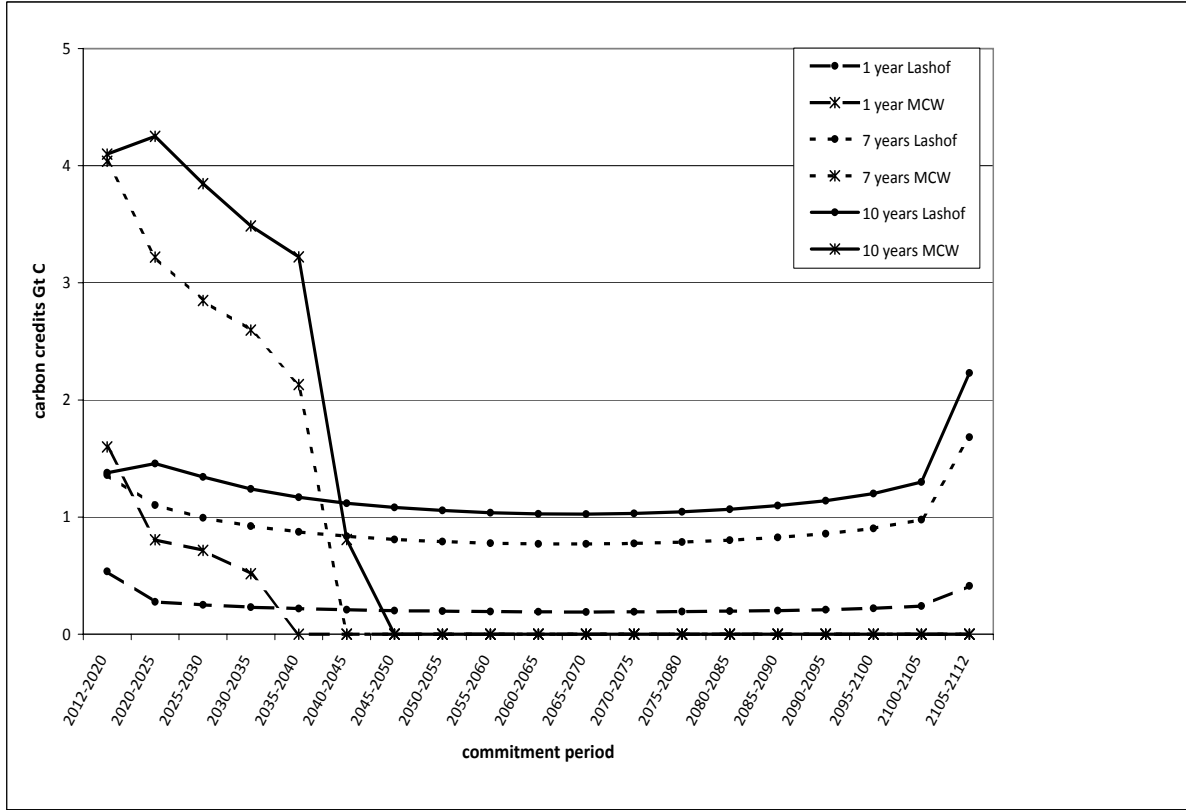


Figure 1: Gross amount of carbon credits for the *equivalence* method on the basis of additional oceanic carbon uptake with high fertilization effectiveness in Gt C.

with parameter values from the Revised Bern Model (Fearnside et al., 2000):

$$\begin{aligned}
 F[CO_2(t)] = & 0.175602 + 0.258868e^{-0.292794t} + 0.242302e^{-0.0466817t} \\
 & + 0.185762E^{-0.014165t} + 0.137467e^{-0.00237477t},
 \end{aligned}
 \tag{1}$$

where  $t$  is time in years. Based on these parameter values, we obtain an equivalence time of 45.7556 years for the MCW approach (equivalence method). The derived equivalence factor is 0.0219.

Table 2: Caps and cumulative gross carbon credits in commitment period 2012-2020 on the basis of additional oceanic carbon uptake in GtC

| High fertilization effectiveness |                   |                      |                                 |                      |                                 |                       |                                 |                       |                                 |                        |                                 |
|----------------------------------|-------------------|----------------------|---------------------------------|----------------------|---------------------------------|-----------------------|---------------------------------|-----------------------|---------------------------------|------------------------|---------------------------------|
|                                  |                   | Exp. 1<br>1 year OIF |                                 | Exp. 2<br>7 year OIF |                                 | Exp. 3<br>10 year OIF |                                 | Exp. 4<br>50 year OIF |                                 | Exp. 5<br>100 year OIF |                                 |
| Carbon credits                   | Accounting method | Cap                  | Cumulative credits<br>2012-2020 | Cap                  | Cumulative credits<br>2012-2020 | Cap                   | Cumulative credits<br>2012-2020 | Cap                   | Cumulative credits<br>2012-2020 | Cap                    | Cumulative credits<br>2012-2020 |
| permanent<br>(p.)                | <i>net</i>        | 3.33                 | 3.33                            | 13.56                | 13.56                           | 17.96                 | 17.96                           | 74.60                 | 35.00                           | 169.30                 | 35.00                           |
|                                  | <i>average</i>    | 4.87                 | 4.87                            | 18.54                | 18.54                           | 24.13                 | 24.13                           | 77.44                 | 35.00                           | 104.69                 | 35.00                           |
|                                  | <i>discount</i>   | 6.05                 | 6.05                            | 21.26                | 21.26                           | 26.84                 | 26.84                           | 63.68                 | 35.00                           | 76.26                  | 35.00                           |
|                                  | <i>equ-Lash.</i>  | 4.56                 | 0.54                            | 17.62                | 1.36                            | 23.05                 | 1.38                            | 78.90                 | 1.38                            | 114.84                 | 1.38                            |
|                                  | <i>equ-MCW</i>    | 3.64                 | 1.60                            | 14.83                | 4.04                            | 19.71                 | 4.10                            | 85.34                 | 4.10                            | 144.26                 | 4.10                            |
| temporary<br>(t.)                | <i>shorttemp</i>  | no                   | 8.06                            | no                   | 32.22                           | no                    | 35.00                           | no                    | 35.00                           | no                     | 35.00                           |
|                                  | <i>longtemp</i>   | 3.94                 | 3.94                            | 16.03                | 16.03                           | 21.33                 | 21.33                           | 95.90                 | 35.00                           | 122.40                 | 35.00                           |
| p. and t.                        | <i>mixed</i>      | no                   | 5.22                            | no                   | 24.43                           | no                    | 27.21                           | no                    | 27.21                           | no                     | 27.21                           |
| Low fertilization effectiveness  |                   |                      |                                 |                      |                                 |                       |                                 |                       |                                 |                        |                                 |
| permanent<br>(p.)                | <i>net</i>        | 0.61                 | 0.61                            | 2.50                 | 2.50                            | 3.53                  | 3.53                            | 19.02                 | 11.32                           | 56.47                  | 11.32                           |
|                                  | <i>average</i>    | 0.76                 | 0.76                            | 4.06                 | 4.06                            | 5.65                  | 5.65                            | 23.43                 | 11.32                           | 34.92                  | 11.32                           |
|                                  | <i>discount</i>   | 0.95                 | 0.95                            | 5.14                 | 5.14                            | 6.92                  | 6.92                            | 20.08                 | 11.32                           | 25.34                  | 11.32                           |
|                                  | <i>equ-Lash.</i>  | 0.72                 | 0.09                            | 3.74                 | 0.41                            | 5.24                  | 0.42                            | 23.33                 | 0.42                            | 38.31                  | 0.42                            |
|                                  | <i>equ-MCW</i>    | 0.61                 | 0.28                            | 2.78                 | 1.22                            | 3.97                  | 1.26                            | 23.38                 | 1.26                            | 48.11                  | 1.26                            |
| temporary<br>(t.)                | <i>shorttemp</i>  | no                   | 1.21                            | no                   | 9.58                            | no                    | 11.32                           | no                    | 11.32                           | no                     | 11.32                           |
|                                  | <i>longtemp</i>   | 0.61                 | 0.61                            | 3.09                 | 3.09                            | 4.44                  | 4.44                            | 28.10                 | 11.32                           | 40.94                  | 11.32                           |
| p. and t.                        | <i>mixed</i>      | no                   | 0.72                            | no                   | 7.17                            | no                    | 8.91                            | no                    | 8.91                            | no                     | 8.91                            |



Table 2 shows for each accounting method, for each model experiment, and for both growth rates the gross amount of carbon credits generated in the first commitment period (2012-2020) plus the caps that take carbon release in later periods into account. The figures are based on oceanic carbon uptake as set out in Table B.1 in the Appendix. According to the scientific literature, the total effect of OIF is described by the *net* method. The results of the model experiments show a wide range of changes in oceanic carbon stocks for the two levels of OIF effectiveness. If OIF effectiveness is low (growth rate 0.26 per day), the model experiments result in an average annual uptake of 0.56 GtC for a fertilization duration of 100 years. If OIF effectiveness is high (growth rate 10.0 per day), the corresponding value increases to 1.69 Gt C. Compared to the values of earlier modeling studies ranging from 0.7 to 1.6 Gt C for iron fertilization in the Southern Ocean for a fertilization duration of 100 years (Sarmiento and Orr, 1991; Aumont and Bopp, 2006), the lower bound given by Oschlies et al. (2010) for low fertilization effectiveness is considerably lower.

Table 3: Gross amount of short-term temporary carbon credits on the basis of additional oceanic carbon uptake with high fertilization effectiveness in Gt C

| <i>Shorttemp</i> method  |                      |             |                       |             |                        |             |
|--------------------------|----------------------|-------------|-----------------------|-------------|------------------------|-------------|
| Commitment period        | Exp. 1<br>1 year OIF |             | Exp. 2<br>7 years OIF |             | Exp. 3<br>10 years OIF |             |
|                          | Carbon credits       | Replacement | Carbon credits        | Replacement | Carbon credits         | Replacement |
| 2012 - 2020              | 8.06                 | 0           | 32.22                 | 0           | 35.00                  | 0           |
| 2020 - 2025              | 6.99                 | 1.07        | 27.86                 | 4.36        | 37.81                  | 0           |
| 2025 - 2030              | 6.28                 | 0.71        | 25.03                 | 2.83        | 33.69                  | 4.12        |
| 2030 - 2035              | 5.76                 | 0.52        | 22.99                 | 2.04        | 30.83                  | 2.86        |
| 2035 - 2040              | 5.34                 | 0.42        | 21.40                 | 1.59        | 28.65                  | 2.18        |
| 2040 - 2045              | 5.02                 | 0.32        | 20.13                 | 1.27        | 26.92                  | 1.73        |
| 2045 - 2050              | 4.77                 | 0.25        | 19.09                 | 1.04        | 25.52                  | 1.40        |
| 2050 - 2055              | 4.52                 | 0.25        | 18.19                 | 0.90        | 24.30                  | 1.22        |
| 2055 - 2060              | 4.31                 | 0.21        | 17.44                 | 0.75        | 23.25                  | 1.05        |
| 2060 - 2065              | 4.15                 | 0.16        | 16.80                 | 0.64        | 22.38                  | 0.87        |
| 2065 - 2070              | 3.99                 | 0.16        | 16.23                 | 0.57        | 21.60                  | 0.78        |
| 2070 - 2075 <sup>a</sup> | 3.94                 | 0.05        | 16.03                 | 0.20        | 21.33                  | 0.27        |
| 2075 - 2080              | 0                    | 3.94        | 0                     | 16.03       | 0                      | 21.33       |

<sup>a</sup>Carbon credits issued in the commitment period 2070-2075 are based on stock change until 2072 only.

Comparing the caps for permanent credits in Table 2, the *net* method provides the lowest cap for short-term projects (Experiments 1-3) because all years are weighted equally. The other methods assume a time value and hence give later years less weight. They provide larger caps for short-term projects because later years with lower uptake than in the baseline count less. However, later years with higher uptake than in the baseline also count less. Accordingly the *net* method provides the largest cap for Experiment 5 (100 years fertilization). For the short-term projects, the *discount* method provides the largest cap, followed by the *average* method and the *equivalence* method with the Lashof Approach. Reducing the discount rate to 1 percent, the cap of the *discount* method is in the same order of magnitude as the two other methods, again

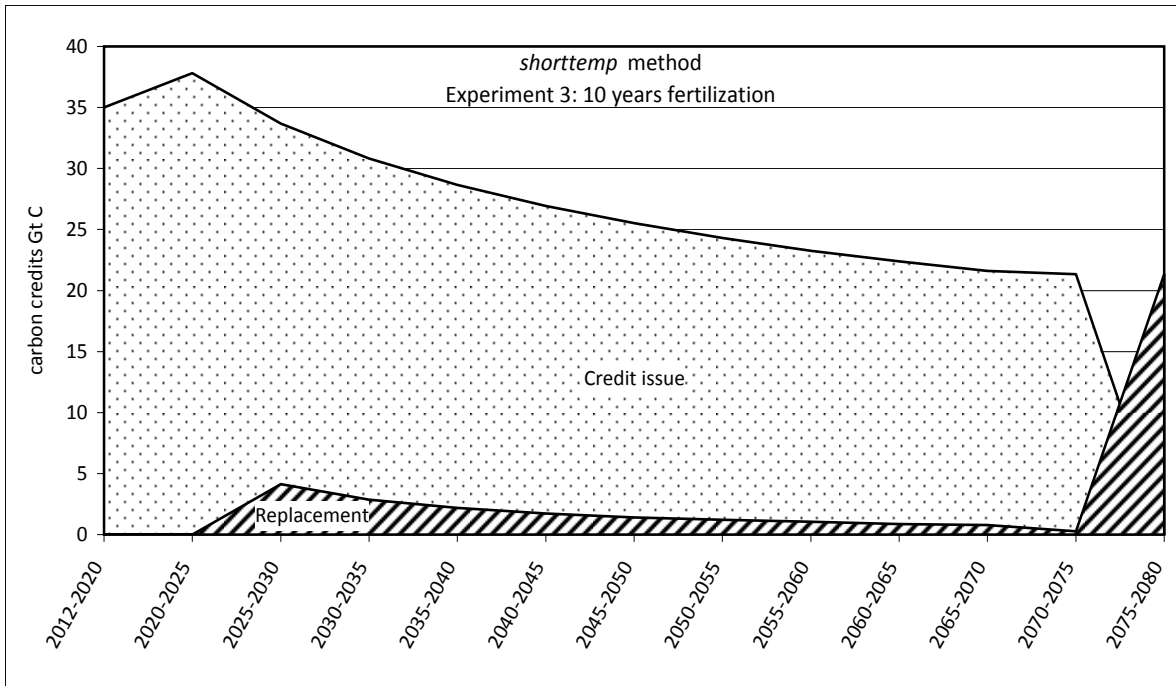


Figure 2: Gross amount of temporary carbon credits and replacement for Experiment 3 (10 years OIF) on the basis of additional oceanic carbon uptake with high fertilization effectiveness in Gt C.

for short-term projects.

Looking at the *equivalence* methods, the Lashof Approach provides larger caps than the MCW Approach in comparison of results for the short-term projects. This is not intuitive. Under the MCW Approach, 46 years of storage is sufficient to earn a full carbon credit, whereas a time-period of 100 years is required under the Lashof Approach. This can be explained by the fact that with the MCW Approach both higher and lower uptakes than in the baseline count as full carbon credits for the years 0 to 54.<sup>9</sup> Under the Lashof Approach, only the change in carbon stocks in the first year counts fully, because time-decaying abundance is integrated over the complete permanence period of 100 years. For all later years, time-decaying abundance is integrated over a shorter period (less than 100 years) so that changes in carbon stocks never lead to a complete carbon credit. Applying the *shorttemp*, *longtemp*, and *mixed* methods, a cap is required only for the long-term temporary credits in the *longtemp* method. The other two methods require no cap. The cap is determined by carbon stocks after 60 years (2072) and is therefore higher than the cap of the *net* method for Experiments 1 to 4 and lower than the cap for Experiment 5.

For most methods the amount of carbon credits for short-term OIF projects is limited by the binding cap. The only non-binding caps for short-term OIF projects arise with the *equivalence* method under the Lashof Approach, because due to the inclusion of an equivalence measure it generates only a fraction of the

<sup>9</sup>The permanence period of 100 years minus the equivalence time of 46 years.

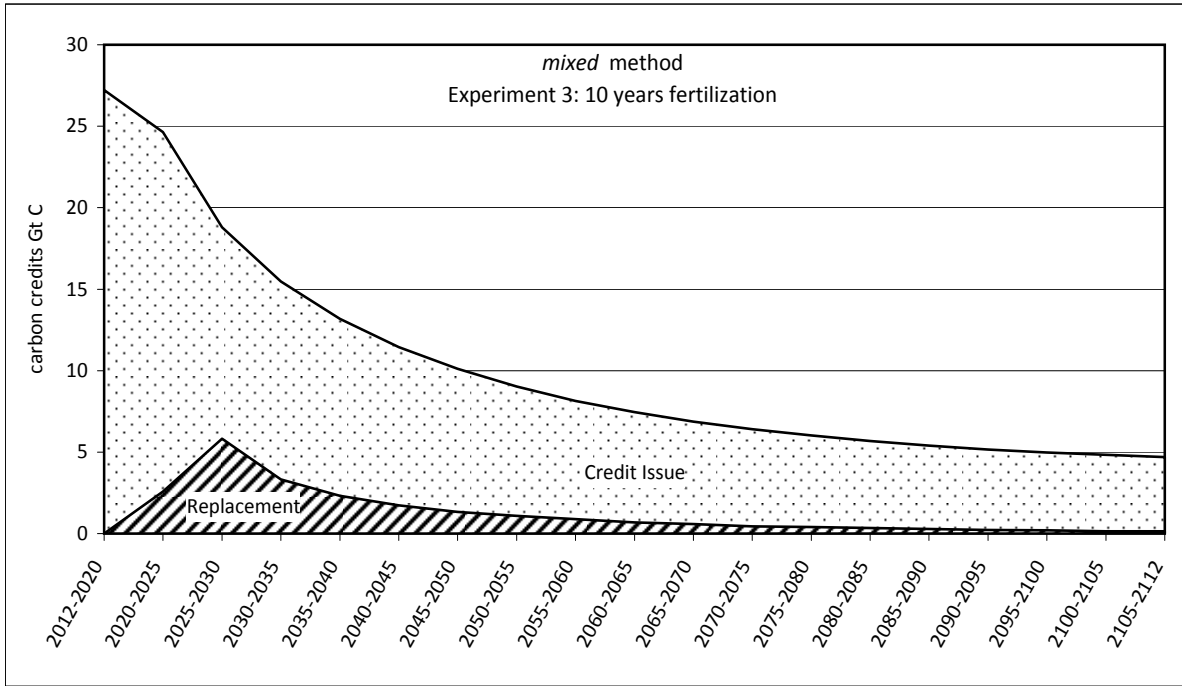


Figure 3: Gross amount of carbon credits with *mixed* method for Experiment 3 (10 years OIF) on the basis of additional oceanic carbon uptake with high fertilization effectiveness in Gt C.

actual carbon stocks. Figure 1 and Table B.2 in the Appendix show the gross amounts of carbon credits for the two *equivalence* methods in short-term OIF projects and high iron fertilization effectiveness. With the Lashof Approach, carbon credit issuance extends until the final commitment period. The cap is achieved in the final commitment period and is therefore never binding. With the MCW Approach we have a binding cap so carbon credit issuance ends after a number of commitment periods. Comparing the amount of credits, the MCW Approach provides larger amounts of credits at a much earlier stage. Note that with the Lashof Approach, the amount of carbon credits first decreases, then slightly increases over the commitment periods. One reason is the pattern of carbon change for the short-term OIF projects. Another is the non-linear time-decaying abundance of carbon in the atmosphere. The first years after a pulse of carbon into the atmosphere show higher decay rates, followed by slightly declining decay rates in later years. Consequently, the increase in ton-years until the end of the permanence period is larger if storage is extended from say 80 to 90 years rather than 50 to 60 years.

The *shorttemp* method provides the largest amount of carbon credits in the first commitment period for short-term OIF projects. In the next commitment period these carbon credits have to be replaced either by new short-term temporary carbon credits or by other carbon credits, e.g. Assigned Amounts. Table 3 shows the gross amount of short-term temporary carbon credits generated in each commitment period over the crediting period of 60 years. It also shows the necessary replacement by other carbon credits in each

commitment period by other carbon credits. In the commitment period 2075-2080, all short-term temporary credits from the previous commitment period have to be replaced by other carbon credits. These amounts are equal to the caps for the long-term temporary carbon credits. Figure 2 shows the evolution of temporary carbon credits and replacement as exemplified by Experiment 3 (10 years of fertilization).

The amount of carbon credits in the first commitment period (2012-2020) for the long-term OIF projects (Experiment 4 and 5) is not limited by the caps. Accordingly, all methods provide the same amount of carbon credits within the first commitment period, except for the *equivalence* method and the *mixed* method (see Table 2). For the *equivalence* method the reason has already been discussed. As they are based on an equivalence measure, they generate only a fraction of the actual carbon stocks as carbon credits. For the *mixed* method, the effect is not caused by an equivalence measure but rather by the lower basis on which credits are generated. This basis is not determined by the actual carbon stocks but by calculating the time-decaying abundance of atmospheric carbon for these carbon stocks. This lowers the amount of carbon credits because the carbon uptake in the years between 2012 and 2020 has already decayed to some extent. As with the *shorttemp* method carbon credits have to be replaced in the following commitment period. Table B.3 in the Appendix shows the amount of carbon credits generated and the necessary replacement by other carbon credits for the *mixed* method. The *mixed* method generates more carbon credits in the first commitment period than say the *net* method, but the fraction of credits that turn out to be permanent at the end of the permanence period is rather low (14 to 17 percent for the short-term OIF projects). Compared to the *shorttemp* method, fewer carbon credits are generated in the first commitment period, but the necessary replacement in the second commitment period is larger due to the calculated decay of the underlying carbon stocks. Figure 3 shows the evolution of carbon credits and necessary replacement for the *mixed* method as exemplified by Experiment 3 (10 years of fertilization). Comparing the evolution of carbon credits in Figure 2 and 3, we see that the *shorttemp* method provides more carbon credits and lower replacement in each commitment period than the *mixed* method. However, the *shorttemp* method requires complete replacement in the final commitment period, whereas the *mixed* method does not, the reason being that a fraction of initially temporary credits turns out to be permanent.

### 3.2. Deduction rates for leakage

In the previous section the accounting methods were applied on the basis of global data including the effect of spatial leakage. Accordingly, the figures in the previous section already constitute net figures with respect to spatial leakage. Applying local data from the carbon uptake in the fertilized area would have implied using a deduction rate for spatial leakage in the order of eight percent (Oschlies et al., 2010).

The deduction rate in this section are designed to address the offset from emissions of other GHGs than carbon by correcting the gross amount of carbon credits to a net amount that can be used for compliance purposes. Stipulating the oceanic carbon sink by OIF influences the production of a range of trace gases,

notably methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), and dimethylsulphide (DMS) (e.g., Fuhrman and Capone, 1991; Jin and Gruber, 2003; Law, 2008). Enhanced CH<sub>4</sub> and N<sub>2</sub>O emissions, both more powerful GHGs than carbon, would offset the climate-change mitigation potential of OIF (Fuhrman and Capone, 1991). Enhanced DMS emissions would potentially contribute to climate change mitigation by increasing the earth's albedo (Law, 2008).<sup>10</sup> Combined physical-biogeochemical ocean models have shown that OIF could lead, in particular, to greater N<sub>2</sub>O emissions (Jin and Gruber, 2003). Following Oschlies et al. (2010) we focus on N<sub>2</sub>O emissions for the determination of the appropriate deduction rates as changes in CH<sub>4</sub> emissions are estimated negligible and increases in DMS emissions would potentially contribute to climate change mitigation.<sup>11</sup>

N<sub>2</sub>O is relatively long-lived in the atmosphere and has a GWP 310 times that of CO<sub>2</sub> (Forster et al., 2007). To take this into account, we use the N<sub>2</sub>O emission anomalies simulated by Oschlies et al. (2010) relative to the relative to the unfertilized control run. The authors apply two different parametrizations of N<sub>2</sub>O production as a function of organic matter remineralization and oxygen concentration. These are based on Suntharalingam and Sarmiento (2000) and Nevison et al. (2003).<sup>12</sup>

A calibration based on Nevison et al. (2003) leads to larger N<sub>2</sub>O emissions during the fertilization period. On the other hand, after fertilization is stopped, emissions decrease faster compared to a calibration based on Suntharalingam and Sarmiento (2000) (Figure 4). The plots also indicate that with the calibration based on Nevison et al. (2003) the fertilization-induced N<sub>2</sub>O emissions of Experiments 1 to 4 are negative towards the end of the permanence time period. For Experiment 5 (100 years fertilization) the fertilization-induced N<sub>2</sub>O emissions first decrease, then increase, reaching a peak after 84 and 92 years respectively for the two calibrations before starting to decrease again. To account for the mitigation offset, we use the annual N<sub>2</sub>O emissions and the relative GWP for N<sub>2</sub>O to obtain the equivalent amount of annual CO<sub>2</sub> emissions, which we measure in C.<sup>13</sup> These emissions represent the annual carbon offsets induced by N<sub>2</sub>O emissions. We subtract the annual carbon offsets from the annual oceanic carbon uptake, thus obtaining annual oceanic uptake corrected for N<sub>2</sub>O.

In a next step, we use the corrected amount of oceanic uptake and again apply the various accounting methods. We do this for low and high OIF effectiveness scenarios and for both calibrations (Suntharalingam and Sarmiento (2000) and Nevison et al. (2003)), thus obtaining four different scenarios for carbon credits

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<sup>10</sup>Dimethylsulphide (DMS), which might be produced by stimulated OIF blooms, is the principal natural source of sulfur to the atmosphere. It influences climate by its role in cloud formation and therefore changes the radiative forcing properties (Cullen and Boyd, 2008).

<sup>11</sup>Measurements of dissolved CH<sub>4</sub> emissions during the Southern Ocean Iron Enrichment Experiment (SOFEX) revealed a very small increase of less than 1 percent (Wingenter et al., 2004).

<sup>12</sup>For the parametrization by Suntharalingam and Sarmiento (2000), the control run without OIF fertilization simulates oceanic N<sub>2</sub>O emissions of about 3.5 Tg N/year. For the parametrization by Nevison et al. (2003) the control run simulates 4.6 Tg N/year. Both estimates are well within the 3.8 ± 2.0 Tg N/year range of the most recent IPCC report (Denman et al., 2007). For more details see Oschlies et al. (2010).

<sup>13</sup>Converting N to N<sub>2</sub>O requires multiplying by  $\frac{44.0128}{2 \cdot 14.0067}$ . Converting N<sub>2</sub>O to equivalent CO<sub>2</sub> requires multiplying by 310, which is the GWP of N<sub>2</sub>O relative to CO<sub>2</sub>. Converting CO<sub>2</sub> to C requires multiply by  $\frac{12.0107}{44.0095}$ .

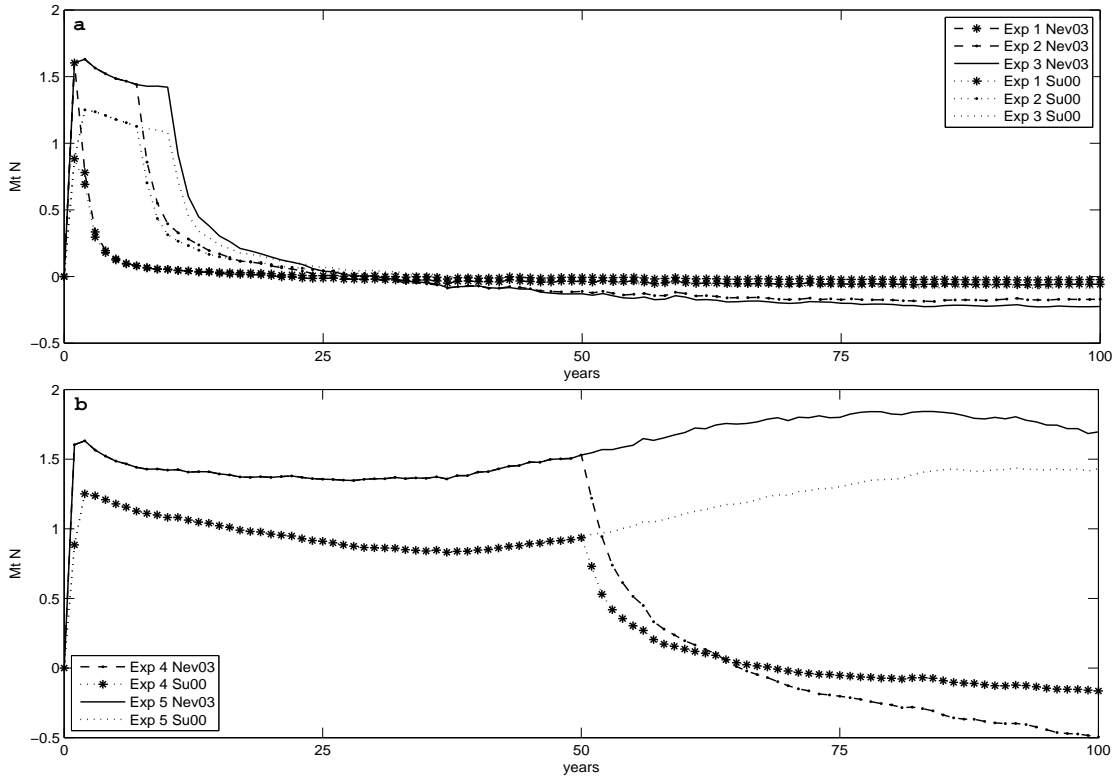


Figure 4: Path of released N compared to the baseline (without OIF) for high fertilization effectiveness in Mt N, Nev03 and Su03 abbreviate calibration based on Nevison et al. (2003) and Suntharalingam and Sarmiento (2000), respectively: **a** short-temp projects (1, 7, and 10 years OIF), **b** long-term projects (50 and 100 years OIF).

based on corrected oceanic uptake. Comparing the four scenarios with the gross amount of carbon credits from Section 3, we obtain the potential deduction rates that reduce the gross amount of carbon credits to net carbon credits with respect to  $N_2O$  emissions. We obtain deduction rates for the amount of carbon credits in each commitment period as well as for the various caps. The former factors indicate the  $N_2O$  offset over time, the latter indicate the overall  $N_2O$  offset. We refer to the former as the *actual* discount factors and to the latter as the *overall* discount factors. Two accounting methods exist that have no cap, the *shorttemp* and the *mixed* method. For both methods we calculate the average deduction rates over the commitment periods to also obtain information on overall offset. The average for the *shorttemp* method is calculated for the commitment periods until 2075 only, when the last credits are issued. Table 4 shows the range of possible deduction rates for each model experiment and each accounting method. The lowest deduction rate is obtained for Experiment 1 and the *net* method (0.23 percent), the largest deduction rate is obtained for Experiment 3 and the *longtemp* method (13.26 percent). The average deduction rate is 7.85 percent. The average range between the lower and upper bound for the deduction rates is 3.97 percent. The average range would be lower if the presentation would be restricted to one effectiveness scenario (3.50

Table 4: Range of *overall* deduction rates with respect N<sub>2</sub>O offset in percent

| Accounting method | Exp. 1<br>1 year<br>OIF | Exp. 2<br>7 years<br>OIF | Exp. 3<br>10 years<br>OIF | Exp. 4<br>50 years<br>OIF | Exp. 5<br>100 years<br>OIF |
|-------------------|-------------------------|--------------------------|---------------------------|---------------------------|----------------------------|
| <i>net</i>        | 0.23 - 7.44             | 3.66 - 8.19              | 4.84 - 8.33               | 6.32 - 11.88              | 4.74 - 12.44               |
| <i>average</i>    | 6.53 - 8.43             | 5.97 - 9.78              | 5.91 - 9.91               | 5.18 - 9.76               | 4.54 - 9.61                |
| <i>discount</i>   | 5.48 - 8.24             | 4.63 - 8.51              | 4.60 - 8.55               | 4.31 - 8.43               | 4.10 - 8.42                |
| <i>equ-Lash.</i>  | 6.17 - 7.76             | 6.21 - 9.64              | 6.17 - 9.85               | 5.45 - 10.05              | 4.62 - 10.11               |
| <i>equ-MCW</i>    | 5.20 - 8.67             | 7.68 - 9.78              | 7.66 - 10.33              | 6.58 - 11.67              | 4.87 - 10.97               |
| <i>shorttemp</i>  | 7.18 - 11.34            | 6.65 - 11.70             | 6.39 - 11.47              | 4.21 - 8.50               | 3.96 - 8.07                |
| <i>longtemp</i>   | 8.05 - 10.29            | 8.58 - 13.10             | 8.40 - 13.26              | 6.14 - 11.74              | 4.84 - 9.53                |
| <i>mixed</i>      | 4.28 - 11.82            | 5.71 - 13.02             | 6.30 - 12.98              | 6.18 - 11.43              | 4.50 - 10.03               |

percent for low and 1.91 percent for high fertilization effectiveness).

Overall, the *net* method shows lower values for the upper bound of deduction rates for short-term projects, but larger values for long-term projects compared with other methods that also generate permanent credits. Again, the reason is that the *net* method does not distinguish between earlier and later years. All years are valued equally, so for short-term projects later years with negative N<sub>2</sub>O emissions have a higher relative status. The other methods place a lower weight on later years, so for long-term projects later years with higher N<sub>2</sub>O emissions count less. The highest deduction rates for the short-term projects are calculated for the *longtemp* method. Here the carbon stocks after 60 years constitute the cap (see Subsection 2.2 and Section 3), so later years with low or even negative N<sub>2</sub>O emissions are not taken into account. For the long-term projects, the *longtemp* method provides deduction rates in the same order of magnitude as the other methods.

For Experiment 5 (100 years fertilization) and high fertilization effectiveness Table B.4 in the Appendix shows the evolution of deduction rates for accounting methods that assign permanent credits. The results illustrate that for all methods at least until the third commitment period (2025-2030) the *actual* deduction rates are lower than the *overall* deduction rates for the cap. For some methods this holds true for an even longer period. For example, the *equivalence* method based on the Lashof Approach has lower *actual* deduction rates until the 14th commitment period (2080-2085). Use of the *overall* deduction rate for deducting carbon credits ensures that even in early commitment periods sufficient carbon credits are deducted to balance the overall offset, although the actual offset is lower in early commitment periods. Applying the *actual* deduction rates for the commitment periods would result in lower deductions in the early commitment periods and higher deductions in the later commitment periods compared with the application of the *overall* deduction rate to the cap. In the short-term projects, however, no difference exists between applying the *actual* or the *overall* deduction rate in the accounting methods for which the cap is already binding in the first commitment period.

Deducted permanent carbon credits are not necessarily lost. They can be retained within buffer accounts

Table 5: Range of *actual* deduction rates corresponding to N<sub>2</sub>O emissions for the shorttemp method in percent

| <i>Shorttemp</i> method |                      |   |                       |      |                        |       |                        |   |                         |      |   |       |      |   |      |
|-------------------------|----------------------|---|-----------------------|------|------------------------|-------|------------------------|---|-------------------------|------|---|-------|------|---|------|
| Commitment period       | Exp. 1<br>1 year OIF |   | Exp. 2<br>7 years OIF |      | Exp. 3<br>10 years OIF |       | Exp. 4<br>50 years OIF |   | Exp. 5<br>100 years OIF |      |   |       |      |   |      |
| 2012 - 2020             | 3.87                 | - | 7.76                  | 2.44 | -                      | 5.43  | 2.22                   | - | 5.00                    | 2.22 | - | 5.00  | 2.22 | - | 5.00 |
| 2020 - 2025             | 5.05                 | - | 9.88                  | 3.96 | -                      | 8.12  | 3.48                   | - | 7.27                    | 2.79 | - | 6.03  | 2.79 | - | 6.03 |
| 2025 - 2030             | 5.94                 | - | 11.56                 | 5.06 | -                      | 10.02 | 4.67                   | - | 9.38                    | 3.24 | - | 6.83  | 3.24 | - | 6.83 |
| 2030 - 2035             | 6.66                 | - | 12.44                 | 5.92 | -                      | 11.40 | 5.59                   | - | 10.94                   | 3.60 | - | 7.48  | 3.60 | - | 7.48 |
| 2035 - 2040             | 7.24                 | - | 12.74                 | 6.56 | -                      | 12.30 | 6.29                   | - | 12.01                   | 3.86 | - | 7.95  | 3.86 | - | 7.95 |
| 2040 - 2045             | 7.69                 | - | 12.71                 | 7.02 | -                      | 12.85 | 6.80                   | - | 12.71                   | 4.10 | - | 8.35  | 4.10 | - | 8.35 |
| 2045 - 2050             | 8.00                 | - | 12.61                 | 7.42 | -                      | 13.23 | 7.22                   | - | 13.17                   | 4.29 | - | 8.67  | 4.29 | - | 8.67 |
| 2050 - 2055             | 8.31                 | - | 12.32                 | 7.73 | -                      | 13.42 | 7.55                   | - | 13.42                   | 4.47 | - | 8.96  | 4.47 | - | 8.96 |
| 2055 - 2060             | 8.58                 | - | 11.84                 | 8.09 | -                      | 13.59 | 7.83                   | - | 13.48                   | 4.62 | - | 9.20  | 4.62 | - | 9.20 |
| 2060 - 2065             | 8.59                 | - | 11.32                 | 8.43 | -                      | 13.61 | 8.20                   | - | 13.62                   | 5.30 | - | 10.37 | 4.73 | - | 9.37 |
| 2065 - 2070             | 8.22                 | - | 10.57                 | 8.59 | -                      | 13.34 | 8.38                   | - | 13.42                   | 5.94 | - | 11.42 | 4.80 | - | 9.48 |
| 2070 - 2075             | 8.05                 | - | 10.29                 | 8.58 | -                      | 13.10 | 8.40                   | - | 13.26                   | 6.14 | - | 11.74 | 4.84 | - | 9.53 |
| Average                 | 7.18                 | - | 11.34                 | 6.65 | -                      | 11.70 | 6.39                   | - | 11.47                   | 4.21 | - | 8.50  | 3.96 | - | 8.07 |

from which they can be released later, if leakage is lower than expected (Ellis, 2001). Consequently, applying the *overall* deduction rate ensures that sufficient carbon credits are stored in the buffer account if leakage is higher than expected. The situation is different for temporary credits, which have to be replaced anyway. If leakage is higher than expected, fewer carbon credits will be issued, and a larger fraction of existing temporary carbon credits has to be replaced. Consequently, temporary carbon credits might be deducted by the *actual* deduction rate in each commitment period. For the short-term projects, this situation only applies to the *shorttemp* and *mixed* methods. For the *longtemp* method, the cap is already binding in the first commitment period. For the *shorttemp* method and short-term OIF projects Table 5 shows the range of deduction rates over time until the final commitment period. The range is again based on both scenarios for fertilization effectiveness and both calibrations. Applying the *actual* deduction rates to the amount of carbon credits in each commitment period for the *shorttemp* method would result in lower deductions of carbon credits in at least the first two commitment periods. But replacement by other carbon credits would be higher in the following commitment periods. Considering all model experiments and all accounting methods we find a maximum overall deduction rate of 13.26 percent and an average value of 7.85 percent to address the offset by enhanced N<sub>2</sub>O emissions. In addition to offsets from emissions of other GHGs than carbon, offsets from CO<sub>2</sub> emissions emerging in operation need to be considered, in particular from fossil fuel burning to power ships. Climos, a company proposing commercial OIF, estimates the deduction rate for emissions from operation to be approximately 1 percent.<sup>14</sup> However, this estimate does not consider different durations for OIF. For short-term OIF projects, for example, the CO<sub>2</sub> emissions released by implementation and monitoring are relatively higher than for long-term OIF projects. Given these and other uncertainties

<sup>14</sup><http://www.climos.com/faq.php>



regarding CH<sub>4</sub> emissions, it seems appropriate to apply slightly larger deduction rates and to retain the deducted amount of carbon credits in a buffer account, which can be released later if complete leakage is observed with respect to N<sub>2</sub>O emissions, CH<sub>4</sub> emissions, and operation. However, using the Climos estimate and taking into account the fact that even an increase of 20 percent in CH<sub>4</sub> emissions would offset less than 1 percent of the OIF-induced carbon sequestration within the model experiments (Oschlies et al., 2010), an average overall deduction rate of 10 percent and a maximum value of 15 percent might serve as a rule of thumb.

#### 4. Discussion and conclusion

Our objective in this paper has been to analyze how carbon credits generated by large-scale sink enhancement projects could be accounted for. Different approaches are discussed in the literature. Our quantitative assessment is based on an application of the various accounting methods to hypothetical large-scale Southern Ocean iron fertilization projects, fertilizing the Southern Ocean (south of 30°) for 1, 7, 10, 50, and 100 years.

To determine the amount of carbon credits generated, we have applied all relevant carbon accounting methods, grouped into three categories according to the kind of credits they issue. In the first category we have summarized accounting methods that issue permanent carbon credits: the *net* method, the *average* method, the *discount* method, and the *equivalence* method (permanent methods). Two *equivalence* methods exist, based on different concepts of time equivalence (the Lashof and the MCW Approach). In the second category we have summarized accounting methods which issue temporary carbon credits: the *shorttemp* and the *longtemp* method (temporary methods). The carbon credits issued are comparable to tCER and ICER for LULUCF projects under the Kyoto Protocol. In the third category we have described a method that issues temporary carbon credits that are replaced by permanent carbon credits if the carbon is stored for a sufficient period of time. This method is rarely discussed in the literature. We refer to it as the *mixed* method. Applying the various accounting methods to OIF, we have supplemented all methods except the *shorttemp* and the *mixed* method with caps. These caps ensure that carbon credits are issued only up to an upper bound and no credits are required in periods with negative carbon uptake compared to the baseline. The *shorttemp* and *mixed* method do not require a cap because these methods entail carbon credit replacement in each period.

For the short-term OIF projects (1, 7, and 10 years of fertilization), the *discount* method provides the largest amount of permanent carbon credits, using an discount rate of 3 percent to convert future CO<sub>2</sub> units into present CO<sub>2</sub> units. The *average* and the *equivalence* method based on the Lashof Approach provide the second and third largest amounts of permanent carbon credits, respectively. However, the *equivalence* method spreads carbon credits out over a longer time period, providing only a fraction of the total credits in the first commitment period. All other methods provide the full amount of permanent carbon credits in

the first commitment period, which makes them more beneficial from an economic perspective. Overall, the *shorttemp* method provides the highest amount of temporary carbon credits, followed by the *mixed* method and the *longtemp* method. For the *longtemp* method, the amount of carbon credits is determined by the binding cap. But the cap is calculated on the basis of a shorter time period than the caps in the permanent methods.

Judging the approaches by the time for which they assign credits, the *shorttemp* method provides the largest amount of carbon credits in the first commitment period, but the temporary carbon credits have to be replaced in the next commitment period. However, only a fraction has to be replaced by other carbon credits since short-term temporary carbon credits are issued in the following commitment period as well. This fraction declines across the crediting period, so the stream of short-term temporary carbon credits is constantly larger than the total amount of carbon credits provided by the *net* method. Consequently, an amount of carbon credits that is larger than the amount of permanent carbon credits would not have to be replaced until the end of the crediting period. Furthermore, the *shorttemp* method provides additional temporary carbon credits during this period. Given constant or slowly increasing carbon prices and a sufficiently high discount rate to obtain present values for CO<sub>2</sub> units, this might result in economic benefits that overcompensate economic losses due to complete replacement after the end of the crediting period.

As the duration of OIF increases, the span between the *net* method and the other methods decreases. Since the *net* method does not value time, later years have the same weight as early years. The remaining permanent methods attach less value to the late years. For an project duration of 50 years, the *net* method provides an amount of carbon credits in the same order of magnitude as the other permanent methods. For a duration of 100 years, the *net* method provides the largest amount of carbon credits. The results for the application of the *shorttemp* and *longtemp* methods to long-term OIF are limited, because the crediting period for these methods was set to 60 years. However, for an project duration of 50 years the *longtemp* method provides the largest cap. The cap for the *longtemp* method is equal to credits issued by the *shorttemp* method in the final commitment period before the crediting period ends. Consequently, the *shorttemp* method again provides larger amounts of carbon credits - albeit temporary - than the permanent methods.

For the long-term projects (50 and 100 years), the *mixed* method leads to a lower amount of credits than most other methods, as it accounts for atmospheric carbon decay. Again, temporary carbon credits are issued that have to be replaced in each commitment period. However, the carbon credits issued in the final commitment period are permanent. For the short-term OIF projects, only an average fraction of 15 percent of carbon credits issued in the first commitment period is permanent in the end. We assume that the crediting period for this method is equal to the permanence period. Reducing the credit period would therefore increase the fraction of temporary carbon credits that turn permanent. This method is rarely discussed in the literature, and we have not explored it in great detail but have rather included it for

completeness, sake. Accordingly, analysis of the effect of other assumptions regarding the crediting period must be left to future research.

To answer the question of how many carbon credits can be generated, potential leakage needs to be accounted for. To address spatial leakage of carbon outside the enhancement region, we have used global rather than local data for oceanic carbon uptake. For local data, the corresponding deduction rate for spatial leakage would have been about eight percent. To address leakage by other GHGs, we have discussed deduction rates that lower the gross amount of carbon credits to the net amount. Only the net amount can be used for compliance. Leakage by other GHGs is mainly determined by enhanced N<sub>2</sub>O emissions. Considering all project durations and all accounting methods, we find a maximum deduction rate of 13.26 percent and an average value of 7.85 percent to address the offset by enhanced N<sub>2</sub>O emissions. The calculated deduction rates correspond to the overall amount of carbon credits (*overall* deduction rate). Alternatively, one could also use deduction rates for each commitment period (*actual* deduction rate). In earlier periods these *actual* deduction rates are lower than the *overall* deduction rates and would therefore lead to larger amounts of carbon credits in the early stages. However, applying the *overall* deduction rate ensures that a sufficient number of carbon credits will be deducted in early periods to balance offsets. Exceptions are the *shorttemp* method and the *mixed* method, where the corresponding temporary carbon credits have to be replaced in each commitment period. Therefore, if leakage were higher than expected, fewer new temporary carbon credits would be issued, and a larger fraction of temporary carbon credits already issued would have to be replaced. However, additional emissions from operation, together with remaining uncertainties regarding CH<sub>4</sub> emissions, will probably lead to the enforcement of higher deduction rates. In particular, the appropriate deduction rates for addressing leakage induced by operation are rather uncertain. We suggest raising the average deduction rate to 10 percent and the maximum deduction rate to 15 percent.

The results indicate that overall, and from an economic perspective, the *shorttemp* method seems most appropriate for short-term large-scale sink enhancement projects like OIF. This method provides for the largest amount of carbon credits the lowest deduction rates at an early stage. Also, the fraction that is permanently provided until the end of the crediting period is larger than with the other methods. From an environmental perspective, the *shorttemp* method also seems most appropriate, as no additional carbon emissions will be released because all credits have to be replaced at some point in time. Instead, even permanently stored carbon has to be replaced, so the application of the *shorttemp* method would provide extra climate benefits by reducing atmospheric carbon concentration.

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# Appendices

## Appendix A. Hypothetical large-scale Southern Ocean iron fertilization

For the analysis of hypothetical large-scale Southern Ocean iron fertilization, Oschlies et al. (2010) use the University of Victoria (UVic) Earth System Climate Model (Weaver et al., 2001) in the configuration described by Schmittner et al. (2008). The oceanic component is a fully three-dimensional primitive-equation model with 19 levels in the vertical, ranging from 50m thickness near the surface to 500m in the deep ocean. It contains a simple marine ecosystem model with the two major nutrients nitrate and phosphate and two phytoplankton classes, nitrogen fixers and other phytoplankton, with the former being limited only by phosphate. Organic matter is produced, processed, and remineralized according to a fixed elemental stoichiometry of C:N:P=112:16:1. Detritus sinks with a velocity that increases linearly with depth from 7 m/day at the surface to 40 m/day at 1000m depth and constant below. The production of calcium carbonate is assumed to be proportional to the production of nondiazotrophic detritus, and its instantaneous export and dissolution is parameterized by an e-folding depth of 3500 m.

The ocean component is coupled to a single-level energy moisture balance model of the atmosphere and a dynamic-thermodynamic sea ice component. The terrestrial vegetation and carbon cycle component is based on the Hadley Centre's TRIFFID model (Cox et al., 2000).

Because of the difficulty of explicitly modeling the complex iron chemistry and its interaction with marine biology, the model does not include an explicit parametrization of the iron cycle, but is parameterized against the changes in export production observed for persistent natural iron fertilization at the Kerguelen Plateau and Crozet Islands in the Southern Ocean (Blain et al., 2007; Pollard et al., 2009). Although the pragmatic model does not include an explicit parameterization of the iron cycle, it can nevertheless be tuned to achieve a reasonable fit with observed biogeochemical tracer distributions, in particular by using a low phytoplankton growth rate that allows for the persistence of HNLC areas (Schmittner et al., 2008; Oschlies et al., 2008).

The effect of ocean iron fertilization is simulated by doubling the phytoplankton maximum growth rate from 0.13 per day to 0.26 per day over the fertilized area and during the fertilization period. Increasing the maximum growth rate mimics the effect of iron in relaxing light limitation (Sunda and Huntsman, 1997), and the factor-2 enhancement results in an increase in simulated carbon export across  $z=125\text{m}$  by a factor of 2 to 3 with respect to an unfertilized control experiment. This is in good agreement with the impact of natural iron fertilization near Kerguelen and Crozet Islands, where Blain et al. (2007) and Pollard et al. (2009) estimated particulate carbon export fluxes two to three times higher than in the adjacent unfertilized regions. Additionally, Oschlies et al. (2010) analyze sensitivity experiments with maximum phytoplankton growth rates enhanced by factors of 3 and 5 and, in an attempt to simulate an upper bound for possible OIF impacts, to a hypothetical and very high value of 10 per day, because it cannot be ruled out that natural

iron fertilization is not saturating and that artificial fertilization could be engineered to have an even larger impact. None of these experiments showed complete depletion of macronutrients in the fertilized area.



## Appendix B. Tables

Table B.1: Annual change in oceanic carbon stocks for both levels of fertilization effectiveness in GtC

| year | Exp. 1<br>1 year OIF |       | Exp. 2<br>7 years OIF |       | Exp. 3<br>10 years OIF |       | Exp. 4<br>50 years OIF |      | Exp. 5<br>100 years OIF |      |
|------|----------------------|-------|-----------------------|-------|------------------------|-------|------------------------|------|-------------------------|------|
|      | high                 | low   | high                  | low   | high                   | low   | high                   | low  | high                    | low  |
| 1    | 8.91                 | 2.10  | 8.91                  | 2.10  | 8.91                   | 2.10  | 8.90                   | 2.10 | 8.90                    | 2.10 |
| 2    | 1.58                 | -0.03 | 5.56                  | 1.88  | 5.56                   | 1.88  | 5.60                   | 1.88 | 5.60                    | 1.88 |
| 3    | -0.44                | -0.28 | 4.42                  | 1.58  | 4.42                   | 1.58  | 4.40                   | 1.58 | 4.40                    | 1.58 |
| 4    | -0.51                | -0.19 | 3.81                  | 1.36  | 3.81                   | 1.36  | 3.80                   | 1.36 | 3.80                    | 1.36 |
| 5    | -0.46                | -0.14 | 3.42                  | 1.23  | 3.42                   | 1.23  | 3.40                   | 1.23 | 3.40                    | 1.23 |
| 6    | -0.39                | -0.11 | 3.14                  | 1.13  | 3.14                   | 1.13  | 3.20                   | 1.13 | 3.20                    | 1.13 |
| 7    | -0.33                | -0.08 | 2.95                  | 1.05  | 2.95                   | 1.05  | 2.90                   | 1.05 | 2.90                    | 1.05 |
| 8    | -0.30                | -0.07 | 0.01                  | -0.75 | 2.79                   | 0.99  | 2.80                   | 0.99 | 2.80                    | 0.99 |
| 9    | -0.25                | -0.06 | -1.00                 | -0.76 | 2.65                   | 0.94  | 2.70                   | 0.94 | 2.70                    | 0.94 |
| 10   | -0.24                | -0.05 | -0.97                 | -0.59 | 2.54                   | 0.90  | 2.50                   | 0.90 | 2.50                    | 0.90 |
| 11   | -0.21                | -0.04 | -0.88                 | -0.46 | -0.19                  | -0.86 | 2.40                   | 0.86 | 2.40                    | 0.86 |
| 12   | -0.19                | -0.04 | -0.79                 | -0.39 | -1.12                  | -0.86 | 2.40                   | 0.84 | 2.40                    | 0.84 |
| 13   | -0.18                | -0.03 | -0.72                 | -0.33 | -1.07                  | -0.67 | 2.30                   | 0.80 | 2.30                    | 0.80 |
| 14   | -0.16                | -0.03 | -0.65                 | -0.28 | -0.98                  | -0.54 | 2.20                   | 0.77 | 2.20                    | 0.77 |
| 15   | -0.15                | -0.03 | -0.61                 | -0.26 | -0.88                  | -0.46 | 2.20                   | 0.75 | 2.20                    | 0.75 |
| 16   | -0.14                | -0.02 | -0.56                 | -0.22 | -0.81                  | -0.40 | 2.10                   | 0.73 | 2.10                    | 0.73 |
| 17   | -0.14                | -0.02 | -0.52                 | -0.21 | -0.75                  | -0.35 | 2.00                   | 0.70 | 2.00                    | 0.70 |
| 18   | -0.12                | -0.02 | -0.49                 | -0.19 | -0.70                  | -0.31 | 2.00                   | 0.69 | 2.00                    | 0.69 |
| 19   | -0.12                | -0.02 | -0.46                 | -0.17 | -0.64                  | -0.29 | 2.00                   | 0.67 | 2.00                    | 0.67 |
| 20   | -0.11                | -0.02 | -0.43                 | -0.15 | -0.61                  | -0.25 | 2.00                   | 0.65 | 2.00                    | 0.65 |
| 21   | -0.10                | -0.01 | -0.40                 | -0.14 | -0.57                  | -0.23 | 1.80                   | 0.64 | 1.80                    | 0.64 |
| 22   | -0.09                | -0.01 | -0.39                 | -0.14 | -0.53                  | -0.22 | 1.90                   | 0.63 | 1.90                    | 0.63 |
| 23   | -0.10                | -0.01 | -0.36                 | -0.12 | -0.51                  | -0.19 | 1.80                   | 0.62 | 1.80                    | 0.62 |
| 24   | -0.09                | -0.01 | -0.35                 | -0.11 | -0.48                  | -0.19 | 1.80                   | 0.61 | 1.80                    | 0.61 |
| 25   | -0.08                | -0.01 | -0.33                 | -0.11 | -0.46                  | -0.17 | 1.80                   | 0.60 | 1.80                    | 0.60 |
| 26   | -0.09                | -0.01 | -0.32                 | -0.10 | -0.43                  | -0.15 | 1.80                   | 0.61 | 1.80                    | 0.61 |
| 27   | -0.08                | -0.01 | -0.31                 | -0.09 | -0.42                  | -0.14 | 1.70                   | 0.60 | 1.70                    | 0.60 |
| 28   | -0.08                | -0.01 | -0.28                 | -0.08 | -0.39                  | -0.14 | 1.70                   | 0.60 | 1.70                    | 0.60 |
| 29   | -0.07                | -0.01 | -0.28                 | -0.08 | -0.38                  | -0.12 | 1.70                   | 0.58 | 1.70                    | 0.58 |
| 30   | -0.07                | -0.01 | -0.26                 | -0.08 | -0.36                  | -0.12 | 1.60                   | 0.58 | 1.60                    | 0.58 |
| 31   | -0.06                | -0.01 | -0.25                 | -0.07 | -0.34                  | -0.11 | 1.70                   | 0.57 | 1.70                    | 0.57 |
| 32   | -0.06                | -0.01 | -0.24                 | -0.07 | -0.33                  | -0.10 | 1.60                   | 0.55 | 1.60                    | 0.55 |
| 33   | -0.06                | -0.01 | -0.24                 | -0.06 | -0.32                  | -0.11 | 1.60                   | 0.55 | 1.60                    | 0.55 |
| 34   | -0.06                | -0.01 | -0.22                 | -0.06 | -0.30                  | -0.09 | 1.60                   | 0.53 | 1.60                    | 0.53 |
| 35   | -0.06                | -0.01 | -0.22                 | -0.07 | -0.30                  | -0.10 | 1.50                   | 0.53 | 1.50                    | 0.53 |
| 36   | -0.05                | -0.01 | -0.21                 | -0.07 | -0.28                  | -0.09 | 1.60                   | 0.52 | 1.60                    | 0.52 |
| 37   | -0.04                | 0.00  | -0.20                 | -0.06 | -0.27                  | -0.09 | 1.50                   | 0.52 | 1.50                    | 0.52 |
| 38   | -0.04                | 0.00  | -0.19                 | -0.05 | -0.25                  | -0.08 | 1.50                   | 0.52 | 1.50                    | 0.52 |
| 39   | -0.05                | -0.01 | -0.19                 | -0.06 | -0.26                  | -0.08 | 1.50                   | 0.50 | 1.50                    | 0.50 |
| 40   | -0.06                | -0.01 | -0.19                 | -0.05 | -0.25                  | -0.08 | 1.50                   | 0.49 | 1.50                    | 0.49 |
| 41   | -0.04                | -0.01 | -0.18                 | -0.06 | -0.24                  | -0.07 | 1.50                   | 0.49 | 1.50                    | 0.49 |
| 42   | -0.05                | -0.01 | -0.17                 | -0.05 | -0.24                  | -0.07 | 1.40                   | 0.48 | 1.40                    | 0.48 |
| 43   | -0.05                | -0.01 | -0.17                 | -0.05 | -0.23                  | -0.07 | 1.50                   | 0.47 | 1.50                    | 0.47 |
| 44   | -0.05                | 0.00  | -0.16                 | -0.05 | -0.23                  | -0.07 | 1.40                   | 0.47 | 1.40                    | 0.47 |
| 45   | -0.05                | -0.01 | -0.16                 | -0.06 | -0.21                  | -0.06 | 1.40                   | 0.46 | 1.40                    | 0.46 |

Table B.1: continued

| year | Exp. 1<br>1 year OIF |       | Exp. 2<br>7 years OIF |       | Exp. 3<br>10 years OIF |       | Exp. 4<br>50 years OIF |       | Exp. 5<br>100 years OIF |       |
|------|----------------------|-------|-----------------------|-------|------------------------|-------|------------------------|-------|-------------------------|-------|
|      | high                 | low   | high                  | low   | high                   | low   | high                   | low   | high                    | low   |
| 46   | -0.04                | 0.00  | -0.15                 | -0.05 | -0.21                  | -0.06 | 1.40                   | 0.46  | 1.40                    | 0.46  |
| 47   | -0.04                | 0.00  | -0.14                 | -0.04 | -0.20                  | -0.05 | 1.40                   | 0.46  | 1.40                    | 0.46  |
| 48   | -0.03                | 0.00  | -0.14                 | -0.05 | -0.20                  | -0.06 | 1.40                   | 0.46  | 1.40                    | 0.46  |
| 49   | -0.04                | 0.00  | -0.13                 | -0.04 | -0.18                  | -0.06 | 1.40                   | 0.45  | 1.40                    | 0.45  |
| 50   | -0.03                | 0.00  | -0.13                 | -0.04 | -0.18                  | -0.06 | 1.40                   | 0.45  | 1.40                    | 0.45  |
| 51   | -0.03                | -0.01 | -0.13                 | -0.05 | -0.18                  | -0.06 | -1.30                  | -1.49 | 1.40                    | 0.43  |
| 52   | -0.03                | 0.00  | -0.12                 | -0.03 | -0.17                  | -0.06 | -1.70                  | -1.25 | 1.30                    | 0.46  |
| 53   | -0.03                | 0.00  | -0.13                 | -0.03 | -0.16                  | -0.06 | -1.70                  | -1.03 | 1.40                    | 0.44  |
| 54   | -0.03                | 0.00  | -0.11                 | -0.03 | -0.16                  | -0.06 | -1.50                  | -0.90 | 1.30                    | 0.44  |
| 55   | -0.03                | 0.00  | -0.12                 | -0.04 | -0.17                  | -0.06 | -1.30                  | -0.80 | 1.30                    | 0.43  |
| 56   | -0.04                | 0.00  | -0.12                 | -0.03 | -0.15                  | -0.05 | -1.30                  | -0.72 | 1.30                    | 0.43  |
| 57   | -0.03                | 0.00  | -0.11                 | -0.03 | -0.15                  | -0.04 | -1.30                  | -0.65 | 1.30                    | 0.42  |
| 58   | -0.03                | 0.00  | -0.11                 | -0.03 | -0.15                  | -0.04 | -1.10                  | -0.61 | 1.30                    | 0.43  |
| 59   | -0.02                | 0.00  | -0.10                 | -0.02 | -0.14                  | -0.03 | -1.10                  | -0.55 | 1.30                    | 0.42  |
| 60   | -0.03                | 0.00  | -0.10                 | -0.03 | -0.13                  | -0.04 | -1.00                  | -0.52 | 1.30                    | 0.42  |
| 61   | -0.02                | 0.00  | -0.09                 | -0.03 | -0.13                  | -0.04 | -1.00                  | -0.48 | 1.30                    | 0.41  |
| 62   | -0.03                | 0.00  | -0.10                 | -0.03 | -0.12                  | -0.04 | -0.90                  | -0.45 | 1.20                    | 0.43  |
| 63   | -0.02                | 0.00  | -0.09                 | -0.02 | -0.13                  | -0.04 | -0.90                  | -0.42 | 1.30                    | 0.41  |
| 64   | -0.02                | 0.00  | -0.09                 | -0.03 | -0.12                  | -0.03 | -0.90                  | -0.41 | 1.30                    | 0.41  |
| 65   | -0.03                | 0.00  | -0.09                 | -0.02 | -0.13                  | -0.04 | -0.80                  | -0.37 | 1.20                    | 0.41  |
| 66   | -0.02                | 0.00  | -0.08                 | -0.02 | -0.11                  | -0.04 | -0.80                  | -0.36 | 1.30                    | 0.40  |
| 67   | -0.03                | 0.00  | -0.09                 | -0.02 | -0.12                  | -0.03 | -0.70                  | -0.34 | 1.20                    | 0.41  |
| 68   | -0.02                | 0.00  | -0.08                 | -0.03 | -0.11                  | -0.04 | -0.80                  | -0.32 | 1.30                    | 0.39  |
| 69   | -0.02                | 0.00  | -0.09                 | -0.02 | -0.11                  | -0.03 | -0.70                  | -0.32 | 1.20                    | 0.40  |
| 70   | -0.02                | 0.00  | -0.08                 | -0.02 | -0.11                  | -0.03 | -0.70                  | -0.29 | 1.20                    | 0.40  |
| 71   | -0.02                | 0.00  | -0.08                 | -0.02 | -0.10                  | -0.03 | -0.60                  | -0.28 | 1.30                    | 0.40  |
| 72   | -0.02                | 0.00  | -0.08                 | -0.02 | -0.11                  | -0.03 | -0.60                  | -0.27 | 1.20                    | 0.40  |
| 73   | -0.02                | 0.00  | -0.08                 | -0.02 | -0.10                  | -0.02 | -0.70                  | -0.27 | 1.20                    | 0.39  |
| 74   | -0.02                | 0.00  | -0.07                 | -0.02 | -0.10                  | -0.03 | -0.50                  | -0.25 | 1.20                    | 0.40  |
| 75   | -0.02                | 0.00  | -0.08                 | -0.02 | -0.10                  | -0.03 | -0.60                  | -0.24 | 1.20                    | 0.39  |
| 76   | -0.02                | 0.00  | -0.07                 | -0.01 | -0.10                  | -0.03 | -0.60                  | -0.24 | 1.20                    | 0.38  |
| 77   | -0.01                | 0.00  | -0.07                 | -0.02 | -0.09                  | -0.02 | -0.50                  | -0.22 | 1.20                    | 0.39  |
| 78   | -0.02                | 0.00  | -0.06                 | -0.02 | -0.09                  | -0.03 | -0.50                  | -0.23 | 1.20                    | 0.39  |
| 79   | -0.02                | 0.00  | -0.07                 | -0.01 | -0.08                  | -0.02 | -0.50                  | -0.21 | 1.10                    | 0.39  |
| 80   | -0.01                | 0.00  | -0.06                 | -0.02 | -0.09                  | -0.02 | -0.50                  | -0.20 | 1.20                    | 0.38  |
| 81   | -0.02                | 0.00  | -0.06                 | -0.01 | -0.08                  | -0.02 | -0.50                  | -0.20 | 1.20                    | 0.39  |
| 82   | -0.01                | 0.00  | -0.06                 | -0.02 | -0.08                  | -0.02 | -0.50                  | -0.20 | 1.10                    | 0.38  |
| 83   | -0.02                | 0.00  | -0.06                 | -0.01 | -0.08                  | -0.02 | -0.40                  | -0.18 | 1.20                    | 0.38  |
| 84   | -0.01                | 0.00  | -0.06                 | -0.01 | -0.07                  | -0.02 | -0.50                  | -0.18 | 1.10                    | 0.39  |
| 85   | -0.01                | 0.00  | -0.05                 | -0.01 | -0.08                  | -0.02 | -0.40                  | -0.18 | 1.20                    | 0.37  |
| 86   | -0.01                | 0.00  | -0.06                 | -0.01 | -0.07                  | -0.02 | -0.40                  | -0.17 | 1.10                    | 0.38  |
| 87   | -0.01                | 0.00  | -0.04                 | -0.01 | -0.07                  | -0.01 | -0.40                  | -0.16 | 1.20                    | 0.38  |
| 88   | -0.01                | 0.00  | -0.05                 | -0.01 | -0.07                  | -0.02 | -0.40                  | -0.16 | 1.10                    | 0.38  |
| 89   | -0.01                | 0.00  | -0.05                 | -0.01 | -0.06                  | -0.01 | -0.40                  | -0.15 | 1.20                    | 0.37  |
| 90   | -0.01                | 0.00  | -0.04                 | -0.01 | -0.06                  | -0.02 | -0.30                  | -0.15 | 1.10                    | 0.38  |
| 91   | -0.01                | 0.00  | -0.04                 | -0.01 | -0.06                  | -0.01 | -0.40                  | -0.14 | 1.10                    | 0.38  |
| 92   | -0.01                | 0.00  | -0.04                 | 0.00  | -0.06                  | -0.01 | -0.30                  | -0.13 | 1.10                    | 0.37  |
| 93   | -0.01                | 0.00  | -0.03                 | -0.01 | -0.05                  | -0.01 | -0.40                  | -0.13 | 1.10                    | 0.38  |
| 94   | -0.01                | 0.00  | -0.04                 | -0.01 | -0.05                  | -0.02 | -0.30                  | -0.13 | 1.10                    | 0.38  |
| 95   | 0.00                 | 0.00  | -0.03                 | 0.00  | -0.05                  | -0.01 | -0.30                  | -0.11 | 1.10                    | 0.38  |
| 96   | -0.01                | 0.00  | -0.03                 | -0.01 | -0.05                  | -0.01 | -0.40                  | -0.11 | 1.10                    | 0.37  |
| 97   | -0.01                | 0.00  | -0.03                 | 0.00  | -0.04                  | -0.01 | -0.30                  | -0.12 | 1.10                    | 0.37  |
| 98   | -0.01                | 0.00  | -0.03                 | -0.01 | -0.05                  | -0.01 | -0.30                  | -0.10 | 1.10                    | 0.38  |
| 99   | 0.00                 | 0.00  | -0.03                 | 0.00  | -0.04                  | -0.01 | -0.30                  | -0.11 | 1.00                    | 0.37  |
| 100  | -0.01                | 0.00  | -0.04                 | -0.01 | -0.05                  | -0.01 | -0.30                  | -0.10 | 1.10                    | 0.37  |
| Sum  | 3.33                 | 0.61  | 13.56                 | 2.50  | 17.96                  | 3.53  | 74.60                  | 19.02 | 169.30                  | 56.47 |

Table B.2: Gross carbon credits for the *equivalence* method on the basis of additional oceanic carbon uptake with high fertilization effectiveness in Gt C

| <i>Equivalence method</i> |                                     |                                       |  |                                     |                                       |  |
|---------------------------|-------------------------------------|---------------------------------------|--|-------------------------------------|---------------------------------------|--|
|                           | Lashof Approach                     |                                       |  | MCW Approach                        |                                       |  |
|                           | Exp. 1<br>1 year<br>OIF<br>Cap 4.56 | Exp. 2<br>7 years<br>OIF<br>Cap 17.62 | Exp. 3<br>10 years<br>OIF<br>Cap 23.05 | Exp. 1<br>1 year<br>OIF<br>Cap 3.64 | Exp. 2<br>7 years<br>OIF<br>Cap 14.83 | Exp. 3<br>10 years<br>OIF<br>Cap 19.71 |
| Commitment period         | Carbon credits                      |                                       |  | Carbon credits                      |                                       |  |
| 2012 - 2020               | 0.5364                              | 1.3583                                | 1.3789                                 | 1.5994                              | 4.0384                                | 4.0992                                 |
| 2020 - 2025               | 0.2764                              | 1.1031                                | 1.4572                                 | 0.8065                              | 3.2188                                | 4.2515                                 |
| 2025 - 2030               | 0.2495                              | 0.9942                                | 1.3419                                 | 0.7153                              | 2.8499                                | 3.8465                                 |
| 2030 - 2035               | 0.2314                              | 0.9231                                | 1.2397                                 | 0.5160                              | 2.5962                                | 3.4866                                 |
| 2035 - 2040               | 0.2183                              | 0.8726                                | 1.1690                                 | 0                                   | 2.1309                                | 3.2212                                 |
| 2040 - 2045               | 0.2085                              | 0.8359                                | 1.1182                                 | 0                                   | 0                                     | 0.8076                                 |
| 2045 - 2050               | 0.2017                              | 0.8093                                | 1.0818                                 | 0                                   | 0                                     | 0                                      |
| 2050 - 2055               | 0.1968                              | 0.7901                                | 1.0558                                 | 0                                   | 0                                     | 0                                      |
| 2055 - 2060               | 0.1922                              | 0.7774                                | 1.0373                                 | 0                                   | 0                                     | 0                                      |
| 2060 - 2065               | 0.1905                              | 0.7716                                | 1.0278                                 | 0                                   | 0                                     | 0                                      |
| 2065 - 2070               | 0.1899                              | 0.7707                                | 1.0259                                 | 0                                   | 0                                     | 0                                      |
| 2070 - 2075               | 0.1907                              | 0.7756                                | 1.0319                                 | 0                                   | 0                                     | 0                                      |
| 2075 - 2080               | 0.1929                              | 0.7865                                | 1.0456                                 | 0                                   | 0                                     | 0                                      |
| 2080 - 2085               | 0.1965                              | 0.8026                                | 1.0672                                 | 0                                   | 0                                     | 0                                      |
| 2085 - 2090               | 0.2019                              | 0.8256                                | 1.0976                                 | 0                                   | 0                                     | 0                                      |
| 2090 - 2095               | 0.2097                              | 0.8580                                | 1.1406                                 | 0                                   | 0                                     | 0                                      |
| 2095 - 2100               | 0.2214                              | 0.9039                                | 1.2012                                 | 0                                   | 0                                     | 0                                      |
| 2100 - 2105               | 0.2399                              | 0.9781                                | 1.2984                                 | 0                                   | 0                                     | 0                                      |
| 2105 - 2112               | 0.4128                              | 1.6824                                | 2.2291                                 | 0                                   | 0                                     | 0                                      |

Table B.3: Gross amount of carbon credits with *mixed* method on the basis of additional oceanic carbon uptake with high fertilization effectiveness in Gt C

| <i>Mixed</i> method |                      |             |                       |             |                        |             |
|---------------------|----------------------|-------------|-----------------------|-------------|------------------------|-------------|
| Commitment period   | Exp. 1<br>1 year OIF |             | Exp. 2<br>7 years OIF |             | Exp. 3<br>10 years OIF |             |
|                     | Carbon credits       | Replacement | Carbon credits        | Replacement | Carbon credits         | Replacement |
| 2012 - 2020         | 5.22                 | 0           | 24.43                 | 0           | 27.21                  | 0           |
| 2020 - 2025         | 3.87                 | 1.34        | 17.01                 | 7.43        | 24.63                  | 0           |
| 2025 - 2030         | 3.12                 | 0.75        | 13.43                 | 3.57        | 18.80                  | 5.83        |
| 2030 - 2035         | 2.61                 | 0.51        | 11.19                 | 2.24        | 15.48                  | 3.32        |
| 2035 - 2040         | 2.22                 | 0.39        | 9.56                  | 1.63        | 13.17                  | 2.31        |
| 2040 - 2045         | 1.94                 | 0.28        | 8.33                  | 1.23        | 11.44                  | 1.73        |
| 2045 - 2050         | 1.73                 | 0.21        | 7.37                  | 0.96        | 10.11                  | 1.33        |
| 2050 - 2055         | 1.53                 | 0.20        | 6.59                  | 0.78        | 9.02                   | 1.10        |
| 2055 - 2060         | 1.38                 | 0.15        | 5.98                  | 0.61        | 8.13                   | 0.88        |
| 2060 - 2065         | 1.27                 | 0.11        | 5.49                  | 0.49        | 7.45                   | 0.68        |
| 2065 - 2070         | 1.16                 | 0.11        | 5.07                  | 0.42        | 6.87                   | 0.58        |
| 2070 - 2075         | 1.09                 | 0.07        | 4.75                  | 0.32        | 6.42                   | 0.45        |
| 2075 - 2080         | 1.02                 | 0.07        | 4.47                  | 0.28        | 6.02                   | 0.39        |
| 2080 - 2085         | 0.97                 | 0.05        | 4.21                  | 0.26        | 5.68                   | 0.34        |
| 2085 - 2090         | 0.92                 | 0.05        | 4.01                  | 0.20        | 5.39                   | 0.29        |
| 2090 - 2095         | 0.88                 | 0.04        | 3.84                  | 0.17        | 5.16                   | 0.23        |
| 2095 - 2100         | 0.87                 | 0.01        | 3.71                  | 0.13        | 4.97                   | 0.19        |
| 2100 - 2105         | 0.85                 | 0.02        | 3.62                  | 0.09        | 4.83                   | 0.14        |
| 2105 - 2112         | 0.83                 | 0.01        | 3.52                  | 0.10        | 4.68                   | 0.15        |

Table B.4: *Actual* deduction rates over time for *net*, *average*, *discount*, and *equivalence* methods based on Experiment 5 with high fertilization effectiveness in percent

|           | <i>net</i> method    |                     | <i>average</i> method |                     | <i>discount</i> method |                     | <i>equiv.</i> method (Lashof) |                     | <i>equiv.</i> method (MCW) |                     |
|-----------|----------------------|---------------------|-----------------------|---------------------|------------------------|---------------------|-------------------------------|---------------------|----------------------------|---------------------|
|           | Nevison <sup>a</sup> | Sunth. <sup>b</sup> | Nevison <sup>a</sup>  | Sunth. <sup>b</sup> | Nevison <sup>a</sup>   | Sunth. <sup>b</sup> | Nevison <sup>a</sup>          | Sunth. <sup>b</sup> | Nevison <sup>a</sup>       | Sunth. <sup>b</sup> |
| in %      |                      |                     |                       |                     |                        |                     |                               |                     |                            |                     |
| Cap       | 12.44                | 8.76                | 9.61                  | 6.61                | 8.42                   | 5.89                | 10.11                         | 6.95                | 7.95                       | 14.25               |
| 2012 - 20 | 4.60                 | 3.49                | 4.60                  | 3.49                | 4.60                   | 3.49                | 4.35                          | 2.46                | 2.89                       | 4.46                |
| 2020 - 25 | 7.67                 | 5.73                | 7.67                  | 5.73                | 7.67                   | 5.73                | 5.05                          | 4.42                | 3.87                       | 6.31                |
| 2025 - 30 | 8.86                 | 6.46                | 8.86                  | 6.46                | 8.86                   | 6.46                | 5.40                          | 4.03                | 4.35                       | 7.46                |
| 2030 - 35 | 9.51                 | 6.58                | 9.51                  | 6.58                | 9.51                   | 6.58                | 6.63                          | 5.01                | 4.69                       | 8.37                |
| 2035 - 40 | 10.27                | 6.80                | 10.27                 | 6.80                | 21.36                  | 12.60               | 6.66                          | 4.88                | 4.95                       | 9.10                |
| 2040 - 45 | 11.02                | 6.97                | 11.02                 | 6.97                | 100 <sup>c</sup>       | 100 <sup>c</sup>    | 7.20                          | 5.15                | 5.15                       | 9.72                |
| 2045 - 50 | 11.74                | 7.25                | 11.74                 | 7.25                | 0                      | 0                   | 7.68                          | 5.32                | 5.33                       | 10.23               |
| 2050 - 55 | 12.75                | 7.72                | 12.75                 | 7.72                | 0                      | 0                   | 7.89                          | 5.43                | 5.49                       | 10.63               |
| 2055 -60  | 14.05                | 8.54                | 38.10                 | 26.26               | 0                      | 0                   | 8.35                          | 5.67                | 5.87                       | 11.55               |
| 2060 - 65 | 14.83                | 9.25                | 0                     | 0                   | 0                      | 0                   | 8.74                          | 5.83                | 6.99                       | 14.68               |
| 2065 - 70 | 16.77                | 10.43               | 0                     | 0                   | 0                      | 0                   | 9.02                          | 6.23                | 34.47                      | 18.81               |
| 2070 - 75 | 17.65                | 11.84               | 0                     | 0                   | 0                      | 0                   | 9.61                          | 6.28                | 100 <sup>c</sup>           | 37.05               |
| 2075 - 80 | 18.57                | 12.45               | 0                     | 0                   | 0                      | 0                   | 10.00                         | 6.74                | 0                          | 100 <sup>c</sup>    |
| 2080 - 85 | 19.61                | 13.73               | 0                     | 0                   | 0                      | 0                   | 10.38                         | 6.97                | 0                          | 0                   |
| 2085 - 90 | 20.16                | 14.62               | 0                     | 0                   | 0                      | 0                   | 10.80                         | 7.27                | 0                          | 0                   |
| 2090 - 95 | 21.08                | 15.81               | 0                     | 0                   | 0                      | 0                   | 11.18                         | 7.58                | 0                          | 0                   |
| 2095 - 00 | 21.22                | 16.56               | 0                     | 0                   | 0                      | 0                   | 11.58                         | 7.92                | 0                          | 0                   |
| 2100 - 05 | 21.13                | 16.85               | 0                     | 0                   | 0                      | 0                   | 11.92                         | 8.24                | 0                          | 0                   |
| 2105 - 12 | 21.16                | 17.49               | 0                     | 0                   | 0                      | 0                   | 12.29                         | 8.60                | 0                          | 0                   |

<sup>a</sup> Calibration is based on Nevison et al. (2003).

<sup>b</sup> Calibration is based on Suntharalingam and Sarmiento (2000).

<sup>c</sup> A deduction rate of 100 percent for a commitment period indicates that the cap was approached in the previous commitment period if N<sub>2</sub>O emissions are taken into account.

## Part III

# Economic prospects of ocean iron fertilization in an international carbon market

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# Economic prospects of ocean iron fertilization in an international carbon market<sup>☆</sup>

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## Abstract

Staying within the 2°C temperature increase target for climate change requires for ambitious emission reduction targets for the 2012-2020 compliance period. Cost-efficiency is a crucial criterion for the achievement of such targets, requiring analyses of all possible options. Enhancing the oceanic carbon sink via ocean iron fertilization (OIF) provides such an option. Our analysis reveals that the critical unit costs per net ton of CO<sub>2</sub> sequestered by OIF range from 22 to 28 USD (price level 2000) in a post-Kyoto compliance scenario. The critical unit costs are defined as those that would make an emitter indifferent between various abatement options. With reference to hypothetical short-term large-scale Southern Ocean OIF we are able to show that seven years of OIF provide a number of credits exceeding those obtainable from global forestation projects lasting 20 years. From an economic perspective, our results indicate that OIF can be considered a potentially viable carbon-removal option. However, further research is needed, especially on adverse side-effects and their ecological and economical consequences.

*Keywords:* climate change, climate engineering, ocean iron fertilization, CO<sub>2</sub> market, emission trading

*JEL:* Q52, Q54

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## 1. Introduction

Even courageous climate policies run the risk of catastrophic climate change taking place. If this risk increases, climate engineering options become a last resort, so they need to be explored in time (e.g., Kousky et al., 2009; Royal Society, 2009; Keith et al., 2010). Basically, climate engineering can be classified into (a) carbon dioxide removal and (b) solar radiation management. Carbon dioxide removal addresses the root of the problem by directly reducing atmospheric carbon concentration, thus extending the world's carbon emission budget. Carbon dioxide can be biologically removed by enhancing the terrestrial and the oceanic carbon sink. The former can be enhanced by forestry activities etc., the latter by iron fertilization etc.. Forestry activities are included in the present climate agreement (UNFCCC, 2003). Iron fertilization measures are still at the research stage, and some small-scale in situ experiments have been carried out with varying results to test effectiveness with respect to carbon sequestration. Dedicated field trials exploring the potential benefits and side-effects of ocean iron fertilization (OIF) have not yet been carried out, and there is concern that the uncertainties and risks associated with OIF are so substantial that such trials should not even be considered (e.g., Strong et al., 2009). For a better understanding of the potential effectiveness and risks of OIF, Oschlies et al. (2010) have recently extrapolated observations from ongoing natural iron fertilization "experiments" by sedimentary iron release on the Kerguelen Plateau and the Crozet Islands in the Southern Ocean (Blain et al., 2007; Pollard et al., 2009). Their results lead us to believe that further research on the climate engineering potential of OIF is warranted.

Exploring the potential of OIF requires consideration not just of its effectiveness, but also of its efficiency. This paper addresses the economic prospects of OIF within a climate agreement like the Kyoto Protocol. We consider hypothetical, short-term, but large-scale OIF in the Southern Ocean for the duration of 1, 7, and 10 years in a post-Kyoto agreement and derive criteria for assessing the efficiency of OIF as a climate engineering option. Including OIF in a post-Kyoto agreement would also have implications for the distribution of welfare. Accordingly, we also attempt to determine the distributional aspects involved by including carbon credits from OIF. To our knowledge, this has not been done before.

In major regions of the oceans (the Eastern Equatorial Pacific, the North Pacific, and in particular vast areas of the Southern Ocean), macronutrients such as phosphate and nitrate are present in high concentrations under conditions that would seem to be ideal for total depletion of these macronutrients by phytoplankton growth (Sarmiento and Gruber, 2006). In fact, these regions display relatively low phytoplankton growth and have accordingly been named high-nutrient, low-chlorophyll (HNLC) regions. Alongside other limiting factors, such as silicon limitation north of the Polar Front and light limitation south of the Polar Front (Aumont and Bopp, 2006), limited iron concentration has been proposed as the main reason for the existence of HNLC regions (Martin, 1990). The limitation of phytoplankton growth through iron has been demonstrated by mesoscale iron fertilization experiments in all major HNLC regions (Boyd et al., 2007). Despite



large variations in the magnitude of the phytoplankton growth response, all experiments show a substantial increase in chlorophyll and a strong decrease in surface  $p\text{CO}_2$  (de Baar et al., 2005). However, modeling studies have shown that the carbon removal potential of iron fertilization is mainly limited to the Southern Ocean, the net reduction of atmospheric carbon varying between 56 to 160 Gt C for a fertilization period of 100 years (Sarmiento and Orr, 1991; Aumont and Bopp, 2006; Oschlies et al., 2010). The reason is that surface waters are currently subducted into the ocean interior before macronutrients are exhausted. Even though the range indicates uncertainty about the effectiveness of OIF, the lower estimate for the cumulative uptake of about 56 Gt C is far from negligible and approximately corresponds to a “stabilization wedge” introduced by Pacala and Socolow (2004). Nevertheless, the effectiveness of OIF is questioned because of the risk of unintended side-effects, such as an enhanced production of nitrous oxide ( $\text{N}_2\text{O}$ ) and methane ( $\text{CH}_4$ ), or changes in the species composition and the food web (Gnanadesikan et al., 2003; Denman, 2008). Only limited evidence is available about these negative side-effects from previous small-scale OIF experiments, and considerable uncertainty remains about these effects in connection with large-scale OIF projects (Lampitt et al., 2008; Royal Society, 2009).

While there is a large body of literature on the economic prospects of forestry activities, there are relatively few studies on the economic prospects of OIF in general, and on the effects of including OIF in an international climate regime in particular. To our knowledge, the rare exceptions are Sagarin et al. (2007), Leinen (2008), and Bertram (2010). Sagarin et al. (2007) provide a non-technical overview of the scientific, legal, and economic issues related to OIF. Leinen (2008) discusses the requirements of carbon markets for the generation of carbon credits by OIF and argues that potential commercial interest in OIF could fund further OIF experiments. Bertram (2010) also reviews basic aspects of OIF, but with a more detailed focus on the legal status, open-access issues, and the way in which the regulation of afforestation and reforestation activities under the Clean Development Mechanism (CDM) of the Kyoto Protocol could be applied to OIF. However, all three studies discuss OIF in a comparatively general manner. To our knowledge, OIF has not yet been discussed with respect to an explicit reduction target for 2020. Nor is it clear what consequences the inclusion of OIF in a post-Kyoto climate agreement would have on possible carbon-credit prices or distributional effects

In this paper, we consider a hypothetical, large-scale, few-year OIF realized within an international project as part of a post-Kyoto climate agreement. The agreement covers countries with positive carbon emission reduction targets (Annex1 countries), countries with negative carbon emission reduction targets (HotAir countries), and countries without any carbon emission reduction targets (CDM countries). We model a static compliance problem for the countries with a basic  $\text{CO}_2$  market for the next commitment period (2012-2020), including domestic carbon emission reductions and emission trading. It is not likely that OIF will be implemented in the next commitment period. Nevertheless, we have chosen 2012-2020 because data on economic activity, which are essential for our analysis, are more readily available for the

next few years than for later periods. Also, our analysis serves as an initial test whether compared to existing options OIF can play an economically viable role in mitigating of climate change.

The paper is structured as follows: Section 2 explains the static general equilibrium 2020 compliance problem. Subsection 2.1 introduces the basic carbon market with emission trading. In subsection 2.2 we extend the market by introducing carbon credits from forestry activity. Subsection 2.3 sets out our scenarios regarding limitations on emission trading and on carbon credits from forestry activity, before subsection 2.4 introduces carbon credits from OIF. In Section 3, we determine the critical unit costs and the critical amounts for OIF. The critical unit costs and amounts indicate whether OIF credits would be able to compete with carbon credits from HotAir and CDM countries and carbon credits from forestry activities. We compare these critical costs and critical amounts to most latest cost estimates and the latest findings on hypothetical large-scale iron fertilization in the Southern Ocean reported by Oschlies et al. (2010) and Rickels et al. (2010). In Section 4, we consider distributional aspects related to OIF. We investigate who would gain or lose if carbon credits from OIF could be used for compliance. Section 5 concludes.

## 2. The carbon market

### 2.1. The carbon market without forestation and OIF

Assessing the potential of OIF in a post-Kyoto climate regime requires consideration of a carbon market. We model the 2020 compliance problem, restricting it to carbon emissions.<sup>1</sup> Achieving a given emission cap  $A$  requires a given country to reduce its business-as-usual emission  $E$  by the amount  $R$  so that  $E - R \leq A$ . The costs of this action are measured by the abatement cost function  $AC(R)$ . To reduce costs, we allow for emissions trading, defining  $P$  as the net number of carbon credits traded.<sup>2</sup> Consequently, countries face the problem of determining the optimal amount of domestic emission reduction  $R^*$  and the optimal amount of credits traded  $P^*$  so that the sum of abatement costs and emission trading costs is minimized. Denoting the carbon credit price by  $\pi$  and indexing the countries by  $i$ , the optimization problem for each country becomes

$$\min_{R_i, P_i} C_i = AC_i(R_i) + \pi P_i, \quad (1)$$

$$\text{s.t. } E_i - R_i - P_i \leq A_i, \quad (2)$$

$$\text{s.t. } 0 \leq R_i \leq E_i. \quad (3)$$

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<sup>1</sup>From now on, we refer to carbon emissions as “emissions”.

<sup>2</sup>With respect to emission trading, we simplify notation and refer just to carbon credits. Therefore carbon credits contain assigned amount units (AAU) from countries with positive and negative emission reduction targets, emission reduction units (ERU) from joint implementation (JI), certified emission reductions (CER) from clean development mechanism (CDM), and removal units (RMU) from forestry activities.

Note that a positive value for  $P_i$  indicates a credit-buying country, while a negative value indicates a credit-selling country. Solving the optimization problem, we obtain for an interior solution  $0 < R_i^* < E_i$  the well-known efficiency result that marginal abatement costs in each country are equal to the carbon credit price:

$$AC'(R_i^*) = \pi. \quad (4)$$

The optimal degree of emission reduction becomes a function of the carbon credit price  $R_i^*(\pi)$ . The optimal carbon credit price is determined by the overall compliance condition that the sum of individual emission reductions must be sufficient to equal the sum of the individual carbon emission caps:

$$\sum_i^n E_i - \sum_i^n R_i^*(\pi^*) = \sum_i^n A_i. \quad (5)$$

To determine emission caps  $A_i$  we define a Reference Emission Target for 2020 relative to 2005. The EU has made a firm, independent commitment to reduce its emissions by at least 20 percent by 2020 relative to 1990, and by 30 percent if an international agreement on emission reduction is adopted (European Union, 2009, Art. 3). Where countries have announced various targets, we have chosen the more ambitious ones. Where Annex I countries have not announced any targets, we have chosen the emission target from the Garnaut Climate Change Review final report, which corresponds to the EU 30-percent target (Garnaut, 2008), except for the Hot Air countries Russia and Ukraine. Here we assume an emission target that goes no further than their current BAU emission projections for 2020 (Anger et al., 2009).<sup>3</sup> Based on their large potential for generating emission reduction credits via CDM, we include China, India, and countries in Latin America as CDM countries. Here, we assume that no emission targets exist. Consequently, we have three groups of countries: Annex I countries with positive reduction targets (Annex1), Annex I countries with negative reduction targets (HotAir), and countries with no reduction targets at all (CDM). For Annex1 countries the individual emission reduction targets for 2020 relative to 2005 add up to 27.5 percent. If we include the HotAir and both the HotAir and CDM countries, the overall reduction target decreases to 21.7 percent and -5.4 percent, respectively. A detailed description of the determination of emission caps for the various countries can be found in Appendix A. Individual emission targets are shown in column 3 of Table A.2.

To determine the abatement cost functions  $AC(R_i)$  we take a top-down approach based on the computable general equilibrium model DART calibrated to the GTAP-7 database (Narayanan and Walmsley, 2008). The DART (Dynamic Applied Regional Trade) model is a multi-region, multi-sector recursive dy-

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<sup>3</sup>Note that by doing so we still obtain a stricter reduction than we would by taking their historical 1990 emissions as a target.

dynamic CGE model of the world economy for analyzing climate policies. For a more detailed description of the model, see Klepper et al. (2003). The DART version we use divides the world into 12 regions. We calculate abatement cost functions for nine of these regions, the Annex1 regions: Western Europe (WEU), Eastern Europe (EEU), United States (US), Japan (JPN)<sup>4</sup>, and the group Australia, New Zealand and Canada (OAB); for the HotAir region make up of the former Soviet Union (FSU); and for the CDM regions China (CPA), India (IND), and Latin America (LAM).

Our calculations are based on the emission targets for Annex1 and HotAir countries from our Reference Emission Target for 2020. For CDM countries, these targets are equal to their 2020 BAU emission levels. For the region under consideration, we start with a baseline run without an emission target and reduce the permitted emissions stepwise, observing the change in GDP over and against the first baseline run to figure out the relative costs. For a detailed description of this approach, see Klepper and Peterson (2006b). We fit two analytical functional forms to the relative costs modeled:

$$\begin{aligned} \text{Function 1: } 1 - \frac{GDP_{red_i}}{GDP_{base_i}} &= \alpha_{1i} \left(1 - \frac{R_i}{E_1}\right)^2, \\ \text{Function 2: } 1 - \frac{GDP_{red_i}}{GDP_{base_i}} &= \beta_{1i} \left(1 - \frac{R_i}{E_1}\right) + \beta_{2i} \left(1 - \frac{R_i}{E_1}\right)^2. \end{aligned} \tag{6}$$

For each region, the resulting parameters for both functions and for adjusted R<sup>2</sup> can be found in Appendix A, Table A.1. To obtain country-specific abatement cost functions for the DART regions with more than one country, we take the approach proposed by Tol (2005) and assume a 10-percent spread in relative costs between the country with the highest carbon intensity (CO<sub>2</sub>/GDP) and the country with the lowest carbon intensity for a 10-percent reduction. Drawing upon minimum, maximum, and average carbon intensity for each region, we adjust the parameters  $\alpha_{1i}$  for Function 1 and  $\beta_{1i}$  for Function 2 to obtain country-specific abatement cost functions.

There is some evidence that abatement cost estimates obtained from top-down models like DART tend to be lower than those obtained from bottom-up models (Wing, 2006). Top-down models allow greater scope for economic adjustment and provide better estimates of medium-term costs, whereas bottom-up models are better at estimating of short-term costs (Gallagher, 2008). To take this into account, we include a third abatement cost function. It has the same functional form as Function 1, but the parameter values are taken from Tol (2005), who calibrates the parameters to the abatement cost overview by Hourcade et al. (1996). We denote this abatement cost function as Function 3. The country-specific parameter values for the three functional forms Function 1, Function 2, and Function 3, are shown in columns 4 to 7 in the Appendix, Table A.2.

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<sup>4</sup>For Japan, we calculate the abatement cost function based on the equivalent variation instead on GDP to obtain a monotonically increasing abatement cost function.

## 2.2. Extending the carbon market for carbon credits from forestation

To include forestation in our carbon market, we use the results presented by Hertel et al. (2009), because neither the DART model (Klepper et al., 2003) nor the calibrated model of Tol (2005) explicitly model the forestry sector. Hertel et al. (2009) apply the global timber model proposed by Sohngen and Mendelsohn (2003; 2007). The global timber model is a partial-equilibrium, dynamic optimization model of global timber markets that maximizes the net present value of consumer surplus in timber markets, taking into account the costs of managing, harvesting, and maintaining forests. The model determines the optimal age for harvesting trees, the quantity harvested, the area of land converted to agriculture, and timber management (Hertel et al., 2009). If a carbon rental fee for landowners is introduced for every additional ton of carbon stored each year, the value of forest land increases and landowners respond by converting other land into forests, increasing rotation length, and stepping up management intensity (Sohngen and Mendelsohn, 2003). The additional cumulative amount of carbon sequestered is obtained by comparing the situation with a carbon rental fee to the situation without such fee. Hertel et al. (2009) obtain the annual sequestration potential from the global timber model by calculating the annual equivalent amount of carbon in response to the carbon rental fee based on a 20-year projection of carbon storage. The equivalent annual amount is derived from the present-value carbon equivalent, using a 5-percent social rate of time preference.

Using these results, we extend our model to include a forestry sector for each country responding to the prevailing carbon price with forest carbon sequestration  $F_i(\pi)$ . We assume that the contribution of the forestry sector to GDP is negligible. Thus the objective function in the abatement cost minimization problem of a country (1) does not change, but the first constraint (2) does:

$$E_i - R_i - P_i - F(\pi) \leq A_i, \tag{7}$$

as does the optimal carbon credit price, because the overall compliance condition changes:

$$\sum_i^n E_i - \sum_i^n R_i^*(\pi^*) - \sum_i^n F_i(\pi^*) = \sum_i^n A_i. \tag{8}$$

Note that  $F_i$  is not marked with an asterisk because the carbon sequestration response of the forestry sector goes into the model as an optimized function.

Based on the global carbon credit supply schemes from forestry activities for the US, China, and the rest of the world taken from Hertel et al. (2009), we estimate simple linear forest sequestration supply functions  $F_i(\pi) = f_i\pi$ . We use the share of additional carbon stored without the US and China presented in Sohngen and Mendelsohn (2007) to divide the forest supply function of the rest of the world into less aggregated regions. We use the share of forest areas from FAO (2009) to further divide the forest supply curve of the remaining aggregated regions of Europe, Central America, South America, and Oceania into country levels.

The results are shown in Appendix A, column 8 of Table A.2. Column 9 in this table shows the current annual limits for sequestration by forestation for each Annex1 and HotAir country under the Kyoto Protocol  $\bar{F}_i$  (UNFCCC, 2001, Art. 3.4). We assume that for CDM countries no limits to sequestration by forestation exist.

### 2.3. Scenarios for the carbon market with forestation

Table 1: Scenarios for emission trading and inclusion of forestation

|   | Emission trading restricted to Annex1 | Emission trading including CDM and HotAir up to 10 percent of Annex1 reduction targets | Emission trading without limitations for CDM and HotAir |
|---|---------------------------------------|--|---|
| No forestation<br>$F_i(\pi) = 0$  | <i>Trade</i><br><i>NoForest</i>       | <i>LimitCDM</i><br><i>NoForest</i>   | <i>FullCDM</i><br><i>NoForest</i>                       |
| Limited forestation (Annex Z)<br>$F_i(\pi) = f_i\pi$ if $f_i\pi < \bar{F}_i$<br>$F_i(\pi) = \bar{F}_i$ if $f_i\pi \geq \bar{F}_i$ | <i>Trade</i><br><i>LimitForest</i>    | <i>LimitCDM</i><br><i>LimitForest</i><br>(Reference Scenario)                          | <i>FullCDM</i><br><i>LimitForest</i>                    |
| Unlimited forestation<br>$F_i(\pi) = f_i\pi$  | <i>Trade</i><br><i>FullForest</i>     | <i>LimitCDM</i><br><i>FullForest</i>   | <i>FullCDM</i><br><i>FullForest</i>                     |

Under the Kyoto Protocol, there are limits to the exchange of carbon credits with CDM and HotAir countries and the use of domestically generated carbon credits from forestation. For a given emission reduction target, increasing the exchange of credits with CDM and HotAir countries or allowing for more carbon credits from forestation leads to declining abatement costs, lower carbon credit prices and smaller amounts of domestic emission reduction  $R_i$  in Annex1 countries. This is as expected. Judging by the announcements of a post-Kyoto climate agreement, the most likely scenario includes emission trading but restricts the use of carbon credits from HotAir and CDM countries and carbon credits from domestic forestation projects for compliance purposes (e.g. European Union, 2009, Art. 32). We take this into account and consider various scenarios allowing emission trading with CDM and HotAir countries and various others using carbon credits from domestic forestation projects (Table 1). We define the scenario *LimitCDMLimitForest* as our Reference Scenario. Here, the volume of trade with CDM and HotAir countries is limited to 10 percent, and the inclusion of carbon credits from forestation is limited by Annex Z (UNFCCC, 2001, Art. 3.4).

### 2.4. Extending the carbon market to carbon credits from OIF

We assume that carbon sequestration via OIF is realized within an international project as part of a post-Kyoto climate agreement. The reason for this assumption is that without international coordination its benefits would be inefficiently low and it would be more difficult to establish a mechanism for the monitoring of effects and side-effects (Kousky et al., 2009). Consequently, determining the optimal amount of OIF does

not enter the individual country's objective function, but releases the overall reduction cap. We use  $I$  to denote the number of carbon credits obtained from OIF and used for compliance and  $C(I)$  to denote the costs of OIF. Determining the optimal amount of OIF from a social planner's perspective requires equalizing the marginal costs of the various abatement options, which implies  $\pi = C'(I^*)$ .<sup>5</sup> The optimal use of OIF becomes a function of the carbon credit price  $I^*(\pi)$ , so that the overall compliance condition with forestation and OIF becomes

$$\sum_i^n E_i - \sum_i^n R_i^*(\pi^*) - \sum_i^n F_i(\pi^*) - I^*(\pi^*) = \sum_i^n A_i. \quad (9)$$

In connection with large-scale OIF, information about  $I$  is not available as a continuous function but only in the shape of discrete figures (e.g. Oschlies et al., 2010), while estimates for  $C(I)$  are rare and still uncertain (Barker et al., 2007; Bertram, 2010). To solve this problem, we turn the question around and determine a critical cost level and a critical amount for OIF. These make emitters indifferent between using carbon credits from emission trading, including forestry activities, and using carbon credits from OIF.

To determine the critical cost level, we assume that the costs of OIF can be expressed by a simple linear function  $C(I) = c_I I$ , implying that marginal costs are equal to unit costs.<sup>6</sup> We calculate an upper and lower level for the critical unit costs of OIF. The upper level is calculated by observing the carbon credit price in a carbon market where credits from OIF are not traded:  $\pi_0^*$ . Only if  $c_I < \pi_0^*$  is fulfilled can OIF be considered as a carbon-removal option. The lower level is calculated by observing the carbon credit price when credits from OIF can be traded on the market:  $\pi_1^*$ . At the lower level, three cases can be distinguished:

Case 1:  $\pi_1^* > c_I$  implies that the optimal amount of  $I$  should be larger and OIF should be extended;

Case 2:  $\pi_1^* = c_I$  implies that the optimal amount of  $I$  is provided;

Case 3:  $\pi_1^* < c_I$  implies that the optimal amount of  $I$  should be smaller and OIF should be reduced.

Depending on the scenario, we obtain different prices for the critical unit costs. To determine the upper level of the critical unit costs  $\pi_0^*$ , we choose the scenario *LimitCDMLimitForest* because it represents the current status of climate policy for the next commitment period. The restrictions on the use of carbon credits generated outside the Annex1 countries (in CDM and HotAir countries) or by domestic forestation in this scenario are based on the belief that those options should only be used to supplement domestic action. Without these restrictions, carbon credit prices would be lower, hampering technological change

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<sup>5</sup>Note, if large-scale OIF were performed by a company or one country, the optimization would require taking the price effect of OIF into account. OIF would be provided according to  $\pi'(I)I + \pi(I) = C'(I)$ , resulting in a lower amount of OIF, than is optimal from a social planners perspective,  $I < I^*$ .

<sup>6</sup>Considering a potential range for carbon credits generated by OIF  $I \in \{I_{min}, I_{max}\}$ , the characteristics of large-scale OIF imply that  $I_{min} \gg 0$ . The costs of OIF will be dependent on the overall scale of the project scale not on the marginal unit of carbon sequestered.

toward a low-carbon economy in the Annex1 countries. Including OIF in a post-Kyoto agreement would have the same effect. Consequently, it seems more likely that restrictions on existing abatement options will be loosened before a new, uncertain abatement option like OIF is introduced. To determine the lower level  $\pi_1^*$ , we exclude carbon credits from OIF and choose  $\pi_0^*(FullCDMFullForest)$  instead. We argue that including OIF should at least generate the same efficiency gains as extending existing options like unlimited trade with CDM and HotAir countries and unlimited carbon credits from forestation.

Depending on the scenario, we pick for emission trading and forestry activities, different critical amounts can be determined. Here we pursue three approaches. In the first approach, we calculate the critical amount as the average amount of carbon credits necessary to obtain the same decrease in carbon credit price as by switching from scenarios with *NoForest* to scenarios with *FullForest* (equivalence forestation). In the second approach, we calculate the critical amount as the average amount of carbon credits necessary to obtain the same decrease in carbon credit price as by switching from scenarios with *Trade* to scenarios with *FullCDM* (equivalence CDM). In the third approach, we calculate the critical amount as the amount of carbon credits necessary to obtain the same decrease in carbon credit price as by switching from Scenario *LimitCDMLimitForest* to the Scenario *FullCDMFullForest* (equivalence policy). The first and second approaches are straightforward. They ensure an equivalence of OIF (a) to forestry activities and (b) to unlimited emission trading. The third approach describes an actual policy option because it implies switching from our Reference Scenario to a minimum-cost scenario for compliance.

### 3. Critical unit costs and critical amounts for OIF

Prices and costs for the various scenarios are measured in USD for the price level of 2000. Data on GDP (for 2005) and population (for 2005 to 2020) were taken from the World Resource Institute. Data on emissions (measured in CO<sub>2</sub>) were provided by the IEA (2007). The data for emissions and GDP were projected to 2020 using information on the average annual percent change for the period 2005 to 2020 (IEA, 2007; OECD, 2008, respectively). The emission reduction targets are those discussed in subsection 2.1.

#### 3.1. Critical unit costs

Table 2 shows the carbon credit prices and the total compliance costs in 2020 both for our three functional forms and for the various scenarios.<sup>7</sup> Carbon credits from OIF are not considered. Our calibrated functions (Function 1 and Function 2) provide results in the same order of magnitude. Only for the scenarios including *FullCDM* (last three scenarios in the Table) does Function 2 provide significantly lower total costs than

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<sup>7</sup>In addition, we calculate the carbon credit prices and total costs for scenarios where the CDM volume is restricted to 20 percent and 30 percent of Annex1 countries targets, respectively. Results are not shown but can be obtained from the authors on request. As expected, the results indicate that carbon credit prices and total costs decline with the increasing volume of carbon credits from CDM. The overall results are the same.



Table 2: Abatement costs and carbon credit prices

| Scenario                               | Function 1                           |                                    | Function 2                           |                                    | Function 3                           |                                    |
|--|--------------------------------------|------------------------------------|--------------------------------------|------------------------------------|--------------------------------------|------------------------------------|
|  | credit price<br>USD tCO <sub>2</sub> | total costs<br>10 <sup>9</sup> USD | credit price<br>USD tCO <sub>2</sub> | total costs<br>10 <sup>9</sup> USD | credit price<br>USD tCO <sub>2</sub> | total costs<br>10 <sup>9</sup> USD |
| Trade<br>NoForest                      | 141                                  | 292                                | 106                                  | 271                                | 248                                  | 515                                |
| Trade<br>LimitForest                   | 133                                  | 261                                | 102                                  | 247                                | 234                                  | 459                                |
| Trade<br>FullForest                    | 104                                  | 159                                | 89                                   | 181                                | 153                                  | 195                                |
| LimitCDM<br>NoForest                   | 127                                  | 235                                | 98                                   | 221                                | 223                                  | 437                                |
| LimitCDM<br>LimitForest<br>(Reference) | 119                                  | 209                                | 95                                   | 209                                | 209                                  | 367                                |
| LimitCDM<br>FullForest                 | 94                                   | 129                                | 83                                   | 151                                | 138                                  | 158                                |
| FullCDM<br>NoForest                    | 29                                   | 60                                 | 35                                   | 40                                 | 40                                   | 83                                 |
| FullCDM<br>LimitForest                 | 23                                   | 37                                 | 24                                   | 16                                 | 30                                   | 45                                 |
| FullCDM<br>FullForest                  | 22                                   | 34                                 | 23                                   | 13                                 | 28                                   | 39                                 |

Function 1.<sup>8</sup> The reason is that compared to Function 1 Function 2 has a stronger curvature, in particular for CDM and HotAir countries (see Table A.1 and A.2 in the Appendix). Consequently, the unlimited use of carbon credits from CDM and HotAir countries leads to low reduction targets and reduces total costs. But the marginal costs, and hence the carbon credit price, are higher. This effect, lower total costs but a higher carbon credit price, is dampened for scenarios including *FullCDM* because the solutions for Function 2 are restricted. If carbon credit prices are relatively low, negative reduction shares would occur for some countries. To avoid this, these shares are set equal to zero, implying a restricted solution for these countries.<sup>9</sup>

Compared to Functions 1 and 2, Function 3 provides much higher carbon credit prices for scenarios with *Trade* and with *LimitCDM*, but only slightly higher carbon credit prices for scenarios with *FullCDM*. The reason is that Function 3 is originally calibrated to lower emission reduction targets than our Reference Emission Targets. In scenarios with *FullCDM*, the reductions realized are much lower, so that Function 3 provides similar results to the other two functions. Except for scenarios with *FullForest*, Function 3 leads to much higher total costs. The reason is that due to the high carbon credit price, many carbon credits are provided by forestation  $F(\pi)$ , which has no influence on GDP (see subsection 2.2).

<sup>8</sup>Function 2 provides moderately lower cost estimates than Function 1, except for two scenarios: *TradeFullForest* and *LimitCDMFullForest*. This can be explained by the fact that the higher carbon credit price for Function 1 mean that more carbon credits are provided by forestation in scenarios with *FullForest*. The underlying changes in the forestry sector, e.g. adjusting the provision of carbon credits, are assumed to have no influence on GDP (see subsection 2.2).

<sup>9</sup>In total, there are five countries in scenario *FullCDMNoForest*, seven countries in scenario *FullCDMLimitForest*, and nine countries in scenario *FullCDMFullForest*.

In sum, the upper level of the critical unit cost ranges from 95 to 119 USD per t CO<sub>2</sub> (scenario *LimitCDMLimitForest*), or even up to 209 USD, if we consider Function 3. The lower level of the critical unit cost ranges from 22 to 23 USD per t CO<sub>2</sub> (scenario *FullCDMFullForest*), or up to 28 if we consider Function 3. The cost estimates based on carbon credit prices in the scenarios are comparable to previous studies (e.g., Klepper and Peterson, 2006a; Anger et al., 2009) for Function 1 and Function 2, whereas the carbon credit prices for the various scenarios with Function 3, based on Tol (2005), are much higher. Using recent sequestration efficiency ratios from patch OIF experiments, Boyd (2008) estimates that the costs are between 8 and 80 USD per t CO<sub>2</sub> sequestered. Although these cost estimates may not be representative for large-scale OIF (Bertram, 2010), the upper and lower levels in those estimates are below the corresponding range of the upper and lower levels in our estimates.

### 3.2. Critical amounts

In the following, we focus on Function 1, since Function 2 provides similar results, but includes restricted solutions for scenarios with *FullCDM*. Function 3 overestimates the carbon credit price for all scenarios except for those with *FullCDM* and overestimates total costs for all scenarios except the ones with *FullCDM* and *FullForest*. Applying Function 1 to determine the critical amounts, OIF would have to provide carbon credits to the tune of 0.944 Gt CO<sub>2</sub> (equivalent forestation), 3.274 Gt CO<sub>2</sub> (equivalent CDM), and 2.924 Gt CO<sub>2</sub> (equivalent policy) to be equivalent. Information on the effectiveness of OIF is required to answer the question whether large-scale OIF would be able to provide carbon credits to the same extent. For our quantitative assessment we use the results of hypothetical large-scale iron fertilization in the Southern Ocean obtained recently by Oschlies et al. (2010) and Rickels et al. (2010).

In their model experiments, Oschlies et al. (2010) realize OIF by increasing the phytoplankton growth rate in the Southern Ocean (south of 30°) for 1, 7, 10, 50, and 100 years, while the carbon emissions are represented by the IPCC SRES A2 scenario (see Appendix B for a description of the model experiments).<sup>10</sup> The maximum phytoplankton growth rate is increased from 0.13 per day at 0° C to either 0.26 per day (calibrated against the changes in export production observed for persistent natural iron fertilization on the Kerguelen Plateau and Crozet Islands in the Southern Ocean (Blain et al., 2007; Pollard et al., 2009)), or to 10.0 per day to simulate an upper bound for OIF. We refer to the former growth rate as “low fertilization effectiveness” and to the latter as “high fertilization effectiveness”. Though the latter rate is beyond a physiologically sensible range, but the intended effect in the model is a bigger drawdown of macronutrients than that observed in island-induced natural iron fertilization. We do not currently know whether island-induced iron fertilization is sufficient to completely relieve phytoplankton from iron stress. So the “high

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<sup>10</sup>The SRES A2 non-intervention scenario assumes high population growth and moderate, uneven economic growth, leading to an increase from today’s emissions of about 8 Gt C per year to about 29 Gt C per year in the year 2100. After 2100, annual emissions are assumed to decline by 1.45 Gt C per year, reaching zero at year 2300.

fertilization effectiveness” growth rate explores a hypothetical scenario where intentional OIF impact is much larger than that of island-induced natural OIF (Oschlies et al., 2010). In this paper, we consider the two different levels of effectiveness but restrict ourselves to the short-term OIF model experiments (1, 7, and 10 years), to which we refer to Experiments 1 to 3. We exclude the findings from the long-term experiments (50 and 100 years) on the assumption that short-term experiments are a more realistic alternative to existing enhancement projects. Also, the potentially negative side-effects are presumably much less marked than with long-term OIF.

Estimating of the actual amount of carbon removed is a complex business. A substantial fraction captured by increased phytoplankton growth is returned to its inorganic mineral form as a result of respiration in surface waters (cf., Buesseler and Boyd, 2003; Royal Society, 2009). Also fewer nutrients are available outside the fertilized region, resulting in lower phytoplankton growth and lower carbon uptake (e.g., Gnanadesikan et al., 2003; Royal Society, 2009). To account for these issues, carbon-removal is measured in terms of the net global oceanic carbon uptake derived from the fully three-dimensional and seasonally cycling Earth System model (Oschlies et al., 2010). The uptake is traced for 100 years to account for later periods after fertilization has stopped with lower uptake than in the control run. To include OIF as an additional carbon-removal option in a global carbon market, carbon credits have to be assigned to the OIF-induced sequestered carbon. Rickels et al. (2010) use these global oceanic carbon uptake data to analyze the impact of various carbon accounting methods on assigning carbon credits. Four carbon accounting methods exist that assign permanent carbon credits: the net method, the average method, the discount method, and the equivalence method. Two carbon accounting methods assign temporary carbon credits: the shorttemp method and the longtemp method. One carbon accounting method assigns both permanent and temporary carbon credits: the mixed method. Temporary carbon credits used for compliance have to be replaced at some point in time, permanent carbon credits do not.

For the analysis of critical amounts we focus on accounting methods that assign permanent carbon credits, because we are only considering a short-term compliance problem for the period 2012 to 2020. Issuing temporary credits would require possible replacement issues in later compliance periods to be taken into account, and this would unnecessarily complicate things. In our analysis, we choose two accounting methods: the net method and the discount method. We choose the net method because it is implicitly applied in most OIF modeling studies. It measures the overall effect of OIF over a period of 100 years, no matter when the carbon fluxes take place within that period. In addition, we choose the discount method because it is also used for the calculation of carbon credits from forestry activities (see Section 2.2).<sup>11</sup> The discount method weights the carbon fluxes in earlier years higher than in later years. We ignore the average method in our analysis because it leads to results between those of the net and the discount

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<sup>11</sup>Note that the discount rate applies a social discount rate to convert future tons of CO<sub>2</sub> into present tons of CO<sub>2</sub>.

method, and we ignore the equivalence method because it has aroused controversy in the literature (e.g., Dornburg and Marland, 2008). Additionally, with the equivalence method issuing credits spreads out over a relatively long period and is less attractive from an economic perspective. For comparison, we include one accounting method that assigns temporary carbon credits. We choose the shorttemp method because it provides the largest amount of carbon credits in the first commitment period when applied to short-term OIF. As indicated above, these carbon credits have to be replaced in the subsequent commitment period. For further details, see Rickels et al. (2010).

Rickels et al. (2010) also analyze the issue of leakage. The leakage issue addresses all potential offsets that have to be taken into account to obtain the net amount of carbon credits in the various accounting methods. Potential offsets arise due to (1) carbon emissions outside the enhancement region (spatial leakage) and to (2) changes in emissions of other GHGs than carbon (GHG leakage). Spatial leakage is addressed by applying the accounting methods to global data for oceanic carbon uptake, rather than to local data (see above). The GHG leakage is addressed by deduction rates.<sup>12</sup> The deduction rates reduce the gross amount of carbon credits  $I_{gross}$  to the net amount  $I_{net}$ , which can then be used for compliance. Stipulating the oceanic carbon sink by OIF influences the production of a range of trace gases, notably methane ( $\text{CH}_4$ ), nitrous oxide ( $\text{N}_2\text{O}$ ), and dimethylsulphide (DMS) (e.g., Fuhrman and Capone, 1991; Jin and Gruber, 2003; Law, 2008). Combined physical and biogeochemical ocean models have shown that OIF, in particular, might lead to greater  $\text{N}_2\text{O}$  emissions (Jin and Gruber, 2003). Oschlies et al. (2010) focus on  $\text{N}_2\text{O}$  emissions for the determination of the appropriate deduction rates, as changes in  $\text{CH}_4$  emissions are estimated to be negligible and increases in DMS emissions would potentially contribute to climate change mitigation.<sup>13</sup>

Table 3: Annual OIF carbon credits in 2012-2020 in Gt  $\text{CO}_2$

| Accounting method | Exp 1: 1 year OIF           |        | Exp 2: 7 years OIF          |        | Exp 3: 10 years OIF         |        |
|-------------------|-----------------------------|--------|-----------------------------|--------|-----------------------------|--------|
|                   | fertilization effectiveness |        | fertilization effectiveness |        | fertilization effectiveness |        |
|                   | high                        | low    | high                        | low    | high                        | low    |
| net               | 1.5252                      | 0.2812 | 6.2108                      | 1.1451 | 8.2261                      | 1.6168 |
| discount          | 3.1491                      | 0.4993 | 10.4365                     | 2.6642 | 12.8699                     | 3.4945 |
| shorttemp         | 3.6917                      | 0.5528 | 14.7575                     | 4.3879 | 16.0308                     | 5.1848 |

Source: Rickels et al. (2010)

In the first step we use the gross amount of carbon credits  $I_{gross}$  from Rickels et al. (2010) even though only the net amount of carbon credits  $I_{net}$  can be used for compliance,. Table 3 shows the corresponding amounts of carbon credits for a single year in the first compliance period 2012-2020. To obtain the amount for a single year, the cumulative amount for the whole period is distributed equally over the 8 years. For

<sup>12</sup>Note that Rickels et al. (2010) misname the deduction rates as discount factors. We revert to the correct notation: deduction rates.

<sup>13</sup>Measurements of dissolved  $\text{CH}_4$  emissions during the Southern Ocean Iron Enrichment Experiment (SOFeX) revealed a very small increase of less than 1 percent (Wingenter et al., 2004).

the discount method, we apply a social discount rate of 5 percent taken from Hertel et al. (2008), where it is applied to determine the amount of carbon credits from forestation (subsection 2.2).

By comparing the gross amount of carbon credits shown in Table 3 to the three critical amounts discussed above, we are able to calculate potential maximum feasible deduction rates. These imply equivalence between actual net carbon credits from OIF and the critical amounts. Comparing the maximum feasible deduction rates to the actual deduction rates in Rickels et al. (2010) enables us to observe whether there is sufficient safety margin if leakage turns out to be larger than expected. The possible maximum feasible deduction rates are shown in Table 4, where a deduction rate of zero indicates that the gross amount of carbon credits does not exceed the critical amount.

Table 4: Maximum possible deduction rates in percent

|                           |           | Equivalence Forestation<br>0.944 Gt CO <sub>2</sub> |       | Equivalence CDM<br>3.274 Gt CO <sub>2</sub> |       | Equivalence Policy<br>2.924 Gt CO <sub>2</sub> |       |
|---------------------------|-----------|---|-------|---|-------|--|-------|
|                           |           | fertilization<br>effectiveness                      |       | fertilization<br>effectiveness              |       | fertilization<br>effectiveness                 |       |
|                           |           | high  | low   | high  | low   | high   | low   |
| Exp 1:<br>1 year<br>OIF   | net       | 38.08   | 0     | 0   | 0     | 0  | 0     |
|                           | discount  | 70.01   | 0     | 0   | 0     | 7.16   | 0     |
|                           | shorttemp | 74.42   | 0     | 11.32                                       | 0     | 20.81  | 0     |
| Exp 2:<br>7 years<br>OIF  | net       | 84.80   | 17.53 | 47.29                                       | 0     | 52.93  | 0     |
|                           | discount  | 90.95   | 64.55 | 68.63                                       | 0     | 71.99  | 0     |
|                           | shorttemp | 93.60   | 78.48 | 77.82                                       | 25.39 | 80.19  | 33.37 |
| Exp 3:<br>10 years<br>OIF | net       | 88.52   | 41.59 | 60.20                                       | 0     | 64.46  | 0     |
|                           | discount  | 92.66   | 72.98 | 74.56                                       | 6.32  | 77.28  | 16.34 |
|                           | shorttemp | 94.11   | 81.79 | 79.58                                       | 36.86 | 81.76  | 43.61 |

To compare the results in Table 4, note that Rickels et al. (2010) estimate an average deduction rate of 10 percent and a maximum deduction rate of 15 percent. If fertilization effectiveness is high, OIF with a duration of only one year provides annual credits in the commitment period 2012-2020 that allow deduction rates between 38 percent (net method) and 70 percent (discount method) to be equivalent to the first critical amount (equivalence forestation). If fertilization effectiveness is low, the duration of OIF has to be extended to seven years to observe deduction rates between 17 and 64 percent with respect to the first critical amount. The first critical amount implies an equivalence to forestation, the calculation of which is based on global forestation projects for the duration of 20 years. The estimated annual potential of forestry activities in our analysis 0.944 Gt CO<sub>2</sub> is slightly above that of reforestation projects in the literature, but below those also including forest density management, expanded use of forest products, and, in particular, reduced deforestation. The IPCC Fourth Assessment Report estimates the annual carbon removal potential of reforestation to be between 0.44 and 0.88 Gt CO<sub>2</sub> up to 2030, assuming a CO<sub>2</sub> price range of 20 to 100 USD. If, in addition to reforestation, we also include forest carbon density management, expanded use of forest products, and in particular reduced deforestation, the range is estimated to be 1.47 to 2.93 Gt

CO<sub>2</sub> (Nabuurs et al., 2007; Government of Canada, Minister of Environment, 2008). However, applying the shorttemp method for carbon credit assignment (which is also applied for forestry activities under the Kyoto Protocol)<sup>14</sup>, we obtain sufficient amounts of carbon credits from OIF with a duration of of seven years, allowing for deduction rates above 15 percent for all three critical amounts, regardless of the effectiveness of OIF.

#### 4. Distributional prospects of OIF

Transferring the social planner’s solution to the international project level requires the distribution of potential profits from OIF to country level. This can be realized by either distributing the potential profits or the carbon credits to the countries, basing the procedure on an allocation formula. The allocation formula influences the individual countries’ costs but not the overall optimality condition. As an example of the distributional consequences, we include OIF in our Reference Scenario *LimitCDMLimitForest*. We assume that OIF provides net credits equal to the third critical amount (equivalence policy) 2.924 Gt CO<sub>2</sub>, and that the unit costs  $c_I$  are equal to  $\pi(FullCDMFullForest)$  22 USD. This implies that including OIF would have the same effect as loosening the existing limits on carbon credits from CDM and domestic forestation. Additionally, it implies that OIF does not provide any extra profits, as the unit costs are equal to the prevailing carbon credit price. The OIF carbon credits are either sold on the market or allocated to the participating countries. If allocated to the various countries, we assume that only countries with positive emission reduction targets can receive OIF credits. There are several ways of defining and combining allocation criteria. We assume an allocation of carbon credits to countries with binding emission targets (Annex1) based on population, but an allocation of payment based either on CO<sub>2</sub> emissions or GDP (all in 2005). This implies that the bigger the population of a country is, the higher is its share in the initial allocation. The richer a country is, or the more it contributes to global warming, the higher its contribution will be to paying for OIF. Note that if allocation and payment of carbon credits were based on the same criteria, the market solution would be retained. We compare the distributional consequences to those observed by switching from the Reference Scenario *LimitCDMLimitForest* to the Scenario *FullCDMFullForest* (equivalence policy).

Table 5 shows the results of including OIF carbon credits in the Reference Scenario for the eight countries with the highest (all Annex1 countries) and the lowest abatement costs (all CDM or HotAir countries). The

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<sup>14</sup>Two carbon accounting methods that assign temporary carbon credits are applied to account for LULUCF activities under the Kyoto Protocol. With the first method, temporary credits are valid for a fixed period of time but can be renewed if the carbon is still stored. With the second method, temporary credits are valid for a fixed period of time and cannot be renewed, even if the carbon is still stored (Phillips et al., 2001). Decision 5/CMP.1 of the UNFCCC (2003) refers to the first method as temporary certified emission reductions (tCER) and to the second as long-term certified emission reductions (lCER). tCERs expire at the end of the commitment period following the period in which they were issued, while lCERs expire at the end of the crediting period of the project for which they were issued (UNFCCC, 2003; Olschewski et al., 2005)

Table 5: Distributional effects of including OIF into the Reference Scenario (constant 2000 USD)

| Top 8 Payers (absolute)    | Total costs<br>10 <sup>9</sup> USD<br>Reference Scenario<br>(LimitCDM10<br>LimitForest<br>no OIF)<br>credit price<br>119 USD/<br>tCO <sub>2</sub> | Change in total costs compared to Reference Scenario<br>(in percent)   |                           |   |   |
|----------------------------|---|--|---------------------------|---|---|
|                            |   | FullCDM<br>FullForest<br>(no OIF)                                      | LimitCDM10<br>LimitForest |   |   |
|                            |   |  | OIF via market            | OIF via<br>distribution<br>population/CO <sub>2</sub> | OIF via<br>distribution<br>population/GDP |
|                            |   | credit price<br>22 USD/<br>tCO <sub>2</sub>                            |                           |   |   |
| United States              | 147.76  | -71.52   | -71.52                    | -63.74  | -67.00                                    |
| Germany                    | 18.44   | -68.52   | -68.52                    | -74.08  | -72.29                                    |
| Japan                      | 16.09   | -73.61   | -73.61                    | -84.95  | -51.67                                    |
| UK                         | 14.92   | -73.70   | -73.70                    | -80.95  | -73.94                                    |
| France                     | 10.54   | -74.41   | -74.41                    | -92.27  | -79.45                                    |
| Italy                      | 10.21   | -69.32   | -69.04                    | -82.57  | -79.81                                    |
| Australia                  | 9.02  | -70.79   | -62.92                    | -55.30  | -65.13                                    |
| Spain                      | 6.50  | -65.84   | -65.47                    | -80.73  | -83.82                                    |
| Top 8 Receivers (absolute) | Total profits   | Change in total profits compared to Reference Scenario<br>(in percent) |                           |   |   |
| China                      | 27.48   | -24.69   |                           | -82.02  |   |
| Russia                     | 6.11  | 24.23  |                           | -79.44  |   |
| India                      | 5.73  | -20.47   |                           | -81.92  |   |
| Brazil                     | 4.36  | 31.00  |                           | -81.92  |   |
| Ukraine                    | 1.71  | -1.41  |                           | -82.53  |   |
| Venezuela                  | 0.72  | 6.34   |                           | -81.92  |   |
| Colombia                   | 0.58  | 27.80  |                           | -81.92  |   |
| Mexico                     | 0.53  | -30.34   |                           | -82.90  |   |

results are based on our Reference Emission Target for the year 2020. Table C.3 in the Appendix shows the results for all countries.

Our calculation indicates that countries with high abatement costs (Top Payers) are more or less indifferent between the option of switching from the Reference Scenario to the Scenario *FullCDMFullForest* (third column) and the option of including OIF in the Reference Scenario (columns four to six). Both options result in lower carbon credit prices and larger total carbon-credit availability, in lower domestic emission reductions and larger amounts of carbon credits purchased for compliance. However, depending on the allocation rule chosen, moderate differences can be observed. The decrease in costs ranges from 65 to 74 percent for the first option and from 52 to 92 percent for the second option. For some countries, payment based on CO<sub>2</sub> emissions is more beneficial than a rule based on GDP (e.g. Japan and France). For other countries, the opposite is true (e.g. United States and Australia). However, in general, the costs decrease in roughly the same order of magnitude. This is rather straightforward, because we include OIF such as equivalence in volume and carbon credit price effect is assured to switching from the Scenario *LimitCDMLimitForest* to the Scenario *FullCDMFullForest*.

Our calculation also shows that countries with low abatement costs (Top Receivers) are not indifferent between the two options. Under the first option, switching from the Reference Scenario to the Scenario *FullCDMFullForest* (third column), profits either decrease (e.g. Mexico and China) or increase (e.g. Brazil and Columbia). For countries with decreasing profits, the effect of the increase in the amount of carbon credits sold on the market (volume effect) is overcompensated by the effect of the decrease in carbon credit price (price effect). For example, China doubles the number of carbon credits sold from 227 Mt CO<sub>2</sub> to 504 Mt CO<sub>2</sub>, whereas the carbon credit prices decrease by a factor six from 119 USD to 22.92 USD, resulting in a loss of 25 percent overall. For countries with increasing profits, the negative effect of carbon credit sales is compensated for by the positive effect of additional sales of forestry credits (forestation effect). For example, Brazil doubles its sale of forestry carbon credits from 36 Mt CO<sub>2</sub> to 72 Mt CO<sub>2</sub>, gaining 31 percent overall. Under the second option (including OIF carbon credits) the profits for all eight countries decrease by about 80 percent (fourth column). It makes no difference whether OIF carbon credits are sold on the market or are allocated. None of these countries are considered in the allocation since they have no binding emission reduction targets. If we include OIF carbon credits, the price effect remains the same, but is not compensated for by the volume effect or the forestation effect.

Table 6: Reduction targets 2020

| Climate Regime                  |                        | OIF<br>Gt CO <sub>2</sub> | reduction target 2020<br>rel. 2005 in percent |
|---------------------------------|------------------------|---------------------------|---|
| BAU                             | without OIF            | 0                         | -24.7   |
| Reference<br>emission<br>target | without OIF            | 0                         | -5.4  |
|                                 | OIF equiv. forestation | 0.944                     | -0.9  |
|                                 | OIF equiv. policy      | 2.924                     | 8.3   |
|                                 | OIF equiv. CDM         | 3.274                     | 10.0  |
|                                 | OIF max                | 11.583                    | 48.8  |

With respect to the choice between relaxing existing limitations and including carbon credits from OIF, we expect the first option to be chosen for several reasons. The underlying regulation requirements are already in place and potential side-effects are better explored. Realizing both options would decrease the carbon credit price below  $\pi(FullCDMFullForest)$  and therefore decrease the incentives for switching to a low-carbon economy further. To avoid a price decline and to encourage more ambitious emissions reduction targets, we turn the question round and calculate how the overall emission reduction target would change if the carbon credit price  $\pi(FullCDMFullForest)$  were maintained while carbon credits from OIF were included.

Table 6 shows the various emission reduction targets with and without the Reference Emission Target and with and without the inclusion of OIF. The emission targets are for 2020 relative to 2005. For the countries in our analysis, the business-as-usual situation (BAU) without any emissions reduction targets implies an increase in emissions by 24.7 percent. Realizing our Reference Emission Target still implies an



increase in emissions by 5.4 percent. Maintaining the carbon credit price  $\pi(FullCDMFullForest)$  and including OIF at an amount equivalent to forestation (first critical amount), the overall emission target can be intensified but would still lead to an increase in emissions of 0.9 percent. Maintaining the carbon credit price  $\pi(FullCDMFullForest)$  and including OIF at an amount equivalent to the current policy option (second critical amount), the overall reduction target gets stricter and reaches 8.3 percent. Overall emission reduction increases to 10.0 percent if OIF is included at an amount equivalent to CDM (third critical amount). If we include the maximum amount of permanent carbon credits from OIF by realizing Experiment 3 (10 years OIF), use a social discount rate of 5 percent, assume a high level of fertilization effectiveness and the average deduction rate of 10.0 percent suggested by Rickels et al. (2010), the result is an overall emission reduction of 48.8 percent.

## 5. Discussion and conclusion

Our main objective has been to determine critical unit costs and critical amounts for OIF as a carbon-removal option from a market-based perspective and to compare these to existing cost and amount estimates. We have also considered the distributional implications involved by including carbon credits from OIF in an international carbon market.

We determine an upper and lower level for the critical unit costs. The upper level values range from 95 to 119 USD per t CO<sub>2</sub>, and the lower level values from 22 to 23 USD per t CO<sub>2</sub>, both based on a top-down, calibrated abatement cost function. The corresponding levels based on a bottom-up calibrated abatement cost function are considerably higher. We argue that the upper level of our estimates indicates whether OIF can be considered as a carbon removal option at all. The lower level of our estimates then indicates whether OIF is comparable to existing abatement options. Even though existing cost estimates are still rather uncertain and may not be representative of large-scale OIF, the upper and lower levels of those estimates are below the corresponding range in the upper and lower levels of our estimates (Boyd (2008) estimates 8-80 USD/tCO<sub>2</sub>).

To analyze how many credits OIF would have to provide to be equivalent to other options, we calculate three critical amounts. The first indicates the impact of forestry activities on carbon prices, the second the impact of emission trading with HotAir and CDM countries on the carbon price, and the third the impact of an actual policy option (switching to the most efficient scenario) on carbon price. We compare these critical amounts to the amount of carbon credits obtained from hypothetical Southern Ocean iron fertilization based on most recently results provided by Oschlies et al. (2010) and Rickels et al. (2010). Even if iron fertilization effectiveness is on a level equal to observed natural persistent iron fertilization near islands in the Southern Ocean, 7 years of OIF are sufficient to obtain an amount of annual carbon credits that is sufficiently larger than the amount provided by forestry activity over 20 years. This result is based

on a carbon credit accounting method (the net method) that is implicitly applied in the scientific literature. Applying an accounting method used for assigning carbon credits to forestry activities under the Kyoto Protocol, we obtain sufficient amounts of carbon credits for a fertilization period of 7 years, exceeding all three critical amounts with an adequate safety margin.

The analysis of the distributional implications reveals that including OIF may provide new incentives for the negotiation process of a post-Kyoto climate agreement. Considering the choice between (a) loosening existing limitations with respect to emission trading and usage of carbon credits from forestation and (b) including carbon credits from OIF, our calculation suggests that countries with high abatement costs will be more or less indifferent. Countries with low abatement costs, i.e. sellers of carbon credits, are expected to favor the first option. Even though not all selling countries gain from first option, they are still better off than with the second option. Therefore, one might consider a third option offering both alternatives, but in which CDM and HotAir countries are included in the allocation of OIF, if they accept emissions reduction targets. An allocation formula could be designed to provide incentives for CDM and HotAir countries to accept emissions reduction targets, while at the same time ensuring that Annex1 countries are indifferent between the different options. However, realizing both alternatives requires intensifying overall emission reduction targets, because otherwise the carbon credit price would decline further. Consequently, including OIF may not just provide new incentives for the negotiation process in further climate agreements, it may also favor the negotiation of more ambitious emissions reduction targets in future.

In this study, we have not considered whether and how the model OIF experiments could be realized in the Southern Ocean, a crucial aspect in the consideration of OIF as a carbon-removal option. It should also be noted, that we consider a static 2020 compliance problem. Implementing OIF will generate carbon credits for several years within one commitment period or even spread out over different commitment periods. Accordingly, the costs of OIF should be compared with a time series of carbon credit prices to incorporate the dynamic effects of the carbon market. Nevertheless, our study is in line with assessments of other abatement options, which also concentrate on a given compliance year (e.g., Anger et al., 2009). Additionally, the economic data necessary for conducting our analysis are more readily available for the next commitment period. We have focused on a so far neglected aspect in the discussion of OIF: consideration of the conditions provided by a market for OIF as a carbon-removal option in a post-Kyoto climate regime. Our results provide information on critical unit costs and critical amounts for OIF, which lead us to the conclusion that, based on current knowledge, OIF cannot be excluded from the list of potential carbon-removal options, notably in comparison with forestry activities. This especially holds true if we recall that the potential of forestry activities is not that certain either. For example, van Kooten and Sohngen (2007) show that there is great inconsistency across forestry activity studies in the way carbon uptake and costs are measured, so that the costs estimated for creating carbon credits through forestry vary widely. Hence, they argue that the widely held notion that forestry activities are a low-cost means of reducing atmospheric

CO<sub>2</sub> (Noble et al., 2000) needs to be reassessed.

Future research should concentrate particularly on evaluating the carbon-removal effectiveness of OIF and its potential side-effects. But a more detailed assessment of its distributional and dynamic aspects is also necessary.

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## Appendices

### Appendix A. Emission Reduction Targets, Abatement Cost Functions, and Forestry Activity

The country-specific emission reduction targets for the Reference Emission Reduction Target can be found in column 3 of Table A.2. For the calculation of the country-specific emission commitments for the EU member states, we use aspects of the 20 percent target, the reduction commitment of 21 percent by 2020 relative to 2005 for the European Emission Trading Sector (European Union, 2009, Art. 5), and the individual reduction commitments in Annex IIa by 2020 relative to 2005 for the non-ETS sector (European Union, 2009b). With these two reduction targets for the ETS sector and the non-ETS sector in each country, we calculate the total reduction by 2020 relative to 2005, obtaining the country-specific share of the overall reduction for the 20 percent target. Using this country-specific share, we calculate the country-specific reduction target for the 30 percent overall target.

For Canada, we have chosen the emission reduction announcement of 20 percent relative to 2006 for the industrial sector (Government of Canada, Minister of Environment, 2008). For Japan, we have chosen the emission reduction announcement of 20 percent relative to 2005 indicated in a speech by Prime Minister Fukuda (Fukuda, 9 June 2008). For Switzerland, we have chosen the emission reduction announcement of 30 percent relative to 1990 (Schweizerische Eidgenossenschaft, 2009). For Norway, we have chosen the emission reduction announcement of 30 percent relative to 1990 (Garnaut, 2008). For the US, Australia, and New Zealand, we have chosen the emission entitlement allocation from the final report of the Garnaut Climate Change Review. The reduction target is 28 percent relative to 2000 for the US and 25 percent relative to 2000 for Australia and New Zealand (Garnaut, 2008, p.209). For Russia and Ukraine, we have assumed an emission target no more ambitious than their current BAU emission projections for 2020. For Croatia, we have assumed a zero-percent emission target relative to 2005 and for Iceland a 30 percent emission target relative to 1990. We have converted all emission targets to be based on the reference year 2005.

Table A.1: Estimates for abatement cost functions

| Region             | Function 1 |         | Function 2 |           |         |
|--------------------|------------|---------|------------|-----------|---------|
|                    | $\alpha$   | adj. R2 | $\beta_1$  | $\beta_2$ | adj. R2 |
| WEU                | 0.06438    | 0.99633 | -0.00374   | 0.07544   | 0.99832 |
| EEU                | 0.12604    | 0.97775 | 0.02175    | 0.06177   | 0.99637 |
| USA                | 0.08659    | 0.96463 | 0.01823    | 0.03271   | 0.99165 |
| OAB                | 0.07746    | 0.98097 | 0.01111    | 0.04462   | 0.99337 |
| FSU                | 0.14602    | 0.97242 | -0.03865   | 0.24742   | 0.99673 |
| CPA                | 0.10998    | 0.98493 | -0.02564   | 0.16672   | 0.99851 |
| IND                | 0.06867    | 0.97600 | -0.01980   | 0.11064   | 0.99499 |
| LAM                | 0.07997    | 0.95598 | -0.02498   | 0.14790   | 0.99735 |
| JAPAN <sup>a</sup> | 0.19466    | 0.98698 | -0.02583   | 0.27100   | 0.99812 |

<sup>a</sup> The estimated parameters for Japan are based on the observed change in the equivalent variation and not on the observed change in GDP.



Table A.2: Reduction targets, abatement cost functions and forestation factors and limits

| Country        | Class  | Reduction<br>2020 rel.<br>to 2005<br>(in percent) | Function 1 | Function 2 |           | Function 3 | Forestry<br>factor<br>(Mt CO <sub>2</sub> ) | Forest<br>limitation<br>Annex Z<br>(Mt CO <sub>2</sub> ) |
|----------------|--------|---|------------|------------|-----------|------------|---|--|
|                |        |   | $\alpha$   | $\beta_1$  | $\beta_2$ | $\gamma$   |   |  |
| Austria        | Annex1 | 29.92   | 0.06442    | -0.00374   | 0.07544   | 0.15347    | 0.03490                                     | 2.31021  |
| Belgium        | Annex1 | 29.57   | 0.06536    | -0.00368   | 0.07544   | 0.15281    | 0.00603                                     | 0.11001  |
| Denmark        | Annex1 | 31.99   | 0.06283    | -0.00383   | 0.07544   | 0.15449    | 0.00452                                     | 0.18335  |
| Finland        | Annex1 | 30.62   | 0.06469    | -0.00372   | 0.07544   | 0.15328    | 0.20330                                     | 0.58672  |
| France         | Annex1 | 28.30   | 0.06305    | -0.00382   | 0.07544   | 0.15433    | 0.14054                                     | 3.22696  |
| Germany        | Annex1 | 29.65   | 0.06538    | -0.00368   | 0.07544   | 0.15280    | 0.10008                                     | 4.54708  |
| Greece         | Annex1 | 27.24   | 0.06636    | -0.00363   | 0.07544   | 0.15220    | 0.03390                                     | 0.33003  |
| Iceland        | Annex1 | 39.55   | 0.06181    | -0.00389   | 0.07544   | 0.15546    | 0.00042                                     | 0.00000  |
| Ireland        | Annex1 | 31.94   | 0.06399    | -0.00377   | 0.07544   | 0.15373    | 0.00604                                     | 0.18335  |
| Italy          | Annex1 | 28.67   | 0.06522    | -0.00369   | 0.07544   | 0.15290    | 0.09017                                     | 0.66006  |
| Luxembourg     | Annex1 | 31.73   | 0.06557    | -0.00367   | 0.07544   | 0.15267    | 0.00079                                     | 0.03667  |
| Netherlands    | Annex1 | 30.07   | 0.06538    | -0.00368   | 0.07544   | 0.15280    | 0.00330                                     | 0.03667  |
| Norway         | Annex1 | 45.00   | 0.06163    | -0.00390   | 0.07544   | 0.15570    | 0.08482                                     | 1.46680  |
| Portugal       | Annex1 | 23.55   | 0.06657    | -0.00361   | 0.07544   | 0.15208    | 0.03418                                     | 0.80674  |
| Spain          | Annex1 | 27.66   | 0.06571    | -0.00366   | 0.07544   | 0.15258    | 0.16188                                     | 2.45689  |
| Sweden         | Annex1 | 30.23   | 0.06124    | -0.00393   | 0.07544   | 0.15653    | 0.24874                                     | 2.12686  |
| Switzerland    | Annex1 | 35.76   | 0.06119    | -0.00393   | 0.07544   | 0.15700    | 0.01103                                     | 1.83350  |
| United Kingdom | Annex1 | 29.99   | 0.06376    | -0.00378   | 0.07544   | 0.15386    | 0.02571                                     | 1.35679  |
| United States  | Annex1 | 29.44   | 0.08659    | 0.01823    | 0.03271   | 0.15234    | 4.26042                                     | 102.67600  |
| Australia      | Annex1 | 32.42   | 0.08097    | 0.01182    | 0.04462   | 0.15057    | 1.47895                                     | 0.00000  |
| Canada         | Annex1 | 19.28   | 0.07811    | 0.01124    | 0.04462   | 0.15105    | 2.80229                                     | 44.00400   |
| New Zealand    | Annex1 | 30.37   | 0.07222    | 0.01006    | 0.04462   | 0.15196    | 0.07508                                     | 0.73340  |
| Japan          | Annex1 | 20.00   | 0.19466    | -0.02583   | 0.27100   | 0.15475    | 0.31062                                     | 47.67100   |
| Bulgaria       | Annex1 | 23.68   | 0.13657    | 0.02408    | 0.06177   | 0.14502    | 0.03275                                     | 1.35679  |
| Croatia        | Annex1 | 0.00  | 0.12237    | 0.02094    | 0.06177   | 0.15037    | 0.01929                                     | 0.00000  |
| Czech Rep      | Annex1 | 23.54   | 0.13012    | 0.02265    | 0.06177   | 0.14725    | 0.02393                                     | 1.17344  |
| Estonia        | Annex1 | 25.97   | 0.12915    | 0.02244    | 0.06177   | 0.14764    | 0.02064                                     | 0.36670  |
| Hungary        | Annex1 | 17.06   | 0.12117    | 0.02067    | 0.06177   | 0.15089    | 0.01785                                     | 1.06343  |
| Latvia         | Annex1 | 12.00   | 0.11819    | 0.02001    | 0.06177   | 0.15245    | 0.02657                                     | 1.24678  |
| Lithuania      | Annex1 | 15.80   | 0.12015    | 0.02044    | 0.06177   | 0.15138    | 0.01897                                     | 1.02676  |
| Poland         | Annex1 | 21.60   | 0.12702    | 0.02197    | 0.06177   | 0.14854    | 0.08306                                     | 3.00694  |
| Romania        | Annex1 | 21.06   | 0.12931    | 0.02247    | 0.06177   | 0.14757    | 0.05756                                     | 4.03370  |
| Slovakia       | Annex1 | 21.32   | 0.12544    | 0.02162    | 0.06177   | 0.14919    | 0.01743                                     | 1.83350  |
| Slovenia       | Annex1 | 22.11   | 0.11905    | 0.02020    | 0.06177   | 0.15194    | 0.01142                                     | 1.32012  |
| Russia         | HotAir | -14.38  | 0.14136    | -0.03909   | 0.24742   | 0.14189    | 7.30802                                     | 64.64921   |
| Ukraine        | HotAir | -17.83  | 0.15067    | -0.03820   | 0.24742   | 0.13800    | 0.08652                                     | 4.07037  |
| China          | CDM    | no  | 0.10998    | -0.02564   | 0.16672   | 0.14454    | 7.43928                                     | no limit   |
| India          | CDM    | no  | 0.06867    | -0.01980   | 0.11064   | 0.14763    | 2.56048                                     | no limit   |
| Argentina      | CDM    | no  | 0.07743    | -0.02530   | 0.14790   | 0.15268    | 0.78010                                     | no limit   |
| Bolivia        | CDM    | no  | 0.08280    | -0.02461   | 0.14790   | 0.14836    | 1.38769                                     | no limit   |
| Brazil         | CDM    | no  | 0.07828    | -0.02519   | 0.14790   | 0.15212    | 11.28531                                    | no limit   |
| Chile          | CDM    | no  | 0.07978    | -0.02500   | 0.14790   | 0.15127    | 0.38085                                     | no limit   |
| Colombia       | CDM    | no  | 0.07932    | -0.02506   | 0.14790   | 0.15151    | 1.43466                                     | no limit   |
| Ecuador        | CDM    | no  | 0.08238    | -0.02467   | 0.14790   | 0.14872    | 0.25640                                     | no limit   |
| Guatemala      | CDM    | no  | 0.07841    | -0.02517   | 0.14790   | 0.15204    | 0.58872                                     | no limit   |
| Mexico         | CDM    | no  | 0.07901    | -0.02510   | 0.14790   | 0.15169    | 0.00000                                     | no limit   |
| Nicaragua      | CDM    | no  | 0.08154    | -0.02478   | 0.14790   | 0.14948    | 0.77574                                     | no limit   |
| Panama         | CDM    | no  | 0.07720    | -0.02533   | 0.14790   | 0.15284    | 0.64194                                     | no limit   |
| Paraguay       | CDM    | no  | 0.07733    | -0.02531   | 0.14790   | 0.15275    | 0.43646                                     | no limit   |
| Peru           | CDM    | no  | 0.07729    | -0.02532   | 0.14790   | 0.15277    | 0.00161                                     | no limit   |
| Uruguay        | CDM    | no  | 0.07509    | -0.02560   | 0.14790   | 0.15485    | 0.03558                                     | no limit   |
| Venezuela      | CDM    | no  | 0.08178    | -0.02474   | 0.14790   | 0.14925    | 1.12719                                     | no limit   |

## Appendix B. Hypothetical Large-scale Southern Ocean Iron Fertilization

For the analysis of hypothetical large-scale Southern Ocean iron fertilization, Oschlies et al. (2010) use the University of Victoria (UVic) Earth System Climate Model (Weaver et al., 2001) in the configuration described by Schmittner et al. (2008). The oceanic component is a fully three-dimensional primitive-equation model with 19 levels in the vertical, ranging from 50m thickness near the surface to 500m in the deep ocean. It contains a simple marine ecosystem model with the two major nutrients nitrate and phosphate and two phytoplankton classes, nitrogen fixers and other phytoplankton, the former being limited only by phosphate. Organic matter is produced, processed, and remineralized according to a fixed elemental stoichiometry of C:N:P=112:16:1. Detritus sinks with a velocity that increases linearly with depth from 7 m/day at the surface to 40 m/day at 1000m and remaining constant below that. The production of calcium carbonate is assumed to be proportional to the production of nondiazotrophic detritus, and its instantaneous export and dissolution is parameterized by an e-folding depth of 3500 m.

The ocean component is coupled to a single-level energy moisture balance model of the atmosphere and a dynamic-thermodynamic sea-ice component. The terrestrial vegetation and carbon cycle component is based on the Hadley Centre's TRIFFID model (Cox et al., 2000).

Because of the difficulty of explicitly modeling the complex iron chemistry and its interaction with marine biology, the model does not include an explicit parametrization of the iron cycle, but is parameterized against the changes in export production observed for persistent natural iron fertilization on the Kerguelen Plateau and Crozet Islands in the Southern Ocean (Blain et al., 2007; Pollard et al., 2009). Although the pragmatic model does not include an explicit parameterization of the iron cycle, it can nevertheless be tuned to achieve a reasonable fit with observed biogeochemical tracer distributions, in particular by using a low phytoplankton growth rate that allows for the persistence of HNLC areas (Schmittner et al., 2008; Oschlies et al., 2008).

The effect of ocean iron fertilization is simulated by doubling the maximum phytoplankton growth rate from 0.13 per day to 0.26 per day over the fertilized area and during the fertilization period. Increasing the maximum growth rate mimics the effect of iron in relaxing light limitation (Sunda and Huntsman, 1997), and the factor-2 enhancement results in an increase in simulated carbon export across  $z=125\text{m}$  by a factor of 2 to 3 with respect to an unfertilized control experiment. This is in good agreement with the impact of natural iron fertilization near Kerguelen and the Crozet Islands, where Blain et al. (2007) and Pollard et al. (2009) estimated particulate carbon export fluxes to be two to three times higher than in the adjacent unfertilized regions. Additionally, Oschlies et al. (2010) analyze sensitivity experiments with maximum phytoplankton growth rates enhanced by factors of 3 and 5. In an attempt to simulate an upper bound for possible OIF impacts, they postulate a hypothetical and very high value of 10 per day, because it cannot be ruled out that natural iron fertilization is not saturating and that artificial fertilization could be engineered to have an even larger impact. None of these experiments show complete depletion of macronutrients in the fertilized

area.

## Appendix C. Distributional Implications

Table C.3: Distributional effects of including OIF in the Reference Scenario

| Country        | Total costs in 10 <sup>6</sup> USD (constant 2000 USD) |                                     |                |  |   |
|----------------|--|-------------------------------------|----------------|--|---|
|                | LimitCDM10<br>LimitForest<br>(no OIF)                  | FullCDM10<br>FullForest<br>(no OIF) | OIF via market | LimitCDM10<br>LimitForest<br>OIF via<br>distribution<br>population/CO <sub>2</sub> | OIF via<br>distribution<br>population/GDP |
|                | credit price<br>119 USD/ tCO <sub>2</sub>              |                                     |                | credit price<br>22 USD/ tCO <sub>2</sub>   |   |
| Austria        | 1794.25  | 551.54                              | 551.54         | 425.22   | 509.07                                    |
| Belgium        | 2589.48  | 799.13                              | 799.62         | 720.32   | 718.29                                    |
| Denmark        | 1547.85  | 375.17                              | 375.17         | 277.06   | 430.51                                    |
| Finland        | 1413.05  | 317.04                              | 401.83         | 356.75   | 389.99                                    |
| France         | 10537.23   | 2696.62                             | 2696.62        | 814.35   | 2164.88                                   |
| Germany        | 18440.64   | 5805.50                             | 5805.50        | 4780.05  | 5110.54                                   |
| Greece         | 1616.62  | 611.57                              | 620.62         | 410.92   | 325.28                                    |
| Iceland        | 97.97  | 21.10                               | 21.30          | 13.84  | 27.46                                     |
| Ireland        | 1303.90  | 340.54                              | 340.54         | 305.19   | 366.80                                    |
| Italy          | 10213.34   | 3133.55                             | 3162.39        | 1780.26  | 2061.78                                   |
| Luxembourg     | 280.04   | 85.84                               | 85.84          | 116.30   | 112.14                                    |
| Netherlands    | 4354.86  | 1331.55                             | 1332.33        | 1247.63  | 1243.41                                   |
| Norway         | 1729.46  | 362.31                              | 370.91         | 267.36   | 515.86                                    |
| Portugal       | 675.57   | 344.61                              | 344.61         | -1.78  | -58.95                                    |
| Spain          | 6498.49  | 2220.19                             | 2244.10        | 1252.41  | 1051.19                                   |
| Sweden         | 1523.36  | 272.70                              | 345.56         | 31.81  | 405.46                                    |
| Switzerland    | 1713.63  | 395.42                              | 395.42         | 154.21   | 530.66                                    |
| United Kingdom | 14920.24   | 3924.72                             | 3924.72        | 2842.32  | 3888.08                                   |
| United States  | 147758.28  | 42078.18                            | 42078.18       | 53580.14   | 48753.94                                  |
| Australia      | 9022.80  | 2635.58                             | 3345.96        | 4033.61  | 3146.14                                   |
| Canada         | 1472.30  | 2184.22                             | 2565.83        | 3392.31  | 2428.27                                   |
| New Zealand    | 885.33   | 265.68                              | 285.66         | 206.02   | 168.63                                    |
| Japan          | 16088.57   | 4245.13                             | 4245.13        | 2421.31  | 7775.66                                   |
| Bulgaria       | -362.14  | 319.74                              | 319.74         | 63.61  | -142.59                                   |
| Croatia        | -7.49  | 56.82                               | 66.09          | -117.82  | -173.12                                   |
| Czech Rep      | -92.71   | 617.72                              | 617.72         | 585.74   | 120.43                                    |
| Estonia        | 206.51   | 123.13                              | 125.00         | 122.52   | 57.88                                     |
| Hungary        | 470.23   | 251.32                              | 251.32         | -94.63   | -260.71                                   |
| Latvia         | 15.23  | 31.73                               | 31.73          | -78.41   | -89.65                                    |
| Lithuania      | 184.49   | 81.87                               | 81.87          | -68.51   | -100.24                                   |
| Poland         | 1133.68  | 1479.60                             | 1479.60        | 580.01   | -518.36                                   |
| Romania        | 381.04   | 634.56                              | 634.56         | -281.12  | -648.63                                   |
| Slovakia       | 87.42  | 190.26                              | 190.26         | 45.23  | -97.75                                    |
| Slovenia       | 349.08   | 122.38                              | 122.38         | 75.40  | 47.30                                     |
| Russia         | -6105.01   | -7584.04                            | -1255.23       | -1255.23   | -1255.23                                  |
| Ukraine        | -1707.64   | -1683.53                            | -298.26        | -298.26  | -298.26                                   |
| China          | -27482.72  | -20695.97                           | -4941.01       | -4941.01   | -4941.01                                  |
| India          | -5731.23   | -4558.27                            | -1036.33       | -1036.33   | -1036.33                                  |
| Argentina      | -418.64  | -475.40                             | -75.70         | -75.70   | -75.70                                    |
| Bolivia        | -516.95  | -688.96                             | -93.48         | -93.48   | -93.48                                    |
| Brazil         | -4358.00   | -5708.81                            | -788.02        | -788.02  | -788.02                                   |
| Chile          | -219.19  | -242.28                             | -39.63         | -39.63   | -39.63                                    |
| Colombia       | -583.99  | -746.36                             | -105.60        | -105.60  | -105.60                                   |
| Ecuador        | -149.34  | -164.33                             | -27.00         | -27.00   | -27.00                                    |
| Guatemala      | -218.34  | -291.62                             | -39.48         | -39.48   | -39.48                                    |
| Mexico         | -527.76  | -367.64                             | -90.27         | -90.27   | -90.27                                    |
| Nicaragua      | -279.79  | -378.81                             | -50.59         | -50.59   | -50.59                                    |
| Panama         | -229.75  | -312.25                             | -41.54         | -41.54   | -41.54                                    |
| Paraguay       | -155.81  | -212.03                             | -28.17         | -28.17   | -28.17                                    |
| Peru           | -29.32   | -20.57                              | -5.04          | -5.04  | -5.04                                     |
| Uruguay        | -15.44   | -19.17                              | -2.79          | -2.79  | -2.79                                     |
| Venezuela      | -721.29  | -766.99                             | -130.43        | -130.43  | -130.43                                   |

## Part IV

# Optimal global carbon management with ocean sequestration

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# Optimal global carbon management with ocean sequestration <sup>☆</sup>

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## Abstract

We investigate the socially optimal intervention in the global carbon cycle. Limiting factors are (a) increasing atmospheric carbon concentration due to fossil fuel-related carbon emissions, and (b) the inertia of the global carbon cycle itself. Accordingly, we explicitly include the largest non-atmospheric carbon reservoir, the ocean, to achieve a better representation of the global carbon cycle than the proportional-decay assumption usually resorted to in economic models. We also investigate the option to directly inject CO<sub>2</sub> into the deep ocean (a form of carbon sequestration), deriving from this a critical level for ocean sequestration costs. Above this level, ocean sequestration is merely a temporary option; below it, ocean sequestration is the long-term option permitting extended use of fossil fuels. The latter alternative involves higher atmospheric stabilization levels. In this connection it should be noted that the efficiency of ocean sequestration depends on the time-preference and the inertia of the carbon cycle.

*Keywords:* climate change, global carbon cycle, ocean sequestration

*JEL:* Q30, Q54

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## 1. Introduction

Today, society has recognized the far-reaching consequences of the increase in atmospheric carbon concentration to above its preindustrial level because this contributes to a large extent to global warming. Nevertheless, the carbon concentration in the atmosphere is growing continuously and its growth rate increased even further in the period 2000-2006 (Canadell et al., 2007). This growth depends not only on global economic activity and the carbon intensity of the economy but also on the effectiveness of the natural carbon sinks, namely the terrestrial biosphere and the ocean. The uptake of the terrestrial biosphere is subject to strong fluctuations that are not well understood yet. Looking at the change in the various carbon reservoirs from 1800 to 1994, Sabine et al. (2004) show that the terrestrial biosphere has been a total net source of 39 ( $\pm 28$ ) Gt C.<sup>1</sup> They conclude that ‘the ocean has constituted the only true net sink for anthropogenic CO<sub>2</sub> over the past 200 years’ (p.370). The absolute value of the long-run atmospheric carbon stabilization level and the time pattern of its achievement will depend crucially on the marine carbon cycle, which is therefore perceived to be the most important cycle with regard to the climate (Najjar, 1992). Therefore, any approach to mitigate global warming that ignores the ocean ignores optimization potential.

In this paper, we address the question how the inclusion of the largest carbon reservoir of the carbon cycle, the ocean, changes the optimal path of carbon emissions and whether its inclusion allows additional optimization potential. Since natural forces transport carbon into the deep ocean, where it cannot affect society as adversely as when in the atmosphere, the logical question is: At which cost level would it be beneficial to accelerate the process of downward carbon transfer by injecting carbon into the deep ocean? CO<sub>2</sub> could be transported via pipelines or ships to an ocean storage site, where it would be injected into the water column of the ocean or at the seafloor. This way, it would also become part of the global carbon cycle, but would enter the cycle in a more favorable way (Marchetti, 1977; Ozaki et al., 2001; IPCC, 2005; Keeling, 2009).

The growing knowledge about the importance of the marine carbon cycle for the mitigation of global warming has not just led to the inclusion of the oceanic carbon sink in the pioneering integrated assessment model (see, e.g., modifications from DICE 94 to DICE 99, Nordhaus, 1994; Nordhaus and Boyer, 2000, respectively). It has also led to the development of highly sophisticated computer models that include complex coupled atmosphere-ocean general circulation models to represent the global carbon cycle and the climate system of the world (for an overview of integrated assessment models, see, e.g., Kelly and Kolstad, 1999; Tol, 2006). However, many general properties of the stock externality problem were derived in microeconomic optimal control models, like Plourde (1976) or Forster (1980). In the application of these

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<sup>1</sup>Based on the net increase of 165 Gt C in the atmosphere from 1800 to 1994, Sabine et al. (2004) subtract their ocean inventory estimate of 118 ( $\pm 19$ ) Gt C from the total of fossil-fuel-emitted carbon, which amounted to 244 ( $\pm 20$ ) Gt C during this period. As a consequence, the terrestrial biosphere has to be considered a net source of carbon if the carbon budget is to be balanced.

optimal control models to climate change problems, the global carbon cycle is only roughly approximated. The majority of the models apply a constant rate of decay, which yields a proportional decay of carbon in the atmosphere. As a result, in these models, global warming presents itself merely as a problem of temporary duration and the atmospheric carbon stock is represented as a completely renewable resource (see, e.g., Tahvonen, 1997). The other extremum is to model the atmospheric carbon stock without decay, whereby it becomes a completely non-renewable resource (see, e.g., Section 4 in Hoel, 1978; or Farzin, 1996). The atmospheric carbon stock is neither appropriately represented by a completely renewable description nor by a completely non-renewable description. Whereas the completely renewable description clearly overestimates the storing capacity of the global carbon cycle, the completely non-renewable description underestimates the storing capacity of the global carbon cycle. The first description implies a complete oceanic carbon sink, the second description neglects the oceanic carbon sink. Taking into account this oceanic carbon uptake, the atmospheric carbon stock could be considered as a partial non-renewable resource. This approach is followed by Farzin and Tahvonen (1996). Based on a paper by Maier-Raimer and Hasselmann (1987), they divide the atmospheric carbon stock within their dynamic system artificially into two different stocks, one with a constant rate of decay and the other without. Given that the proportion of emissions to the nondecaying stock is equal to the long-run equilibrium, Farzin and Tahvonen's model captures important aspects of the carbon cycle. Nevertheless, the only management option in their dynamic model is to control the amount of emissions released into the atmosphere, which is proportional to the amount of extracted fossil fuels. Herzog et al. (2003) consider the injection of CO<sub>2</sub> into the deep ocean. They calculate the effectiveness of this activity, measured as the ratio between the net benefit gained from temporary storage and the benefit gained from permanent storage. They find 'that the value of relatively deep ocean sequestration is nearly equivalent to permanent sequestration if marginal damage (i.e., carbon prices) remains constant or if there is a backstop technology that caps the abatement cost in the not too distant future' (p. 306). However, their calculation of ocean sequestration is not embedded within an optimal control framework, and therefore is not the result of a combined extraction and sequestration decision.

We analyze the optimal amount of extraction and consumption of fossil fuels whereby the related emissions can be released into the atmosphere and injected into the deep ocean for purposes of ocean sequestration in a microeconomic partial analysis framework. In Section 2 we explain how we include the oceanic carbon stock in the optimization problem by applying a two-box model representation for the global carbon cycle. Thereby, we replace the constant or nonconstant decay assumption and capture the essential nonrenewable aspects of the global carbon cycle without artificially dividing the atmospheric carbon stock. In Section 3 we present our results. In Section 3.1 we derive the general optimality conditions for the solution, before we start in Section 3.2 by analyzing the scenario, where the fossil-fuel related emissions can only be released to the atmosphere. In Section 3.3 we analyze the scenario where fossil-fuel related carbon emission can also be injected into the deep ocean and derive a critical level for ocean sequestration costs. In Section 3.4 we



analyse the policy relevant case, where the start-up costs of ocean sequestration are below the critical level and the initial levels of atmospheric carbon concentration are still below atmospheric stabilization targets. Finally, Section 4 concludes.

## 2. Anthropogenic intervention into the global carbon cycle

We investigate the optimal anthropogenic intervention into the carbon cycle in the light of global warming as a social planner's problem in which the planer needs to determine the global optimal amount of fossil fuels extraction and consumption with related emissions released to the atmosphere,  $q(t)$ , and the global optimal amount of fossil fuels extraction and consumption with related emissions injected into the deep ocean for purpose of sequestration,  $a(t)$ . Consequently, the total amount of fossil fuels extraction and consumption is  $x(t) = q(t) + a(t)$ . The social welfare function can be formalized as follows:

$$\max_{q(t), a(t)} \int_0^{\infty} (U(q(t) + a(t)) - A(a(t)) - D(S(t)))e^{-\rho t} dt, \quad (1)$$

$$\text{with } a(t), q(t) \geq 0, \quad (2)$$

which has to be maximized subject to the constraints:

$$\dot{S} = q(t) - \gamma(S(t) - \omega W(t)) \quad \text{with } S(t_0) = S_0, \quad (3)$$

$$\dot{W} = a(t) + \gamma(S(t) - \omega W(t)) \quad \text{with } W(t_0) = W_0, \quad (4)$$

$$\dot{R} = -q(t) - a(t) \quad \text{with } R(t_0) = R_0. \quad (5)$$

The total amount of fossil fuel extraction and consumption,  $q(t) + a(t)$ , generates gross utility in the social welfare function at any instant in time. The gross utility of total fossil fuel consumption is described by  $U(x(t))$ , which has the properties  $U' > 0$ ,  $U'' < 0$ , and  $U'(0) = b < \infty$ . The last property implies that there is a choke price or a backstop price. We assume that the costs of fossil fuel extraction are independent from the resource stock and are included in  $U(x(t))$ . The proportional amount of carbon emissions related to total fossil fuels consumption (the proportionality factor is one) can be released directly to the atmosphere,  $q(t)$  (emissions), or injected into the deep ocean,  $a(t)$  (ocean sequestration). Ocean sequestration generates additional costs in the social welfare function at any instant in time. The costs of ocean sequestration are described by  $A(a(t))$ , which has the properties  $A' > 0$  and  $A'' > 0$  and is measured in the same units as utility. Ocean sequestration summarizes the activities of capturing CO<sub>2</sub> generated from the use of fossil fuels, of transporting the captured CO<sub>2</sub> via pipelines or ships to an ocean storage site, and of injecting it into the deep ocean. The IPCC (2005) special report on carbon dioxide capture and storage provides cost ranges for CO<sub>2</sub> capture. The ranges indicate that sequestration costs vary by differences in the design of

CO<sub>2</sub> capture systems and by differences in the operating and financing of the reference plant to which the capture technology is applied (p.27). Additionally, their estimates show that the costs are increasing as the transportation distance on land and on sea increases (p.31, Figure TS.6 and p.39, Table TS.8). We assume that carbon capture would be first applied to the most cost efficient plants and to plants located nearest to the shore. However, in order to increase the amount of ocean sequestration, the capture technology has to be applied to less efficient plants and to plants located far away from the shore. Consequently, by including ocean sequestration into such a microeconomic partial analysis framework such as ours, the most appropriate representation of the costs becomes a convex function.

Both control variables,  $q(t)$  and  $a(t)$ , increase the amount of carbon in the global carbon cycle, whereas only the atmospheric carbon stock influences the objective function. The increase in the atmospheric carbon stock to above preindustrial levels leads to global warming and thereby causes social costs for society at any instant in time. The social costs of global warming are denoted as damage and are described by the strictly convex function  $D(S(t))$ , with the properties  $D' > 0$ ,  $D'' > 0$ , and  $D'(0) = 0$ .

Equations (3) and (4) constitute the two-box model representation of the atmosphere and ocean (see Figure 1), whereby the boxes entail the carbon stocks in the atmosphere and the ocean, respectively. Equation (5) incorporates the endowment of the fossil resource,  $R(t)$ . The equations (3) to (5) describe the dynamics of the global carbon cycle as a consequence of the anthropogenic intervention. The upper box

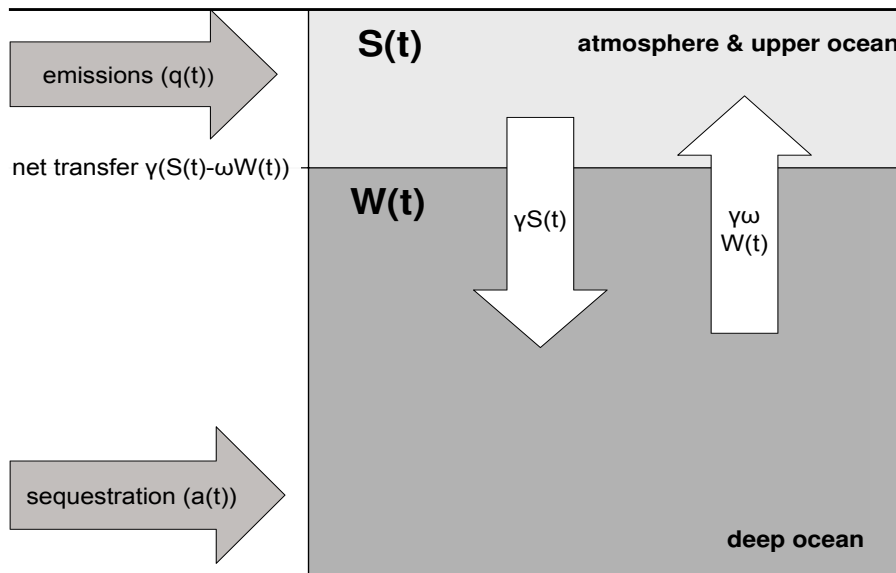


Figure 1: Two-Box Model

aggregates the carbon stocks in the atmosphere and in the upper mixed layer of the ocean. There is a net

transfer of carbon between the atmosphere and the upper mixed layer of the ocean if there is a difference in the partial pressure of carbon dioxide ( $p\text{CO}_2$ ) between these two reservoirs. The equilibration time for the upper layer of the ocean with the atmosphere takes around one year.<sup>2</sup> However, only a small fraction of the ocean is involved in direct exchange with the atmosphere and the uptake bottleneck is the transport of anthropogenic carbon to the deeper parts of the ocean. Consequently, we assume that the atmosphere and the upper mixed layer are always in equilibrium and that the stock of carbon in the atmosphere is a constant fraction of the carbon stock in the upper box,  $S(t)$ .

In order to model the transport of anthropogenic carbon to the deeper parts of the ocean, we include the carbon stock in the deep ocean,  $W(t)$ , in the lower box. The transport of anthropogenic carbon to the deeper parts of the oceans is effected by the biological pump and especially by the solubility pump. The term biological pump designates the small fraction of organic matter and skeletons that survives remineralization in the euphotic zone and sinks to deeper layers. The main contribution to the transport of anthropogenic carbon is provided by the solubility pump. The solubility pump is driven by two phenomena: thermohaline circulation and the solubility of  $\text{CO}_2$ . Surface water in equilibrium with atmospheric  $\text{CO}_2$  takes up additional  $\text{CO}_2$  on its way to the earth's poles, as the decreasing temperature increases the solubility of  $\text{CO}_2$ . The formation of deep seawater is driven by thermohaline circulation, which transports cold and high-solubility high-latitude surface waters into the deep ocean. Consequently, these two phenomena act together to pump carbon from the atmosphere into the ocean's deeper layers until the deep ocean is saturated with respect to the upper layer. At this point in time, the up-welling water in the mid-latitudes transports anthropogenic carbon back to the upper layer.

The downward flux of carbon from the upper box to the lower box is represented by the fraction  $\gamma S(t)$  and the upwards flux of carbon from the lower box to the upper box by the fraction  $\gamma\omega W(t)$ . These two fluxes are represented in Figure 1 by the two white vertical arrows between the boxes. Both arrows have the same size, indicating that the upward flux is balanced by the downward flux. Putting these two fluxes together, we obtain the net transfer between the boxes,  $\gamma(S(t) - \omega W(t))$ . There will be a net flux between these two boxes if there is a difference between the relative stock sizes. An increase in the stock size in the upper box causes a downward transfer of excess carbon into the deep ocean, whereas up-welling water is still free of excess carbon, so that we observe a net transfer from the upper box into the lower box. The upper box is relatively small in comparison to the lower box. Consequently,  $\omega$  is the proportionality factor to scale the stock of carbon in the lower box with respect to the upper box and  $\gamma$  is the turnover factor to describe the speed of the adjustment process.<sup>3</sup> The anthropogenic intervention into the carbon cycle, the

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<sup>2</sup>Most of the  $\text{CO}_2$  dissolves in water, forming carbon acid first and then bicarbonate ( $\text{HCO}_3^-$ ) and carbonate ions ( $\text{CO}_3^{2-}$ ). The sum of these three elements describes the total amount of carbon in the ocean, called dissolved inorganic carbon (DIC). The amount of DIC in the ocean consists to 89.1% of bicarbonate ions, to 10.4% of carbonate ions and only to 0.5% of  $\text{CO}_2$  (Najjar, 1992). Regarding the last figure, the atmosphere "sees" only a tiny fraction of the carbon present in ocean surface water within the chemical process of  $p\text{CO}_2$  equilibration between the atmosphere and the ocean.

<sup>3</sup>Currently, this turnover speed is mainly limiting the uptake process by the ocean, so that the total ocean is estimated to

amount of emissions and the amount of ocean sequestration are depicted by the grey horizontal arrows in Figure 1. The amount of emissions enters the upper box and the amount of ocean sequestration enters the lower box.<sup>4</sup> Even though the carbon stock in upper box entails atmospheric and oceanic carbon, we refer to it as the atmospheric carbon stock.

### 3. Results

#### 3.1. Optimal solution conditions

The corresponding current value Hamiltonian from (1) and (3) to (5) is

$$H_c = U(q + a) - A(a) - D(S) - \psi \dot{S} - \pi \dot{W} + \mu \dot{R}, \quad (6)$$

$$\text{where } \lim_{t \rightarrow \infty} S(t) \geq 0, \quad \lim_{t \rightarrow \infty} W(t) \geq 0, \quad \lim_{t \rightarrow \infty} R(t) \geq 0. \quad (7)$$

Note that from now on we drop the time variable whenever it is convenient. We have changed the signs of the costate variables,  $\psi$  and  $\pi$ , in order to facilitate their economic interpretation as taxes. Together with the two Lagrange multipliers for the control constraints (2),  $\theta_1$  and  $\theta_2$ , we obtain the current value Lagrangian:

$$L_c = H_c - \theta_1(-q) - \theta_2(-a). \quad (8)$$

According to Proposition 6.2 and Propostion 7.5 in Feichtinger and Hartl (1986), the admissible solution candidate has to fulfill the necessary conditions,

$$\frac{\partial L_c}{\partial q} = 0 \quad \Rightarrow \quad U' - \psi - \mu + \theta_1 = 0, \quad (9)$$

$$\frac{\partial L_c}{\partial a} = 0 \quad \Rightarrow \quad U' - A' - \pi - \mu + \theta_2 = 0, \quad (10)$$

$$-\frac{\partial L_c}{\partial S} = -\dot{\psi} + \rho\psi \quad \Rightarrow \quad -D'(S) + \gamma\psi - \gamma\pi = \dot{\psi} - \rho\psi, \quad (11)$$

$$-\frac{\partial L_c}{\partial W} = -\dot{\pi} + \rho\pi \quad \Rightarrow \quad -\gamma\omega\psi + \gamma\omega\pi = \dot{\pi} - \rho\pi, \quad (12)$$

$$-\frac{\partial L_c}{\partial R} = \dot{\mu} - \rho\mu \quad \Rightarrow \quad 0 = \dot{\mu} - \rho\mu, \quad (13)$$

$$\frac{\partial L_c}{\partial \theta_1} \geq 0 \quad \theta_1 \geq 0 \quad \theta_1(-q) = 0, \quad (14)$$

$$\frac{\partial L_c}{\partial \theta_2} \geq 0 \quad \theta_2 \geq 0 \quad \theta_2(-a) = 0, \quad (15)$$

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be undersaturated for a long time (order of  $10^3$  years) (Körtzinger and Wallace, 2002).

<sup>4</sup>Note it would also be possible to apply the control variables  $x(t)$  and  $a(t)$  instead of  $q(t)$  and  $a(t)$ . As a result, only the net emissions,  $x(t) - a(t)$ , would be released to the upper box and the control constraints, (2), would change to  $x(t) - a(t) \geq 0$  and  $a(t) \geq 0$ . Releasing the first constraint by allowing  $x(t) - a(t) \leq 0$  would imply the option of air capture. This possibility is investigated in Lontzek and Rickels (2008).

as well as the transversality conditions,

$$\lim_{t \rightarrow \infty} e^{-\rho t} \psi = 0, \quad \lim_{t \rightarrow \infty} e^{-\rho t} \pi = 0, \quad \lim_{t \rightarrow \infty} e^{-\rho t} \mu R = 0, \quad (16)$$

and the constraint qualification for the control constraints (see Appendix A). As any admissible path for the state and costate variables is non-negative and as any admissible path for the state variables is bounded due to the description of the carbon cycle as a closed system, the fulfillment of the transversality conditions, (16), is sufficient for the fulfillment of the general transversality conditions in a infinity horizon problem (Feichtinger and Hartl, 1986, Remark 2.9 and Remark 7.5). The fulfillment of the necessary conditions, (9) to (16), provides the optimal solution, because our carbon cycle is described by linear equations, (3) to (5), the control constraints (2) are quasi-concave, and in Appendix A we show that the maximized Hamiltonian is concave in the state variables and the Hamiltonian is strictly concave in the control variables (Feichtinger and Hartl, 1986, Proposition 7.5). The strict concavity of the Hamiltonian in the control variables implies that the Hamiltonian is regular and that therefore the controls are continuous, in particular at switching points (Feichtinger and Hartl, 1986, corollary 6.2). Note the equations (3) to (5) constitute a closed system, which means that no carbon vanishes from the cycle,  $\dot{S} + \dot{W} + \dot{R} = 0$  and one state variable, e.g.,  $W(t) = R_0 + S_0 + W_0 - R(t) - S(t)$ , and the corresponding costate variable can be dropped. Consequently, the modified Hamiltonian dynamic system with a full rank is a 4x4 dynamic system. The remaining two costate variables also measure then the influence of the omitted state variable on the objective function. To facilitate interpretation, the analysis is based on the system with all state variables (Full system), whereas some technical arguments and the calculations in the Appendix are based on the system with only two state variables (Redux system).

The optimal amounts of the control variables,  $q$  and  $a$ , are determined by the costate variables,  $\mu$ ,  $\psi$ , and  $\pi$ , where  $\mu$  measures the shadow resource scarcity rent,  $-\psi$  measures the shadow environmental scarcity rent of the atmospheric carbon stock and  $-\pi$  measures the shadow environmental scarcity rent of the oceanic carbon stock (Farzin, 1996). The two costate variables  $\psi$  and  $\pi$  can be interpreted as the optimal tax values throughout time for an implementation of the social optimal solution in a decentralized economy. The costate variable that corresponds to the carbon stock in the upper box,  $\psi$ , denotes an emission tax, and the costate variable that corresponds to the carbon stock in the lower box,  $\pi$ , denotes an ocean sequestration tax. Conditions (11) and (12) indicate that both taxes are always positive and that the emission tax is always larger than the ocean sequestration tax, otherwise the transversality conditions (16) would be violated. This can be seen by solving the equation of motion for the tax difference,  $\lambda = \psi - \pi$ , which coincides with the emission tax in the Redux system, in which the state variable  $W$  and the corresponding costate variable  $\pi$

have been dropped,<sup>5</sup>  $\psi_R$ :

$$\dot{\lambda} = \lambda(\rho + \gamma + \gamma\omega) - D'(S) \quad \Rightarrow \quad \lambda(t) = \psi_R(t) = \int_t^\infty D'(S)e^{-(\rho+\gamma+\gamma\omega)(\tau-t)} d\tau. \quad (17)$$

Consequently, if anthropogenic intervention takes place, the tax difference is positive. For an unconstrained solution,  $\theta_1 = \theta_2 = 0$ , this can be seen directly by simplifying (10) to  $A' = \psi - \pi$ . Both taxes,  $\psi$  and  $\pi$  are increasing in the atmospheric carbon stock as does the tax difference, indicating that the emission tax is increasing stronger than the ocean sequestration tax.<sup>6</sup> The economic interpretation is that the amount of emissions directly increases the harmful carbon stock in the upper box, while the amount of ocean sequestration only indirectly does via the natural transfer. Nevertheless, as the ocean sequestration tax is positive, we see that ocean sequestration does cause social costs due to its temporary storage characteristics and therefore does not completely offset emissions into the atmosphere.

### 3.2. Scenario 1: optimal extraction without the option of ocean sequestration

We start investigating the implications of the representation of the carbon cycle as a two-box model by considering a scenario where only one control variable is available,  $q$ , the extraction and consumption of fossil fuels with related emissions released to the atmosphere (Scenario 1). The anthropogenic intervention into the global carbon cycle ends when no further carbon is added due to the fact that either the marginal damage caused by carbon in the atmosphere has increased to such an extent that the choke price has been hit by the emission tax (Situation A) or the fossil resource stock is completely exploited (Situation B). In Situation A, the solution approaches a steady state as  $t \rightarrow \infty$  and the steady state values for the costate variables, which fulfill the transversality conditions (16), are<sup>7</sup>

$$\psi_\infty^{A1} = \frac{D'(S_\infty)}{\gamma + \rho + \gamma\omega} + \frac{\gamma\omega D'(S_\infty)}{\rho(\gamma + \rho + \gamma\omega)}, \quad \pi_\infty^{A1} = \frac{\gamma\omega D'(S_\infty)}{\rho(\gamma + \rho + \gamma\omega)}, \quad \mu_\infty^{A1} = 0. \quad (18)$$

Using the steady state values for the costate variables, we can derive from (9), in which the Kuhn-Tucker multiplier,  $\theta_1$ , is zero, the level of the steady state atmospheric carbon stock:

$$S_\infty^{A1} = D'^{-1} \left( b \frac{\rho(\gamma + \rho + \gamma\omega)}{\rho + \gamma\omega} \right). \quad (19)$$

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<sup>5</sup>The costate variables  $\mu_R$  and  $\psi_R$  also measure the shadow environmental scarcity rent of the oceanic carbon stock. A lower  $R$  implies cet. par. a higher oceanic carbon stock and therefore  $\mu_R > \mu$  (sum of shadow resource scarcity rent and ocean sequestration tax). A lower  $S$  implies cet. par. also a higher oceanic carbon stock but  $\psi_R < \psi$  because the negative effect of a higher oceanic carbon stock is overcompensated by the positive effect of a lower atmospheric carbon stock (difference between emission and ocean sequestration tax). This can also be seen from (9) and (10) by dropping  $\pi$  in (10).

<sup>6</sup>The increase in the emission tax follows directly from the interpretation of  $-\psi$  being the shadow environmental scarcity rent of the atmospheric carbon stock, measuring the change in the value function due to a change in the corresponding state variable (see, e.g., Sydsæter et al., 2005). The increase in the tax difference follows from (17). The increase in the ocean sequestration tax follows from  $\pi(t) = \gamma\omega \int_t^\infty \lambda e^{-\rho(\tau-t)} d\tau$ .

<sup>7</sup>In the Redux system where the state variable  $W$  and the corresponding state variable  $\pi$  have been dropped,  $\mu_R$  has a positive steady state value equal to the steady state value of  $\pi_\infty^{A1}$  in the Full system.

Equations (3) and (4) indicate that the two-box model is a non-renewable resource model, because no carbon vanishes or decays. Therefore, the release of carbon will increase the stock in both boxes forever and the two-box model approaches a new equilibrium with an atmospheric carbon stabilization level above the preindustrial one. The comparable atmospheric stabilization levels obtained with a renewable description of the global carbon cycle (R), like in Tahvonen (1997), obtained with a non-renewable description of the global carbon cycle (NR), like in Hoel (1978), and obtained with a partially non-renewable description of the global carbon cycle (PNR), like in Farzin and Tahvonen (1996), are<sup>8</sup>

$$S_{\infty}^R = S_0, \quad S_{\infty}^{NR} = D'^{-1}(b\rho), \quad S_{\infty}^{PNR} = D'^{-1} \left( b \frac{\rho(\alpha + \rho)}{a - \alpha a + \rho} \right). \quad (20)$$

Intuitively, the renewable description implies that the atmospheric carbon stock returns to its preindustrial level when the release of carbon emissions has ended due to physical ( $R_{\infty} = 0$ ) or economical ( $R_{\infty} \geq 0$ ) exhaustion of the fossil resource. The atmospheric stabilization levels of the non-renewable and partially non-renewable description are only compared if Situation A also applies, that is, if it is not optimal to completely exploit the fossil resource. The non-renewable description provides lower atmospheric carbon stabilization levels than the two-box model, because all carbon emissions remain in the atmosphere. The partially non-renewable description provides the same atmospheric stabilization levels as the two-box model if  $a$  is chosen to be  $\frac{\gamma + \omega}{\rho + \gamma + \omega}$  and  $\alpha$  is chosen to be  $\gamma$  in  $S_{\infty}^{PNR}$ , whereby the parameter  $a$  describes the fraction of emissions that adds to the decaying carbon stock and the parameter  $\alpha$  describes the fraction of the carbon stock that decays within the decaying carbon stock. The renewable description implies a complete oceanic carbon sink; the non-renewable description neglects the oceanic carbon sink. The reality is somewhere in between: 15% (Körtzinger and Wallace, 2002) to 20% (IPCC, 2005) of all anthropogenic CO<sub>2</sub> will remain in the atmosphere within a new carbon cycle equilibrium. Consequently, the most appropriate description seems to be the partially non-renewable one. The comparison with the partially non-renewable description in Farzin and Tahvonen's model shows that the two-box model has no advantage in itself in representing the global carbon cycle. However, it becomes indispensable if further options to release carbon into the carbon cycle are considered (see Section 3.3).

The new equilibrium of the two-box model implies that there is no net transfer between the boxes and that  $S_{\infty} = \omega W_{\infty}$  is fulfilled. Consequently, we can derive the critical initial level of the fossil resource for the steady state in Situation A as being feasible:

$$R_{crit}^{A1} = \left( \frac{\omega + 1}{\omega} \right) D'^{-1} \left( b \frac{\rho(\gamma + \rho + \gamma\omega)}{\rho + \gamma\omega} \right) - S_0 - W_0. \quad (21)$$

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<sup>8</sup>In Farzin and Tahvonen's model, they divide the atmospheric carbon stock artificially into two different stocks, one with a constant rate of decay and the other without. Their objective function includes stock-dependent extraction costs as well, which we have set to zero in order to compare the steady states.

If  $R_0 < R_{crit}^{A1}$ , extraction stops in finite time because  $U'(0) = b < \infty$  (Farzin and Tahvonen, 1996). The corresponding atmospheric and oceanic carbon stabilization levels are then

$$S_{\infty}^{B1} = \frac{\omega}{1 + \omega}(R_0 + S_0 + W_0), \quad W_{\infty}^{B1} = \frac{1}{1 + \omega}(R_0 + W_0 + S_0), \quad (22)$$

which are lower than the carbon stabilization levels in Situation A. Note the stabilization levels in Situation B are not approached at the point in time when extraction stops, but as  $t \rightarrow \infty$ . According to Meinshausen et al. (2009), the emission of carbon from all proven fossil fuel resources would exceed the atmospheric stabilization levels corresponding to a 2°C temperature increase above preindustrial levels, which has been accepted by most countries as maximum tolerable limit for global warming. We focus therefore in our analysis on Situation A, where the limiting factor for optimal extraction is not the endowment of the fossil resource, but rather harmful levels of atmospheric carbon concentration, and impose therefore

**Assumption 1.**  $R_0 \geq R_{crit}^{A1}$ .

We show in Appendix B that the steady state of the 4x4 Hamiltonian dynamic system is a saddle point with four real eigenvalues, two being positive and two being negative. If Assumption 1 is fulfilled, the steady state is feasible and the optimal solution is the unique saddle path converging to the steady state as  $t \rightarrow \infty$ . Additionally, it can be seen from (13) and from the steady state levels of the costate variable in Situation A (18) that  $\mu(t) = 0$  for  $t \in [0, \infty)$ . The fulfillment of Assumption 1 implies that the fossil resource is not scarce for the optimal solution in Situation A. The optimal path of extraction is therefore only determined by the emission tax,  $\psi$ .

**Proposition 1.** *In Scenario 1 (related emissions can only be released to the atmosphere), if functional forms (9)-(11) are restricted to be quadratic-linear, Assumption 1 holds, and  $U'(0) = b < \infty$ , the global optimal path for the emission tax,  $\psi$ , is either monotonically increasing or U-shaped.*

**Proof.** Because of the saddle path property with four real eigenvalues, two being positive and two being negative (see Appendix B), the optimal path of the emission tax towards the steady state for quadratic-linear functional forms is determined by the two negative real eigenvalues in exponential terms and can therefore only entail one extremum. As a result, the set of possible paths is limited to a monotonically increasing, a monotonically decreasing, a U-shaped, and an inversely U-shaped path. The fulfillment of (9) in the steady state with  $q_{\infty} = 0$  requires  $\psi_{\infty} = U'(0) = b \leq \infty$ . Therefore, the control constraint  $q(t) \geq 0$  for  $t \in [0, \infty)$  allows only tax paths that increase into the steady state.  $\square$

**Proposition 2.** *In Scenario 1 (related emissions can only be released to the atmosphere), if functional forms (9)-(11) are restricted to be quadratic-linear, Assumption 1 holds, and  $U'(0) = b < \infty$ , the global*



optimal path for the ocean sequestration tax,  $\pi$ , and the tax difference,  $\lambda$ , is either monotonically increasing or U-shaped.

**Proof.** Again, the set of possible paths for the ocean sequestration tax and the tax difference is limited to a monotonically increasing, a monotonically decreasing, a U-shaped, and an inversely U-shaped path due to the saddle path property with real eigenvalues and the restriction to quadratic-linear functional forms. From (12),  $\dot{\pi} = (\rho + \gamma\omega)\pi - \gamma\omega\psi$  it can be seen that it is not possible for  $\pi$  to approach its steady state value from above. Such a path would imply that  $\pi$  is decreasing, while the second term with  $\psi$  is increasing due to Proposition 1. As a consequence,  $\pi$  would continue to decrease. As both,  $\psi$  and  $\pi$  have to be increasing into the steady state so does  $\lambda$  as it can be again seen from (12),  $\dot{\lambda} = \rho\pi - \gamma\omega\lambda$ . Paths for  $\pi$  and  $\lambda$  which are decreasing do not allow to approach a steady state which in turn would violate the transversality condition (16).  $\square$

Note, restricting functional forms to be quadratic-linear allows global statement for the tax paths in Proposition 1 and 2. Without the functional restriction, the propositions would only be locally in the neighborhood of the steady state valid. The two excluded paths from the set of possible paths, the monotonically decreasing and the inversely U-shaped path, require an additional term that increases during the movement to the steady state so that (9) allows a declining amount of extraction even if the emission tax is decreasing. This requirement can be fulfilled by modeling extraction costs as not stock-independent, as in our model, but as stock-dependent, as in Farzin and Tahvonen (1996),  $qC(R)$  with  $C' < 0$ .<sup>9</sup> The inclusion of stock-dependent extraction costs allows both physical exhaustibility ( $R_\infty = 0$ ) and economical exhaustibility ( $U'(0) = C(R_\infty)$  with  $R_\infty \geq 0$ ) to be considered. However, our formulation with stock-independent extraction costs allows the implications of the description of the global carbon cycle to be clarified.

The renewable description of the global carbon cycle allows two tax paths, a monotonically decreasing and an inversely U-shaped path (e.g., Tahvonen, 1997). The non-renewable description of the global carbon cycle allows only one tax path, a monotonically increasing path (e.g., Farzin, 1996). The partially non-renewable description allows, compared to the non-renewable description, one additional possible path, a U-shaped path. Note Farzin and Tahvonen (1996) observe as well the two paths from the renewable description within their partially non-renewable description, but not as consequence of the partially non-renewable description but due to the inclusion of stock-dependent extraction costs. The result is confirmed by the fact that the description with the two-box model allows the two additional paths from the renewable description to be observed as well if extraction costs are modeled to be stock-dependent (Lontzek and Rickels, 2008).

Additionally, Farzin and Tahvonen (1996) show that for the partially non-renewable description and for a specific initial level of the atmospheric carbon stock, the possibility of a stationary emission tax with

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<sup>9</sup>An alternative formulation is  $C(X)$  with  $C' > 0$ , where  $X$  measures the cumulative amount of extracted fossil fuels (Farzin, 1992).

a stationary atmospheric carbon level to exist, given that there is no steady state,  $U'(0) \rightarrow \infty$ . The stationary atmospheric carbon level requires that the decaying atmospheric carbon stock in the sum of the total atmospheric carbon stock declines at the rate at which the non-decaying atmospheric carbon stock increases. The decreasing decaying atmospheric carbon stock implies lower decay, so that extraction is decreasing at a constant rate. Such a stationary atmospheric carbon stock where the amount of emission is constantly decreasing is also possible with the two-box model. It requires that the amount of carbon emissions decreases at the same rate as the net transfer between the two boxes decreases due to the carbon accumulation in the deep ocean. The amount of emission would decline according to

$$q(t) = \gamma\omega \left( \frac{\bar{S}}{\omega} - W_0 \right) e^{-\gamma\omega t} \quad (23)$$

and the oceanic carbon stock would increase according to

$$W(t) = \frac{\bar{S}}{\omega} + \left( W_0 - \frac{\bar{S}}{\omega} \right) e^{-\gamma\omega t}, \quad (24)$$

where  $\bar{S}$  denotes the stationary atmospheric carbon level. Additionally, by changing our model formulation so that  $U'(0) \rightarrow \infty$  is valid and stock-dependent extraction costs are included, we could confirm that a constant emission tax occurs even with fossil fuel endowment as a specific feature of the description of the carbon cycle by a two-box model as it could be confirmed by Farzin and Tahvonen (1996) as a specific feature of the description of the carbon cycle by a partially non-renewable atmospheric carbon stock. However, the constant path requires, first, particular functional forms for  $U(q)$  and  $C(R)$  so that a constant percentage of the resource stock is extracted, which implies that extraction declines at this constant percentage rate (p.523), and, second, that the constant percentage coincides with the parameters of the carbon cycle description.<sup>10</sup> Consequently, the partially non-renewable description of the atmospheric carbon stock or the two-box model description of the carbon cycle is the precondition for such a path to occur, but the occurrence of such path is the consequence of a specific extraction path rather than the consequence of the carbon cycle description. In our analysis, we focus on the situation where the global carbon cycle approaches a steady state with non-constant taxes (Situation A).

### 3.3. Scenario 2: optimal extraction with the option of ocean sequestration

We return to the scenario where both control variables,  $q$  and  $a$ , are available, the extraction and consumption of fossil fuels with related emissions released to the atmosphere and the extraction and consumption of fossil fuels with related emissions injected into the deep ocean (Scenario 2). As in the previous section, the

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<sup>10</sup>In Farzin and Tahvonen (1996) the constant percentage is given by  $aa$ , the decay parameter and the fraction being added to the non-decaying stock, whereas in our model the constant percentage is given by the turnover speed between the boxes,  $\gamma$ , and the proportionality parameter,  $\omega$ .

anthropogenic intervention into the global carbon cycle ends when no further carbon is added due to the fact that either the marginal damage caused by carbon in the atmosphere has increased to such an extent that the choke price has been hit or even exceeded by the emission tax (Situation A) or the fossil resource stock is completely exploited (Situation B). Again, in Situation A the solution approaches a steady state as  $t \rightarrow \infty$  and the steady state values for the costate variables are given by (18) from Section 3.2. However, unlike in the previous section, not just (9) has to be fulfilled, but also (10) as well, which can be simplified to

$$A' + \theta_1 - \theta_2 = \psi - \pi. \quad (25)$$

Condition (25) shows that the amount of ocean sequestration is determined by the difference between the two taxes, because by injecting carbon emissions into the ocean, one saves the emission tax, but instead has to pay the ocean sequestration tax. We already pointed out in the previous section that Situation A requires an increasing emission tax for (9),  $U'(0) = \psi_\infty$ , to be fulfilled in the steady state. However, the amount of ocean sequestration is increasing in  $\psi$  due to the convexity of the ocean sequestration cost function, and therefore we cannot further assume that the solution is unconstrained. Using the steady state levels of the taxes (18), we can derive two conditions (a and b) for the steady state atmospheric carbon stock to fulfill (9) and (10):

$$S_\infty^{A2a} = D'^{-1} \left( (b + \theta_1) \frac{\rho(\gamma + \rho + \gamma\omega)}{\rho + \gamma\omega} \right), \quad S_\infty^{A2b} = D'^{-1} \left( (b - A'(0) + \theta_2) \frac{\rho(\gamma + \rho + \gamma\omega)}{\gamma\omega} \right). \quad (26)$$

By equating  $S_\infty^{A2a}$  and  $S_\infty^{A2b}$ , we obtain

$$A'(0) = b \frac{\rho}{\rho + \gamma\omega} - \frac{\gamma\omega}{\rho + \gamma\omega} \theta_1 + \theta_2, \quad (27)$$

by which we distinguish three cases for the steady state:<sup>11</sup>

$$\text{Case 1: } A'(0) > b \frac{\rho}{\rho + \gamma\omega} \Rightarrow \theta_1 = 0 \quad \theta_2 > 0, \quad (28)$$

$$\text{Case 2: } A'(0) = b \frac{\rho}{\rho + \gamma\omega} \Rightarrow \theta_1 = 0 \quad \theta_2 = 0, \quad (29)$$

$$\text{Case 3: } A'(0) < b \frac{\rho}{\rho + \gamma\omega} \Rightarrow \theta_1 > 0 \quad \theta_2 = 0. \quad (30)$$

The value of  $A'(0)$  is somehow the counterpart of the choke price  $b$ . Whereas  $b$  denotes the maximum value for marginal utility,  $A'(0)$  is the minimum level of the marginal sequestration costs. Therefore,  $A'(0)$  can

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<sup>11</sup>We only consider carbon cycle equilibriums that are approached via anthropogenic intervention into the global carbon cycle and do not consider a potential Case 4 with both Kuhn-Tucker multipliers being positive, because in such a case the carbon cycle equilibrium is determined only by the initial levels,  $S_0$  and  $W_0$ .

be interpreted as the start-up cost for ocean sequestration. Due to the importance of  $A'(0)$  within Case 1 to 3, we define

$$A_{crit} = b \frac{\rho}{\rho + \gamma\omega}. \quad (31)$$

**Proposition 3.** *In Scenario 2 (related emissions can be released to the atmosphere and injected into the deep ocean), if  $A'(0) < A_{crit}$  holds, the atmospheric stabilization level increases compared to Scenario 1 .*

**Proof.** If  $A'(0) \geq A_{crit}$ ,  $\theta_1$  is zero, (28) and (29), and we obtain

$$S_{\infty}^{A2a} = S_{\infty}^{A2b} = S_{\infty}^{A1} = D'^{-1} \left( b \frac{\rho(\gamma + \rho + \gamma\omega)}{\rho + \gamma\omega} \right) \quad \text{with} \quad \theta_2 = A'(0) - A_{crit}. \quad (32)$$

If  $A'(0) < A_{crit}$ ,  $\theta_1 = \frac{b\rho - A'(0)(\rho + \gamma\omega)}{\gamma\omega} > 0$ ,  $\theta_2$  is zero, and the function arguments in  $S_{\infty}^{A2a}$  and  $S_{\infty}^{A2b}$  increase uniformly and consequently the atmospheric stabilization level increases, so that  $S_{\infty}^{A2a} = S_{\infty}^{A2b} > S_{\infty}^{A1}$ .  $\square$

If the atmospheric carbon stabilization level increases compared to Scenario 1, so does the oceanic carbon stabilization level in order to satisfy the carbon cycle equilibrium condition  $S_{\infty} = \omega W_{\infty}$ . Consequently, we can again derive the critical initial level of the fossil resource for the steady state in Situation A as being feasible:

$$R_{crit}^{A2}(A'(0)) = \left( \frac{\omega + 1}{\omega} \right) D'^{-1} \left( \left( b - A'(0) \frac{\rho(\gamma + \rho + \gamma\omega)}{\gamma\omega} \right) - S_0 - W_0, \quad (33)$$

whereas  $R_{crit}^2(A'(0)) > R_{crit}^1$  requires  $A'(0) < A_{crit}$  to be fulfilled. If  $R_0 < R_{crit}^{A2}(A'(0))$ , extraction stops again in finite time, as in Section 3.2, because  $U'(0) = b < \infty$  (Situation B). The corresponding atmospheric and oceanic carbon stabilization levels are only determined by the initial level of the fossil resource,  $R_0$  (see (22)). It is possible to observe  $R_{crit}^{A2}(A'(0)) > R_0 > R_{crit}^{A1}$  if  $A'(0) < A_{crit}$ , so that the opportunity to inject carbon emissions related to fossil fuel consumption directly into the ocean would lead to the complete exploitation of the fossil resource (Situation B), whereas without this opportunity the fossil resource would not be completely exploited (Situation A). In Scenario 2, we also concentrate on Situation A and therefore extend Assumption 1,

**Assumption 2.**  $R_0 \geq R_{crit}^{A2}(A'(0))$ .

Again, if Assumption 2 is fulfilled, it can be seen from (13) and from the steady state level of the costate variable in Situation A (18) that  $\mu(t) = 0$  for  $t \in [0, \infty)$ . The fulfillment of Assumption 2 implies that the fossil resource is not scarce for the optimal solution in Situation A. The optimal path of extraction is therefore determined only by the emission tax,  $\psi$ , and the ocean sequestration tax,  $\pi$ . The steady states in Case 1, (28), and Case 3, (30), have positive Kuhn-Tucker multipliers. Taking into account the continuity of

the control variables, a point in time has to emerge,  $t_s$ , with  $t_s < \infty$ , after which the dynamic system is either described by  $q(t) \geq 0$  and  $a(t) = 0$  for  $t \in [t_s, \infty)$  (Case 1) or by  $q(t) = 0$  and  $a(t) \geq 0$  for  $t \in [t_s, \infty)$  (Case 3) on the path towards the steady state. Note after  $t_s$  the dynamic system leading toward the steady state coincides with a dynamic system which allows only extraction with related emissions released into the atmosphere (Case 1) or with a dynamic system which allows only extraction with related emissions injected into the deep ocean (Case 3). To formalize this idea, we define three control regimes:<sup>12</sup>

Regime 1: *No sequestration*:  $a = 0$  and  $q \geq 0$  ( $\theta_1 = 0$  and  $\theta_2 > 0$ ),

Regime 2: *Sequestration*:  $a \geq 0$  and  $q \geq 0$  ( $\theta_1 = 0$  and  $\theta_2 = 0$ ),

Regime 3: *Only sequestration*:  $a \geq 0$  and  $q = 0$  ( $\theta_1 > 0$  and  $\theta_2 = 0$ ).

**Proposition 4.** *In Scenario 2 (related emissions can be released to the atmosphere and injected into the deep ocean), if Assumption 2 holds, and  $U'(0) = b < \infty$ , the movement into the steady state is not an interior solution, but is, after some point in time,  $t_s$ , described either by Regime 1 ( $A'(0) \geq A_{crit}$ ;  $R_0 > R_{crit}^{A2}(A'(0)) = R_{crit}^{A1}$ ), or by Regime 3 ( $A'(0) < A_{crit}$ ;  $R_0 > R_{crit}^{A2}(A'(0)) > R_{crit}^{A1}$ ).*

**Proof.** Movement into the steady cannot be determined by Regime 2 because  $q(t) \rightarrow 0$  requires an increasing emission tax, whereas  $a(t) \rightarrow 0$  requires a decreasing emission tax so that the tax difference is also decreasing. Consequently, movement into the steady state implies at least one control constraint to be active (either  $\theta_1$  or  $\theta_2$ ).  $\square$

We already referred in Section 3.2 to Appendix B, where we show that Regime 1 (which is equal to Scenario 1), obeys saddle path properties with real eigenvalues. In Appendix B we also show that Regime 3 obeys saddle path properties. For the eigenvalues to be real in Regime 3, the condition

$$\frac{1}{4}(\gamma(1 + \omega)(\rho + \gamma + \gamma\omega) - D''(a'_{\mu_R}) + a'_{\pi_R})^2 > -\gamma\omega(\gamma + \rho + \gamma\omega)D''a'_{\mu_R} \quad (34)$$

has to be fulfilled in the steady state, where the subscript  $R$  indicates the costate variables of the Redux system.

**Proposition 5.** *In Scenario 2 (related emissions can be released to the atmosphere and injected into the deep ocean), if functional forms (9)-(11) are restricted to be quadratic-linear, Assumption 2 holds, and  $U'(0) = b < \infty$ , the global optimal path for the emission and ocean sequestration tax after  $t_s$  (final regime) is either monotonically increasing or U-shaped ( $A'(0) \geq A_{crit}$ ) or monotonically increasing ( $A'(0) < A_{crit}$ )*

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<sup>12</sup>We only consider control regimes with anthropogenic intervention into the global carbon cycle and do not consider a potential Regime 4 with  $q = a = 0$  ( $\theta_1 > 0$  and  $\theta_2 > 0$ ).

**Proof.** After point  $t_s$ , the optimal path is either determined by Regime 1 or Regime 3. We showed already in Propositions 1 and 2 that the optimal path is either monotonically increasing or U-shaped for Regime 1. For Regime 3, we see from (10),  $U'(a) - A'(a) = \pi$ , that only ocean sequestration tax paths that increase into the steady state fulfill the condition due to the concavity of the utility function and the convexity of the ocean sequestration cost function. We can therefore exclude paths that decrease into the steady state such as an inversely U-shaped path. Additionally, at  $t_s$ ,  $U'(a(t_s)) = \psi(t_s)$ ,  $U'(a(t_s)) - A'(a(t_s)) = \pi(t_s)$ , and  $q(t_s) = 0$  have to be fulfilled. We know from (12) that a U-shaped ocean sequestration tax requires a U-shaped emission tax for the transversality conditions to be fulfilled, (16). The decreasing emission tax  $\psi(t)$  on the U-shaped path contradicts  $q(t) = 0$  for  $t \in [t_s, t^*]$ , where  $t^*$  is defined by  $\dot{\psi}(t^*) = 0$  and  $\ddot{\psi}(t^*) > 0$ , because  $a(t)$  would be decreasing for  $t \in [t_s, t^*]$  due to the decreasing tax difference (see Proposition 2) and therefore the LHS in  $U'(a(t)) = \psi(t)$  would be increasing whereas the RHS would be decreasing. Consequently, if  $A'(0) < A_{crit}$  only monotonically increasing tax paths are possible for  $t \in [t_s, \infty]$ .  $\square$

Proposition 5 is only valid for  $t \in [t_s, \infty)$ . Before the point  $t_s$  is reached, various successions of regimes are possible, so that the possible set of optimal emission and ocean sequestration tax paths becomes more complex. Additionally, the dynamics in the regimes before the final regime are no longer determined by just the negative eigenvectors, but by the full set of eigenvectors. The reason for this is that the negative eigenvectors describe the optimal path towards the steady state corresponding to the regime (saddle path). However, in regimes prior to the final regime, the corresponding steady state is not feasible, and as a result the path towards such a non-feasible steady state cannot describe the optimal path towards the regime switching point.

#### 3.4. Utilizing ocean sequestration within a global carbon management strategy

Consider the situation where the initial values for atmospheric and oceanic carbon stocks,  $S_0$  and  $W_0$ , are low, the initial value for the fossil resource,  $R_0$ , fulfills Assumption 1, and the start-up costs for ocean sequestration are at least equal to the critical level,  $A'(0) \geq A_{crit}$ . In this situation, the optimal solution is completely described by Regime 1 for  $t \in [0, \infty)$ . The tax difference between the emission and ocean sequestration tax is never sufficient to bear the additional costs of ocean sequestration. The tax difference, which determines the amount of ocean sequestration,  $A'(a) = \psi - \pi$ , does not reach the critical level,  $A_{crit}$ , before the steady state, so that with  $A'(0) \geq A_{crit}$  ocean sequestration is not beneficial. Obviously, if the initial levels for the carbon stocks are low, there is no difference between ocean sequestration that is too costly ( $A'(0) \geq A_{crit}$  in Scenario 2) and ocean sequestration that is not available or prohibited (Scenario 1). We refer to this situation as Policy 1.

Consider the situation where the initial values for atmospheric and oceanic carbon stocks,  $S_0$  and  $W_0$ , are low, the initial value for the fossil resource stock,  $R_0$ , fulfills Assumption 2, and the start-up costs for

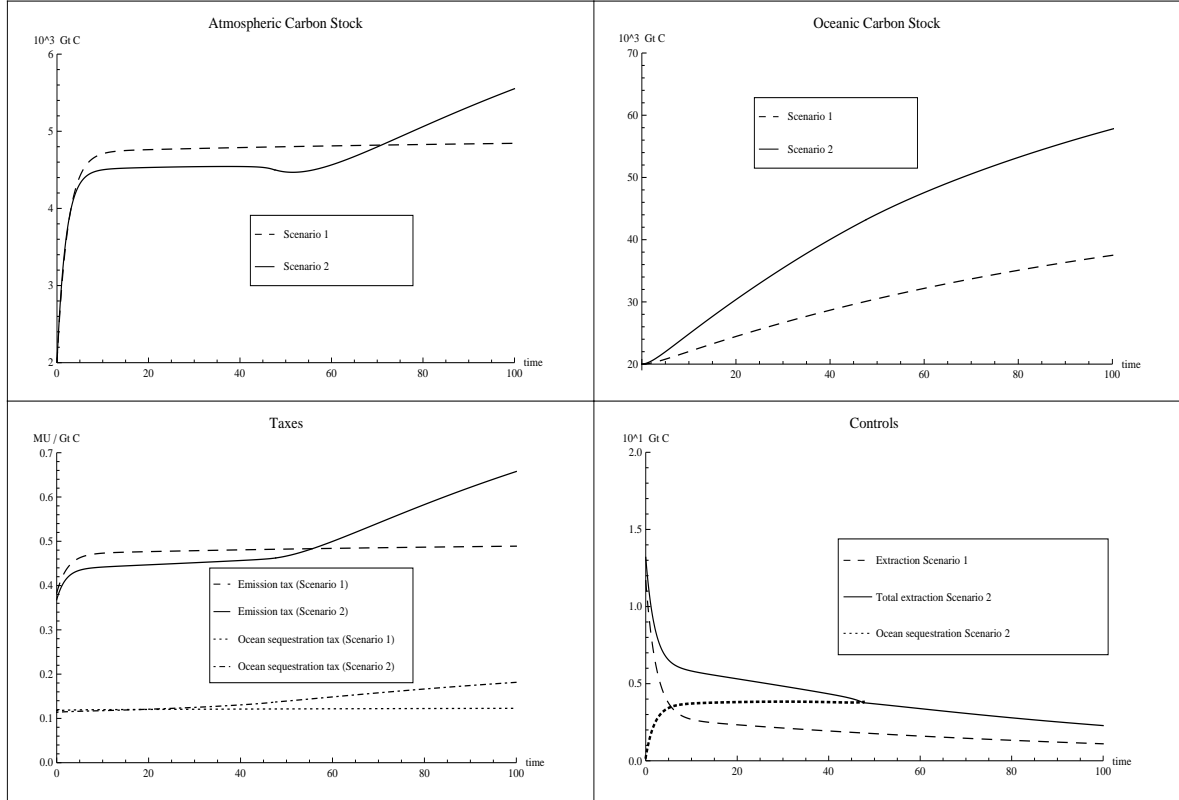


Figure 2: Dynamics for low initial atmospheric carbon stocks with constant extraction costs

ocean sequestration are below the critical level,  $A'(0) < A_{crit}$ . In this situation, the optimal solution might be described by a succession of various regimes, but each succession involves Regime 3 for  $t \in [t_s, \infty)$ . Even though a succession of various regimes is possible before  $t_s$ , the non-renewable description of the carbon cycle by the two-box model and the low initial levels imply tax paths that are increasing in direction towards  $t_s$ . Consequently, the tax difference will be at some point in time,  $t < t_s$ , above the start-up costs for ocean sequestration. Then it becomes beneficial to pay the ocean sequestration costs for some fraction of the emissions but to save the emission tax (Regime 1 to Regime 2). With the tax difference increasing into the steady state, the overall amount of fossil fuel consumption decreases, but the fraction of ocean sequestration for the related emissions increases. Consequently, at  $t_s$  the complete amount of emissions related to fossil fuel consumption is injected into the deep ocean (Regime 2 to Regime 3). We see that from  $t_s$  onwards, ocean sequestration is declining until  $b - \pi_\infty = A'(0)$  is fulfilled and that the emission tax increases above the choke price,  $b = \psi_{ss} - \theta_1$  with  $\theta_1 > 0$ . The increasing tax paths prevent backward regime switches, e.g., from Regime 2 to Regime 1. Consequently, if ocean sequestration is not too costly, more than one regime can occur in the optimal solution. We refer to this situation as Policy 2.

In Figure 2 we show the dynamics of the atmospheric and oceanic carbon stock, the emission and ocean

sequestration tax and the controls for Policy 1 and Policy 2 for low initial levels by using simple quadratic-linear functional forms.<sup>13</sup> Policy 2 shows the succession from Regime 2 to Regime 3. We see in the upper left graph that the atmospheric carbon stock increases slower in the beginning with Policy 2 than with Policy 1. With Policy 2 carbon emissions are not only released into the atmosphere but are also injected into the deep ocean, consequently, the oceanic carbon stock increases faster with Policy 2 than with Policy 1, where it only increases due to the natural carbon transfer (upper right graph). Due to a slower increase in atmospheric carbon concentration, fossil fuel consumption declines slower with Policy 2 than with Policy 1 (lower right graph). The fraction of ocean sequestration for the related carbon emissions increases until it reaches 100 percent and only fossil fuels which allow related carbon emissions to be captured and injected into the deep ocean are consumed. This occurs, before upper and lower box have equilibrated, which can be seen by a slight temporary decrease in the atmospheric carbon stock. However, in the long run, the atmospheric carbon concentration increases more with Policy 2 due to the extended use of the fossil resource and by a positive net transfer from the ocean to the atmosphere. Both taxes are increasing with Policy 2 in the long run above the levels which are obtained with Policy 1.

Even though we observe in Figure 2 with Policy 2 a switch from Regime 2 to Regime 3, the dynamics are not characterized by a significant increase in volatility. One reason for this is that the long-run dynamics are mainly influenced by the natural transfer parameters,  $\gamma$  and  $\omega$ , which are rather low in order to represent the inertia of the carbon cycle. Consequently, the eigenvalues have a different magnitude and the Hamiltonian dynamic system is rather stiff. To demonstrate this effect, in Figure 3 we again show Policy 1 and Policy 2 with a switch from Regime 2 to Regime 3, but this time with stock-dependent extraction costs included.<sup>14</sup> However, instead of the emission tax and the ocean sequestration tax we show in Figure 3 the difference between the two taxes. Due to the presence of stock-dependent extraction costs, the use of fossil fuels cannot be extended through ocean sequestration as it can in the case without stock-dependent extraction costs. Consequently, the atmospheric and oceanic stabilization levels are not affected by the magnitude as in Figure 2. Total fossil fuel consumption in Scenario 2 is rather similar to fossil fuel consumption in Scenario 1 and at some point in time even slightly lower (lower right graph). Note that even with rather similar paths for total fossil fuel consumption, the atmospheric peak concentration is significantly lower due to the presence of ocean sequestration (upper left graph). Additionally, we see that both the atmospheric carbon stock and tax difference show an inverted S-shape with Policy 2 and confirm that the inclusion of ocean sequestration extends the set of possible tax paths so far discussed in the literature. The influence of ocean sequestration

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<sup>13</sup>The utility function is  $U(q) = bq - u_2q^2$ , the ocean sequestration cost function is  $A(a) = a_1a + a_2a^2$ , and the damage function is  $D(S) = v_1(sS - A_{preind})^2$ . As a result of the linear-quadratic functional forms, the start-up costs,  $A'(0)$ , simplify to the parameter value  $a_1$ . The parameter values are  $b = 5/10$ ,  $\gamma = 1/10$ ,  $\omega = 1/10$ ,  $\rho = 3/100$ ,  $a_1 = 1/4$ ,  $a_2 = 1/10$ ,  $u_2 = 1/20$ ,  $v_1 = 0.1$ ,  $s = 3/10$ , and  $A_{preind} = 6/10$ ,  $S_0 = 2$ ,  $W_0 = 20$ . These parameter values yield  $a_{crit} = 3/8$  and  $R_{crit}^{A_2}(a_1) = 64.1667$ .

<sup>14</sup>The stock-dependent extraction cost function is  $c_1 - c_2 * R(t)$ , with the parameter values  $c_1 = 5/10$ ,  $c_2 = 1/200$ , and  $R_0 = 100$ . Note the parameter value for  $a_1$  has to be smaller than  $1/8$  in order to still observe a final Regime 3, because, with the stock-dependent extraction costs, the critical level for the start-up costs changes to  $A_{crit} = (b - C(R_\infty)) \frac{\rho}{\rho + \gamma\omega}$ .



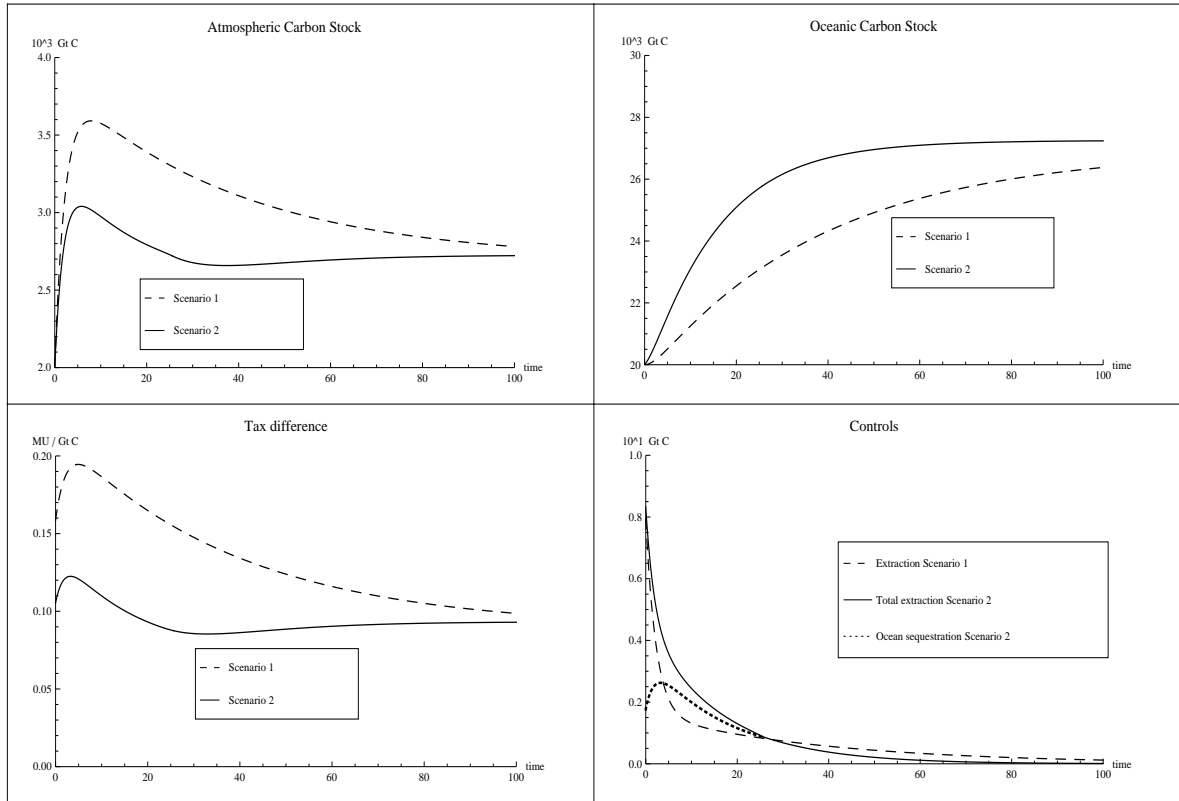


Figure 3: Dynamics for low initial atmospheric carbon stocks with stock-dependent extraction costs

on atmospheric peak concentration and also the possibility of an interior solution due to inversely U-shaped tax paths are investigated in Lontzek and Rickels (2008).

The situation where the initial values for the atmospheric carbon,  $S_0$ , stock is high, whereas the initial level of the oceanic carbon stock,  $W_0$ , is low and the initial value for the fossil resource stock,  $R_0$ , fulfills Assumption 2 remains to be briefly considered. In this situation, the optimal solution might be described by a succession of various regimes, even with  $A'(0) \leq A_{crit}$ . In contrast to the non-renewable atmospheric carbon stock models (e.g. Hoel, 1978; Farzin, 1996), the non-renewable two-box model allows periods of time where the atmospheric carbon stock is decreasing. A decreasing atmospheric carbon stock implies that the natural downward transfer into the deep ocean exceeds the amount of emissions released into the atmosphere. If the harmful carbon stock in the atmosphere is initially high, the emission tax starts at a high initial level so that only small amounts of emissions are released into the atmosphere and the atmospheric carbon stock can equilibrate with the oceanic carbon stock due to the natural transfer while the emission tax is declining. However, whereas high emission tax levels imply low extraction with related emissions released to the atmosphere, they favor the utilization of ocean sequestration for the related emissions. Consequently, given that the tax difference starts decreasing at a initial level that is higher than its steady state level,

$\lambda(t) > \lambda_\infty$  for  $t \in [0, t_a)$ , ocean sequestration is utilized if  $\lambda(t) \geq A'(0) \geq A_{crit} = \lambda_\infty$  for  $t \in [0, t_a)$  with  $t_a$  defined by  $\lambda(t_a) = \lambda_\infty$ .

If the start-up costs are above the critical level, ocean sequestration can only be utilized until  $t_a$ , thereafter the dynamics are again completely described by Regime 1. Consequently, if the initial levels for the atmospheric carbon stock are high, there is a difference between ocean sequestration that is too costly ( $A'(0) > A_{crit}$  in Scenario 2) and ocean sequestration that is not available or prohibited (Scenario 1). Even though ocean sequestration is not an option for the long-run management of the global carbon cycle because it is too costly, it might be beneficial to utilize ocean sequestration for some period of time for the consumption of fossil fuels if the atmospheric carbon stock is rather high, but the oceanic carbon stock is still rather low.

If the start-up costs are below the critical level, ocean sequestration will be utilized beyond  $t_a$ , but not necessarily as the only control option. If the emission tax decreases sufficiently along the U-shaped path, it might be beneficial to switch back to Regime 2 and release some of the emissions again to the atmosphere, or even switch further back to Regime 1 and release all of the emissions again into the atmosphere. However, as the atmospheric carbon stock will start increasing again at some point in time so will the emission tax and therefore the dynamic system will return to Regime 3 at  $t_s$  if  $A'(0) < A_{crit}$ .

Irrespective of the tax paths that are realized, the effectiveness of ocean sequestration in this two-box model depends crucially on generating utility by using fossil fuels while delaying the damage resulting from increased levels of carbon in the atmosphere. As a result, the effectiveness of sequestration depends on the time preferences and the adjustment times of the two boxes. The critical level,  $A_{crit}$ , is determined by the discount rate and the adjustment parameters of the two-box model. When the discount rate decreases, the critical level also decreases. As a result, the effectiveness of sequestration decreases because, with a lower discount rate, delaying damage pays off less. When  $\gamma$  and  $\omega$  decrease, the critical level increases. As a result, the effectiveness of sequestration increases because, with lower adjustment factors, the adjustment time of the two boxes decreases. A smaller value of  $\gamma$  implies a slower mixing of the two boxes. A smaller value of  $\omega$  implies a greater lower box, which in turn implies that the lower box can contain greater amounts of carbon. In the context of our two-box model, variations in the amount of carbon active in the lower box can be used to approximate various injection depths for ocean sequestration. A deeper injection depth goes along with a greater lower box and a slower adjustment process. Therefore, the effectiveness of ocean sequestration depends on the injection depth.

#### 4. Conclusions

In this paper, we investigated optimal intervention into the global carbon cycle. To capture the complete accumulation of carbon in the global carbon cycle, we included, besides the atmospheric carbon stock, the oceanic carbon stock in a two-box model representation. Using a two-box model to describe the global

carbon cycle does not in itself provide optimal atmospheric stabilization levels that are different from models with a partially non-renewable description of the atmospheric carbon stock. However, factoring in ocean sequestration may do so. Thus it is important to account for the amount of carbon that ‘decays’ by including the oceanic sink in the lower box. By doing so, we could show that ocean sequestration does not serve as a complete offset for a carbon emission tax, but has a price itself, an ocean sequestration tax. Furthermore, we clarified the implications of the non-renewable description of the carbon cycle and therefore also for the partial non-renewable description of the atmospheric carbon stock for the optimal tax paths.

By deriving the critical level for the start-up costs of ocean sequestration we could determine the role of ocean sequestration in a global carbon management strategy. For ocean sequestration start-up costs above this level, ocean sequestration is merely a temporary option given initial atmospheric carbon concentration is high; below this level, ocean sequestration is the long-term option permitting extended use of fossil fuels. The latter alternative accompanies higher atmospheric and oceanic stabilization levels.

Given a climate policy that formulates an atmospheric carbon stabilization goal, ocean sequestration cannot increase the total amount of fossil fuels that can be consumed. Carbon injected into the deep ocean in excess of the atmosphere-ocean equilibrium amount corresponding to the atmospheric stabilization goal is expected to leak back to the atmosphere, because the ocean becomes supersaturated in relation to the atmosphere. However, the option of ocean sequestration does extend the period of time in that fossil fuels can be extracted in reasonable amounts, whereas without ocean sequestration the amounts of extraction would have to decline much earlier due to the inertia of the carbon cycle. Consequently, ocean sequestration constitutes a serious option with which to buy time to deal with the atmospheric carbon accumulation problem. The effectiveness of this option depends on the injection depth of the sequestered carbon and the time preference of society.

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# Appendices

## Appendix A. Necessary and sufficient optimality conditions

For the two constraints,  $g_1(q, a) = -q \leq 0$  and  $g_2(g, a) = -a \leq 0$ , the constraint qualification is fulfilled, if the matrix

$$\begin{pmatrix} \frac{\partial g_1}{\partial q} & \frac{\partial g_1}{\partial a} & g_1 & 0 \\ \frac{\partial g_2}{\partial q} & \frac{\partial g_2}{\partial a} & 0 & g_2 \end{pmatrix} \quad (\text{A.1})$$

has the full row rank (Feichtinger and Hartl, 1986, p.161), which can be seen to be fulfilled from

$$\begin{pmatrix} -1 & 0 & -q & 0 \\ 0 & -1 & 0 & -a \end{pmatrix} \quad (\text{A.2})$$

The concavity of the maximized Hamiltonian follows from the negative semi-definiteness of the Hessian matrix of the Hamiltonian (Feichtinger and Hartl, 1986, Remark 2.4). For the calculation of the Hessian matrix we eliminate the state variable  $W(t)$  so that the carbon cycle equations (3) to (5) simplify to

$$\dot{S} = q - \gamma(S - \omega(S_0 + R_0 + W_0 - S - R)) \quad (\text{A.3})$$

$$\dot{R} = -q - a. \quad (\text{A.4})$$

Consequently, the Current Value Hamiltonian is  $H^c = U(q + a) - A(a) - D(S) + \mu_R \dot{R} - \psi_R \dot{S}$ , where the subscript  $R$  indicates the costate variables of the Redux system, and we can calculate the Hessian matrix:

$$\begin{pmatrix} H_{SS} & H_{SR} & H_{Sq} & H_{Sa} \\ H_{RS} & H_{RR} & H_{Rq} & H_{Ra} \\ H_{qS} & H_{qR} & H_{qq} & H_{qa} \\ H_{aS} & H_{aR} & H_{aq} & H_{aa} \end{pmatrix} = \begin{pmatrix} -D'' & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & U'' & U'' \\ 0 & 0 & U'' & U'' - A'' \end{pmatrix}, \quad (\text{A.5})$$

which has the eigenvalues

$$\sigma_{1,2,3,4} = \left( -D'', \frac{1}{2}(2U'' - A'' - \sqrt{4(U'')^2 + (A'')^2}), \frac{1}{2}(-U'' - A'' + \sqrt{4(U'')^2 + (A'')^2}), 0 \right). \quad (\text{A.6})$$

The Hessian matrix being negative semi-definite requires  $\sigma_{1,2,3,4} \leq 0$ . Taking into account our function properties,  $A'' > 0$ ,  $U'' < 0$ , and  $D'' > 0$ , the negativeness of the third eigenvalue can be see from:

$$A'' - 2U'' > \sqrt{(A'')^2 + 4(U'')^2}, \quad \text{and} \quad -4A''U'' > 0, \quad (\text{A.7})$$

whereas the first and second eigenvalue are obviously negative and the fourth eigenvalue is zero.

The regularity of the Hamiltonian follows from the strict concavity of the Hamiltonian in the control variables. The strict concavity can be seen from the lower right bloc matrix in the Hesse matrix (A.5), because the first leading principal minor is negative ( $U'' < 0$ ) and the determinant of the lower right bloc matrix is positive,  $-A''U'' > 0$ .

## Appendix B. Saddle path properties for Regime 1 and Regime 3

Following Dockner (1985, Theorem 3) the fulfillment of first  $K < 0$  and second  $0 < \text{Det}(MHDS) < (K/2)^2$  is necessary and sufficient for the eigenvalues to be real, two being negative and two being positive. *MHDS* abbreviates modified Hamiltonian dynamic system and  $K$  is defined as

$$K = \text{Det} \begin{pmatrix} \frac{\partial \dot{x}}{\partial x} & \frac{\partial \dot{x}}{\partial \lambda_x} \\ \frac{\partial \dot{\lambda}_x}{\partial x} & \frac{\partial \dot{\lambda}_x}{\partial \lambda_x} \end{pmatrix} + \text{Det} \begin{pmatrix} \frac{\partial \dot{y}}{\partial y} & \frac{\partial \dot{y}}{\partial \lambda_y} \\ \frac{\partial \dot{\lambda}_y}{\partial y} & \frac{\partial \dot{\lambda}_y}{\partial \lambda_y} \end{pmatrix} + 2\text{Det} \begin{pmatrix} \frac{\partial \dot{x}}{\partial y} & \frac{\partial \dot{x}}{\partial \lambda_y} \\ \frac{\partial \dot{\lambda}_x}{\partial y} & \frac{\partial \dot{\lambda}_x}{\partial \lambda_y} \end{pmatrix}, \quad (\text{B.8})$$

where  $x$ ,  $y$ ,  $\lambda_x$ , and  $\lambda_y$  denote state variables and the corresponding costate variables, respectively.

### Regime 1

The *MHDS* for Scenario 1 as well as for Regime 1 is, again based on the system with full rank and eliminated state variable  $W(t)$ , where the subscript  $R$  indicates the costate variables of the Redux system:

$$\begin{aligned} \dot{R} &= -q(\mu_R, \psi_R), \\ \dot{S} &= +q(\mu_R, \psi_R) - \gamma(S - \omega(S_0 + R_0 + W_0 - S - R)), \\ \dot{\mu}_R &= \rho\mu_R - \gamma\omega\psi_R, \\ \dot{\psi}_R &= (\rho + \gamma + \gamma\omega)\psi_R - D', \end{aligned} \quad (\text{B.9})$$

and the corresponding Jacobian is

$$J_{R1} = \begin{pmatrix} 0 & 0 & -q'_{\mu_R} & -q'_{\psi_R} \\ -\gamma\omega & -\gamma - \gamma\omega & q'_{\mu_R} & q'_{\psi_R} \\ 0 & 0 & \rho & -\gamma\omega \\ 0 & -D'' & 0 & \rho + \gamma + \gamma\omega \end{pmatrix}. \quad (\text{B.10})$$

We see that the determinate of  $\det(J_{R1}) = -\gamma^2\omega^2 D'' q'_{\mu_R} - \gamma\rho\omega D'' q'_{\psi_R}$  and  $K_{R1} = -\gamma(1 + \omega)(\rho + \gamma + \gamma\omega) + D'' q'_{\psi_R}$  fulfill the conditions  $K_{R1} < 0$  and  $\det(J_{R1}) > 0$ , because  $q'_{\mu_R} < 0$  and  $q'_{\psi_R} < 0$ . Additionally,  $\det(J_{R1}) < (K/2)^2$  is fulfilled, because

$$(K/2)^2 - \det(J_{R1}) = \gamma\omega D'' (\gamma\omega q'_{\mu_R} + \rho q'_{\psi_R} + \frac{1}{4}(\gamma(1 + \omega)(\rho + \gamma + \gamma\omega)) - D'' q'_{\psi_R})^2 > 0. \quad (\text{B.11})$$

*Regime 3*

The *MHDS* for Regime 3 is, again based on the system with full rank and eliminated state variable  $S(t)$ , where the subscript  $R$  indicates the costate variables of the Redux system:

$$\begin{aligned}
\dot{R} &= -a(\mu_R, \pi_R), \\
\dot{W} &= a(\psi_R, \pi_R) + \gamma(S_0 + R_0 + W_0 - R - W) - \gamma\omega W, \\
\dot{\mu}_R &= \rho\mu_R - \gamma\pi_R - D', \\
\dot{\pi}_R &= (\rho + \gamma\omega)\pi_R - D',
\end{aligned} \tag{B.12}$$

and the corresponding Jacobian is

$$J_{R3} = \begin{pmatrix} 0 & 0 & -a'_{\mu_R} & -a'_{\pi_R} \\ -\gamma & -\gamma\omega & a'_{\mu_R} & a'_{\pi_R} \\ D'' & D'' & 0 & -\gamma \\ D'' & D'' & 0 & \rho + \gamma\omega \end{pmatrix}. \tag{B.13}$$

We see that the determinate of  $\det(J_{R3}) = -\gamma\omega(\rho + \gamma + \gamma\omega)D''a'_{\mu_R}$  and  $K_{R3} = -\gamma(1 + \omega)(\rho + \gamma + \gamma\omega) + D''(a'_{\mu_R} + a'_{\pi_R})$  fulfill the conditions  $\det(J_{R3}) > 0$  and  $K_{R3} < 0$ , because  $a'_{\mu_R} < 0$  and  $a'_{\pi_R} < 0$ . Additionally,  $\det(J_{R1}) < (K/2)^2$  is fulfilled, if

$$\frac{1}{4}(\gamma(1 + \omega)(\rho + \gamma + \gamma\omega) - D''(a'_{\mu_R} + a'_{\pi_R}))^2 > -\gamma\omega(\gamma + \rho + \gamma\omega)D''a'_{\mu_R} \tag{B.14}$$

is fulfilled in the steady state. If (B.14) is not fulfilled, the saddle path property is not affected, but the eigenvalues are complex (Tahvonen, 1989).



## Part V

# The role of sequestration costs with a ceiling on atmospheric carbon concentration

Rickels, W. (2011), The role of sequestration costs with a ceiling on atmospheric carbon concentration, Kiel Working Paper 1702, Kiel Institute for the World Economy.

# The role of sequestration costs with a ceiling on atmospheric carbon concentration<sup>☆</sup>

## Abstract

I investigate the optimal role of carbon sequestration for mitigation in the presence of a ceiling on atmospheric carbon concentration and consider aspects that have so far only been analyzed in the context of a damage function to measure the consequences of climate change for society. I assume extraction costs to be stock-dependent, replace the proportional decay description of the global carbon cycle by a two-box model, investigate the differences resulting from linear versus convex sequestration costs, and consider oceanic instead of geological carbon storage. Using a two-box model allows the non-renewable aspects of the global carbon cycle to be accounted for and implies that carbon emissions have to decline at the ceiling due to the ongoing saturation of the ocean with anthropogenic carbon. Convex sequestration costs result in a continuous use of such a technology and allow the ceiling to be reached later than without sequestration, whereas linear sequestration costs result in a discontinuous use of such a technology and earlier reaching of the ceiling. Consequently, taking into the account the uncertainties in defining an appropriate ceiling, the policy recommendations with respect to carbon sequestration differ crucially according to the underlying assumptions of sequestration costs.

*Keywords:* atmospheric ceiling, global carbon cycle, ocean sequestration

*JEL:* Q30, Q54

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## 1. Introduction

Unhindered climate change implies the risk of catastrophic damage to society. Quantifying of this risk is complicated or even impossible due to our still limited understanding of the earth's climate system and in particular to the presence of tipping points in the climate system. Exceeding thresholds corresponding to such tipping points might involve sharp and non-linear changes in climate dynamics, determined intrinsically by the climate system and the feedback mechanisms involved. The location of such thresholds with respect to atmospheric carbon concentration or temperature increase and the degree of irreversibility of crossing such thresholds are still very uncertain (e.g., Lenton et al., 2008; Hoffmann and Rahmsdorf, 2009; Zickfeld et al., 2010). With respect to these uncertainties, countries agreed to limit temperature increase to 2°C as it has again been confirmed at the recent global warming summit in Cancun (UNFCCC, 2010). This temperature increase limit can be converted to a ceiling on atmospheric carbon concentration or a cumulative budget for carbon emissions into the atmosphere (Meinshausen et al., 2009).

Actual greenhouse gas emission (GHG) trends and corresponding reduction announcements challenge the credibility of this target. Furthermore, postponement of the necessary emission reductions implies increasing mitigation costs.<sup>1</sup> However, this target or the corresponding corresponding ceilings can still be met if substantial emission cuts are made. To achieve these emissions cuts, in addition to improving energy efficiency and making increased use of renewable energies, increased carbon sequestration, i.e. carbon capture and storage, within energy consumption is expected to be necessary (IEA, 2010).

The optimal global role of carbon sequestration for mitigation in the presence of a ceiling on atmospheric carbon concentration has so far mainly been analyzed quantitatively by numerous integrated assessment models that consider various atmospheric stabilization levels (e.g., Gerlagh and van der Zwaan, 2006; Azar et al., 2006; van der Zwaan and Gerlagh, 2009; Lemoine et al., 2011). The theoretical literature related to carbon sequestration addresses the problem of increasing atmospheric carbon concentration primarily by a damage function that measures the related consequences of climate change for society. As pointed out above, it is obviously difficult to determine or agree on such a damage function. Theoretical implications of imposing a ceiling on atmospheric carbon concentration while carbon emissions can be sequestered have been studied first of all by Chakravorty et al. (2006) and Lafforgue et al. (2008). Chakravorty et al. investigate the implication of a ceiling while energy consumption is provided by fossil fuels and a clean backstop technology. Additionally, in their model it is possible to reduce fossil-fuel-related carbon emissions to the atmosphere by costly abatement. However, there is little potential to abate carbon emissions once fossil fuels have been combusted, implying that abatement implies sequestration but without any scarcity related to potential storage sites. This has been further investigated by Lafforgue et al.. They consider geological

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<sup>1</sup>The rather moderate emission reductions in the Copenhagen Accord until 2020 are estimated to cost an additional 1 trillion USD of investment costs in the period from 2010 to 2035 compared to a more efficient mitigation path (IEA, 2010).

carbon sequestration into a single reservoir or multiple reservoirs where carbon storing capacity is limited. Chakravorty et al. and Lafforgue et al. find that sequestration only takes place in a discontinuous manner once the ceiling has been reached and the availability of sequestration determines endogenously the period when the ceiling is binding.<sup>2</sup> Both papers assume extraction and sequestration units costs to be constant, describe the global carbon cycle by proportional decay of atmospheric carbon, and consider geological carbon storage. In this paper, I take a closer look at these assumptions and clarify the implications of four relevant aspects related to the issue: the implications of stock-dependent extraction cost, (2) the implications of modeling the global carbon cycle with a two-box model instead of a proportional decay, (3) the implications of modeling sequestration costs convexly rather than linearly, and (4) the implications of oceanic instead of geologic carbon storage.

Extraction costs are expected to be determined not only by the extraction rate, but also by the stock of fossil resource left in the ground. Decreasing resource availability in existing deposits and exploitation of economically less favorable deposits might be reflected by increasing marginal costs for a given rate of extraction (Farzin, 1992). The recoverable amount of the resource might therefore not be determined by geological constraints but by economic costs and the opportunity costs of backstop technologies (e.g., Farzin, 1992; Epple and Londregan, 1993; Farzin, 1996).

Furthermore, the carbon fluxes in the global carbon cycle are only roughly approximated by the proportional decay of carbon in the atmosphere that implies that the atmospheric carbon storing capacity is a renewable resource. The dimension and length of the anthropogenic disturbances to atmospheric carbon concentration is, besides the carbon emission path, mainly influenced by oceanic carbon uptake (e.g., Najjar, 1992; Sabine et al., 2004). Oceanic carbon uptake is estimated to increase disproportionately with increasing atmospheric carbon concentration as the buffer capacity declines (e.g., Sarmiento et al., 1995).<sup>3</sup> Even though uptake is currently mainly limited by kinetic constraints implied by the slow mixing of surface waters with the deep ocean (e.g., Sarmiento and Gruber, 2006), it is important to note that a renewable description of the atmospheric carbon concentration overestimates the storing capacity of the global carbon cycle on timescales reasonable to mankind. Consequently, a proportional decay description oversimplifies the atmospheric carbon accumulation problem (Farzin and Tahvonen, 1996; Rickels and Lontzek, 2011).

The IPCC (2005) special report on carbon dioxide capture and storage provides cost ranges for carbon sequestration. The ranges indicate that sequestration costs vary by differences in the design of carbon capture systems and by differences in the operating and financing of the reference plant to which the capture technology is applied. Additionally, their estimates show that the costs increase as the transportation

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<sup>2</sup>Chakravorty et al. (2006) distinguishes in his analysis between decreasing, constant, and increasing demand for energy. For the first two assumptions, abatement takes place at the beginning of the ceiling, for the latter assumption at the end of the ceiling.

<sup>3</sup>Note the buffer capacity should not be confused with the buffer or Revelle factor, as the latter measures the ratio of the change in atmospheric carbon concentration to the change in oceanic carbon concentration,  $\frac{\partial \ln pCO_2}{\partial \ln DIC}$ , and is therefore increasing with anthropogenic carbon perturbation (Sarmiento and Gruber, 2006).

distance on land and on sea increases. By assuming that increasing the amount of carbon capture implies that this technology has also to be applied to less efficient plants and plants that are located farther from storage sites or the shore, the sequestration costs are expected to increase in a convex manner. This is also usually assumed in quantitative analyses, like Gerlagh and van der Zwaan (2006), who assume carbon sequestration to be described by an effort variable which is assumed to be a second-order polynomial function.

The captured carbon can be stored in geological formations like depleted oil fields or saline formations (IPCC, 2005). However, it could also be injected into the deep ocean via pipelines or ships (Marchetti, 1977; IPCC, 2005). As pointed out above, the ocean uptake is not linear, but it is expected that on timescales of several hundred years it will take up about 80 percent of the anthropogenic carbon emitted to the atmosphere (e.g., Archer et al., 1997; Körtzinger and Wallace, 2002; Sarmiento and Gruber, 2006). Consequently, when this fraction of anthropogenic carbon enters the deep ocean, is just a matter of time. Even though currently implicitly prohibited by the London protocol,<sup>4</sup> deep ocean sequestration would be an option to accelerate this process by overcoming kinetic constraints (Keeling, 2009). With respect to the overall carbon storage capacity of the ocean, there are practically no physical limits to oceanic carbon sequestration. However, carbon injected into the deep ocean in excess of the atmosphere-ocean equilibrium amount corresponding to the atmospheric stabilization goal is expected to leak back into the atmosphere, because the ocean will become supersaturated in relation to the atmosphere (IPCC, 2005).

Even though there are further papers that analyze the implications of a ceiling on atmospheric carbon, none of these papers addresses the issue from the perspective used by Chakravorty et al. (2006) and Lafforgue et al. (2008). The papers of Chakravorty et al. (2008) and Smulders and van der Werf (2008) focus on the order of extraction of two fossil fuel resources when these differ with respect to their related carbon emissions. Henriët (2010) focuses on the role of the backstop price and the optimal R&D effort to develop a backstop technology. Dullieux et al. (2010) focus on the strategic interaction between consumers, who set the carbon tax to comply with the ceiling, and fossil fuel producers, who respond by adjusting the fossil fuel prices. However, none of these papers includes carbon sequestration. Hoel and Jensen (2010) focus on the strategic implications involved in carbon sequestration by analyzing its implications in a two-stage decision problem. Amigues et al. (2010) extend the model of Chakravorty et al. (2006) by including stock-dependent extraction costs and the possibility of air capture. They analyze the optimal solution from a decentralized perspective by assuming two different sectors that are distinguished by the availability of abatement options and costs related to these options. They show that abatement can take place before the ceiling has been reached in the sector with the lower abatement costs. However, their result originates from the decentralized perspective

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<sup>4</sup>Paragraph 1.8 in Appendix 1 of the London Protocol allows dumping of “Carbon dioxide streams from carbon dioxide capture processes for sequestration”. However, this is restricted by paragraph 4: “Carbon dioxide streams referred to in paragraph 1.8 may only be considered for dumping, if: (1) disposal is into a sub-seabed geological formation; and (2) they consist overwhelmingly of carbon dioxide. They may contain incidental associated substances derived from the source material and the capture and sequestration processes used; and (3) no wastes or other matter are added for the purpose of disposing of those wastes or other matter.”

and not from the curvature of the related costs, as those are again assumed to be linear. All the papers assume proportional atmospheric carbon decay, except Dullieux et al. (2010) and Hoel and Jensen (2010), who assume no natural decay at all.<sup>5</sup>

The present paper is structured as follows. In Section 2, I explain the optimization problem involved in using fossil fuels and a clean backstop-technology, while extraction costs are stock-dependent. Furthermore, I explain the description of the global carbon cycle using a two-box model. In Section 3 I show the results. Section 3.1 provides the general conditions for the optimal solution. Section 3.2 analyzes first the simple extraction-backstop decision and shows then that the description of the global carbon cycle using a two-box model implies declining carbon emissions at the ceiling. Consequently, it is possible to observe the simultaneous use of fossil fuels and the clean backstop technology from some point at the ceiling onwards even if carbon sequestration is not available. Section 3.3 shows first the difference between convex and linear sequestration costs by using the proportional decay description for the global carbon cycle. Whereas linear sequestration costs imply that the ceiling is reached earlier than without sequestration, convex sequestration costs allow the ceiling to be reached later. Additionally, convex sequestration costs imply that such a technology is used in a continuous manner. Then I show that ocean sequestration allows the kinetic constraints of oceanic carbon uptake to be overcome and that, even though the storage capacity of the ocean is not scarce in and of itself, the ongoing saturation of the global carbon cycle determines the optimal amount of sequestration. Finally, I present a numerical example to demonstrate the dynamics of the simple extraction-backstop decision while atmospheric carbon concentration is limited with a ceiling and how the dynamics change if ocean sequestration is included. In doing so, I distinguish whether sequestration costs are linear or convex. Section 4 concludes.

## 2. Two-box model with oceanic carbon storage and ceiling

I investigate the dynamic global optimal sequestration decision in the presence of a ceiling on atmospheric carbon stock as a social planner's problem where the social rate of discount is assumed to be positive and constant. The optimal sequestration decision is embedded in the decision regarding the global optimal energy consumption. Energy consumption is composed of fossil-fuel-based energy,  $x(t)$ , and non-fossil-fuel-based energy like solar or wind power,  $y(t)$ , which I denote as backstop technology. The total amount of energy consumption,  $x(t) + y(t)$ , generates gross utility in the social welfare function at any instant in time. Gross utility is described by  $U(x(t) + y(t))$  and is assumed to have the properties

**Assumption 1.**  $U' > 0$ ,  $U'' < 0$ .

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<sup>5</sup>Smulders and van der Werf (2008) assume a ceiling for the flow of emissions and abstract therefore from atmospheric carbon accumulation. Note that a ceiling on the flow of emissions, e.g.,  $\bar{q}$ , implies an atmospheric carbon stock with proportional decay, e.g.,  $-\beta S(t)$ , where the emission flow ceiling is equal to natural decay, so that  $\bar{q} = \beta S(t)$ .

The extraction of fossil fuels generates extraction costs at any instant in time which are assumed to depend on the resource stock  $R(t)$  and the extraction cost function  $C(R)$  is assumed to have the property

**Assumption 2.**  $C'(R) < 0$ ,

so that extraction costs increase with the rate of exploitation of the available resource resource stock:<sup>6</sup>

$$\dot{R} = -x(t) \quad \text{with} \quad R(t_0) = R_0. \quad (1)$$

Following Chakravorty et al. (2006) and Lafforgue et al. (2008), I assume that the backstop technology has constant unit costs  $c_y$  and can be provided at an extent such that  $U'(y(t)) = c_y$  with  $y(t) = \bar{y} > 0$  is feasible at each point in time. Due to the presence of a backstop technology with the constant unit costs  $c_y$ , there is no need to specify whether the utility function satisfies the Inada condition or entails a choke price,  $U'(0) = b < \infty$ , as long as  $b > c_y$ . With respect to the constant unit costs of the backstop technology, I assume

**Assumption 3.**  $R_0 > C^{-1}(c_y)$ ,

because otherwise energy consumption would only be provided by the backstop technology. In Section 3.2, I investigate this basic extraction-backstop optimization problem and refer to it as Scenario *Ext*.

The proportional amount of carbon emissions related to fossil fuels consumption (the proportionality factor is assumed to be one) increases the amount of carbon in the atmosphere and therefore in the global carbon cycle. The global carbon cycle is represented by a two-box model, where the upper box  $S(t)$  entails the sum of the carbon stock in the atmosphere and the upper ocean and the lower box  $W(t)$  entails the carbon stock in the deep ocean:

$$\dot{S} = x(t) - \gamma(S(t) - \omega W(t)) \quad \text{with} \quad S(t_0) = S_0, \quad (2)$$

$$\dot{W} = \gamma(S(t) - \omega W(t)) \quad \text{with} \quad W(t_0) = W_0. \quad (3)$$

The atmospheric carbon stock is assumed to be a constant fraction of  $S(t)$ .<sup>7</sup> In the equations of motion for the upper and lower box, (2) and (3), the amounts  $\gamma S(t)$  and  $\gamma \omega W(t)$  represent the natural fluxes between the boxes, which amount to a net transfer if there is a difference between the relative stock sizes, e.g.,  $S(t) > \omega W(t)$ . Consequently, an increase in the atmospheric carbon concentration and therefore an

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<sup>6</sup>An alternative formulation would be to model extraction costs to be increasing in the cumulative amount of fossil fuels extracted:  $C(X)$  with  $C' > 0$ , while  $X(t) = \int_0^t q(\tau) d\tau$  (Farzin, 1992).

<sup>7</sup>There is a net transfer of carbon between the atmosphere and the upper mixed layer of the ocean if there is a difference in the partial pressure of carbon dioxide ( $p\text{CO}_2$ ) between these two reservoirs. It takes around one year for the upper layer of the ocean to equilibrate with the atmosphere. Consequently, I assume that the atmosphere and the upper mixed layer are always in equilibrium and focus on the transport of anthropogenic carbon to the deeper parts of the ocean, which is the limiting factor of oceanic carbon uptake.

increase in the carbon stock in the upper box causes a net downward transfer of excess carbon into the deep ocean because up-welling water is still free of excess anthropogenic carbon. The deep ocean saturates with anthropogenic carbon only at the rate  $\omega$  because anthropogenic carbon reacts with carbonate ions to bicarbonate ions. Consequently, the term inside the parenthesis of the net exchange can be interpreted as a simplified representation of the chemical reactions caused by the uptake of anthropogenic carbon by the ocean.<sup>8</sup> The parameter  $\gamma$  represents the kinetic constraint, as it measures the speed of the adjustment process. Taking into account the inertia of the carbon cycle with respect to the carbon exchange with the deep ocean, realistic initial values are restricted to satisfy  $S_0 \geq \omega W_0$ . For simplicity I impose

**Assumption 4.**  $S_0 = \omega W_0$ .

Even though the two-box model is a very simple representation of the global carbon cycle, it allows a more appropriate description of the inertia and the non-renewable aspects of the global carbon cycle than the proportional-decay description does. A more detailed description of this two-box model can be found in Rickels and Lontzek (2011), where it is also shown that the two-box model does not provide any advantages in itself compared to modeling the atmospheric carbon stock as a partially renewable resource, as is done in Farzin and Tahvonen (1996), but becomes indispensable if options like ocean sequestration are considered. An overview of such box models used to represent the dynamics of the global carbon cycle can be found in Sarmiento and Gruber (2006). Even though the carbon stock in the upper box entails atmospheric and oceanic carbon, I refer to it as the atmospheric carbon stock and to the carbon stock in the lower box as the oceanic carbon stock. If we abstract from the ongoing saturation of the ocean with anthropogenic carbon, the oceanic uptake would only be limited by the kinetic constraint and we would regain the proportional decay description as used by Chakravorty et al. (2006) and Lafforgue et al. (2008):  $\dot{S} = x(t) - \gamma_d S(t)$ , implying that all anthropogenic carbon will be taken up by the ocean in the long run,  $\dot{W} = \gamma_d S(t)$ . The subscript  $d$  indicates that the parameter value does not necessarily coincide in the two-box model and the proportional decay description because in the latter the initial value of  $S$  is normalized to represent the deviation from its preindustrial level.

Further, I assume that society has agreed on that atmospheric carbon concentration should not exceed a certain ceiling:

**Assumption 5.**  $\bar{S} \geq S(t)$  for  $t \in (0, \infty)$  with  $\bar{S} > S_0$ .

In Section 3.2, I investigate in the Scenario *Ceil* how the basic extraction-backstop optimization problem changes in the presence of a ceiling on atmospheric carbon concentration when the global carbon cycle is described by the two-box model.

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<sup>8</sup>I abstract from chemical reactions with the sediments and chemical reactions due to enhanced weathering. These reactions operate on timescales of 1000 to 100 000 years and are assumed to be beyond the economic optimization horizon due to discounting.



Additional to releasing carbon emissions into the atmosphere, I assume that these emissions can also be captured and injected into the deep ocean for purposes of ocean sequestration. I subdivide the total amount of fossil fuels extracted into those with related emissions released into the atmosphere  $q(t)$  and those with related emissions captured and injected into the deep ocean  $a(t)$ , so that  $x(t) = q(t) + a(t)$  with  $q(t), a(t) \geq 0$ .<sup>9</sup>

Ocean sequestration generates additional costs in the social welfare function at any instant in time. These costs are assumed to be described by  $A(a(t))$  and summarize the costs of carbon capture in energy generation, transportation of carbon to the shore, and injecting it via pipelines or ships into the deep ocean. I distinguish two cases for the properties of  $A(a(t))$ :

**Assumption 6.** *Case C:  $A' = a_c$  and Case X:  $A' > 0, A'' > 0$ .*

The costs are measured in the same units as utility. In Section 3.3, I investigate the optimal sequestration decision for both cases when the global carbon cycle is described either by proportional decay or the two-box model. With the former description, this model version coincides with the one used by Chakravorty et al. (2006) apart from stock-dependent extraction costs. Even though Chakravorty et al. refer to the control variable  $a(t)$  as abatement, it should be noted that there exist literally no abatement measures for fossil-fuel-related carbon emissions once the fossil fuels have been combusted.<sup>10</sup> Consequently, abatement in this context can be interpreted as sequestration without scarcity of the carbon storing facility. I refer to the two scenarios with the proportional decay description as *AC* and *AX*, and to the two scenarios with the two-box model description as *SeqC* and *SeqX*.

### 3. Results

#### 3.1. Optimal solution conditions

The social welfare function can be formalized as follows:

$$\begin{aligned} \max_{q(t), a(t), y(t)} \int_0^{\infty} (U(q(t) + a(t) + y(t)) - C(R(t))(q(t) + a(t)) - A(a(t)) - c_y y(t)) e^{-\rho t} dt, \quad (4) \\ \text{with } q(t), a(t), y(t) \geq 0, \quad (5) \end{aligned}$$

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<sup>9</sup>Note that I could also apply the control variables  $x(t)$  and  $a(t)$  instead of  $q(t)$  and  $a(t)$ , which would imply that only the net emissions  $x(t) - a(t)$  would be released into the upper box and the resource stock would decrease by  $x(t)$ . In doing so, I would retain the model description of Chakravorty et al. (2006) and Lafforgue et al. (2008), where it becomes necessary to include the additional control constraints  $x(t) - a(t) \geq 0$  if you do not want to consider the possibility of air capture.

<sup>10</sup>With respect to abatement the variable  $a(t)$  could also be interpreted as costly additional efficiency gains, so that the amount of energy provided by  $q(t)$  increases to  $q(t) + a(t)$ . A more profound description of this interpretation would be  $a(t)q(t)$ , with  $a(t) \in (a_{BAU}, a_{max})$ , where an increase in energy efficiency to above its business-as-usual (BAU) level would be associated with additional costs.

where  $\rho$  is the constant social rate of discount and the dynamic and state variable constraints are given by

$$\dot{S} = q(t) - \gamma S(t) - \gamma\omega W(t) \quad \text{with} \quad S(t_0) = S_0, \quad (6)$$

$$\dot{W} = a(t) + \gamma S(t) - \gamma\omega W(t) \quad \text{with} \quad W(t_0) = W_0, \quad (7)$$

$$\dot{R} = -q(t) - a(t) \quad \text{with} \quad R(t_0) = R_0, \quad (8)$$

$$S(t) \leq \bar{S}. \quad (9)$$

If the carbon cycle is described using the proportional decay description, the term  $\gamma\omega W(t)$  drops out in (6) and (7) and  $\gamma$  is replaced by  $\gamma_d$ . From now on, I drop the time variable whenever it is convenient and the optimization problem described in (4) to (9) leads to the corresponding current value Lagrangian

$$L_c = U(q+a+y) - A(a) - C(R)(q+a) - c_y y - \lambda_R \dot{R} - \lambda_S \dot{S} - \lambda_W \dot{W} - \theta_1(-q) - \theta_2(-a) - \theta_3(-y) - \theta_4(S(t) - \bar{S}), \quad (10)$$

where

$$\lim_{t \rightarrow \infty} R(t) \geq 0, \quad \lim_{t \rightarrow \infty} S(t) \geq 0, \quad \lim_{t \rightarrow \infty} W(t) \geq 0. \quad (11)$$

I have changed the signs of the costate variables,  $\lambda_S$  and  $\lambda_W$ , in order to facilitate their economic interpretation as taxes. According to Proposition 6.2 and Propostion 7.5 in Feichtinger and Hartl (1986), the admissible solution has to fulfill the necessary conditions

$$\frac{\partial L_c}{\partial q} = 0 \quad \Rightarrow \quad U' - C(R) - \lambda_R - \lambda_S + \theta_1 = 0, \quad (12)$$

$$\frac{\partial L_c}{\partial a} = 0 \quad \Rightarrow \quad U' - C(R) - A' - \lambda_R - \lambda_W + \theta_2 = 0, \quad (13)$$

$$\frac{\partial L_c}{\partial y} = 0 \quad \Rightarrow \quad U' - c_y + \theta_3 = 0, \quad (14)$$

$$-\frac{\partial L_c}{\partial R} = \dot{\lambda}_R - \rho\lambda_R \quad \Rightarrow \quad C'(R)(q+a) = \dot{\lambda}_R - \rho\lambda_R, \quad (15)$$

$$-\frac{\partial L_c}{\partial S} = -\dot{\lambda}_S + \rho\lambda_S \quad \Rightarrow \quad \gamma\lambda_S - \gamma\lambda_W - \theta_4 = \dot{\lambda}_S - \rho\lambda_S, \quad (16)$$

$$-\frac{\partial L_c}{\partial W} = -\dot{\lambda}_W + \rho\lambda_W \quad \Rightarrow \quad -\gamma\omega\lambda_S + \gamma\omega\lambda_W = \dot{\lambda}_W - \rho\lambda_W, \quad (17)$$

$$\frac{\partial L_c}{\partial \theta_1} \geq 0 \quad \theta_1 \geq 0 \quad \theta_1(-q) = 0, \quad (18)$$

$$\frac{\partial L_c}{\partial \theta_2} \geq 0 \quad \theta_2 \geq 0 \quad \theta_2(-a) = 0, \quad (19)$$

$$\frac{\partial L_c}{\partial \theta_3} \geq 0 \quad \theta_3 \geq 0 \quad \theta_3(-y) = 0, \quad (20)$$

$$\frac{\partial L_c}{\partial \theta_4} \geq 0 \quad \theta_4 \geq 0 \quad \theta_4(S - \bar{S}) = 0, \quad (21)$$

and also the transversality conditions<sup>11</sup>

$$\lim_{t \rightarrow \infty} e^{-\rho t} \lambda_R R = 0, \quad \lim_{t \rightarrow \infty} e^{-\rho t} \lambda_S = 0, \quad \lim_{t \rightarrow \infty} e^{-\rho t} \lambda_W = 0, . \quad (22)$$

Given the necessary conditions (12) to (22) are fulfilled, the solution is optimal because the control constraints fulfill the constraint qualification (see Appendix A) and are quasi-concave, because the equations of motion are described by linear equations and because the maximized Hamiltonian is concave in the state variables (see Appendix A)(Feichtinger and Hartl, 1986, p.181, Proposition 7.5). Given the optimization problem did not entail the backstop technology  $y$  and sequestration costs had the properties according to Case  $X$  in Assumption 6, the Hamiltonian would be strictly concave in the control variables (see Appendix A), which implies that the control variables are continuous (Feichtinger and Hartl, 1986, p.167, Corollary 6.2). Without this restriction, jumps in the controls variables can be observed when using sequestration (Case  $C$ ) and switching to the backstop technology. Even though there can be jumps in the control variables, the costate variables are continuous if the ceiling constraint for the atmospheric carbon stock is not just tangentially approached (Feichtinger and Hartl, 1986, p.168, Corollary 6.3).

Note the equations of motion (6) to (8) constitute a closed system, so that ,e.g., a decrease in the resource stock must be balanced by an equivalent increase in the atmospheric and oceanic carbon stock,  $\dot{S} + \dot{W} + \dot{R} = 0$ . Therefore, it is possible to reduce the system by replacing one of the state variables. I refer to such a reduced system as a *Redux* <sup>$X$</sup>  system, where the superscript indicates the dropped state variable. If the oceanic carbon stock has been excluded, the equation of motions for *Redux* <sup>$W$</sup>  would read as follows:

$$\dot{R}^W = -q - a, \quad (23)$$

$$\dot{S}^W = q - \gamma(S - \omega(K_0 - S - R)), \quad (24)$$

where  $K_0$  is the sum of the initial values of the stock variables  $K_0 = S_0 + W_0 + R_0$ . In the *Redux* <sup>$X$</sup>  system the corresponding costate variable  $\lambda_X$  vanishes and the remaining two costate variables then also measure the influence of the omitted state variable on the objective function.

### 3.2. Stock-dependent extraction costs and the two-box model

I consider first the implications of our model without the option of oceanic carbon storage to clarify the implications of stock-dependent extraction costs and the two-box model description of the global carbon cycle. However, independent of the carbon cycle representation, without a ceiling on the atmospheric carbon

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<sup>11</sup>As any admissible path for the state and costate variables is non negative and as any admissible path for the state variables is bounded due to the description of the carbon cycle as a closed system, the fulfillment of the transversality conditions, (22), is sufficient for the fulfillment of the general transversality conditions in a infinity horizon problem (Feichtinger and Hartl, 1986, Remark 2.9 and Remark 7.5).

stock in Scenario *Ext*, the optimization problem reduces to the simple extraction-backstop decision. The optimal solution is determined by the stock-dependent extraction costs  $C(R)$ , the shadow resource scarcity rent  $\lambda_R$ , and the constant price of the backstop technology  $c_y$ . As atmospheric or oceanic carbon stocks do not affect the objective function, the corresponding costate variables  $\lambda_S$  and  $\lambda_W$  are zero.<sup>12</sup> The marginal costs for fossil fuel extraction are increasing whereas the marginal costs of using the backstop technology are constant. Consequently, fossil fuels and backstop technology are not used simultaneously (e.g., Dasgupta and Heal, 1979). From Assumption 3 follows that there will be first a period when energy consumption is only provided by fossil fuels. The dynamics are described by

$$\dot{q} = \frac{\rho(U' - C(R))}{U''}, \quad (25)$$

$$\dot{R} = -q, \quad (26)$$

indicating that both  $q$  and  $R$  are monotonically decreasing until  $q = \bar{y}$ . At this point in time fossil fuel extraction drops to zero and energy consumption switches to the backstop technology for  $t \in (t_b, \infty)$  where  $t_b$  denotes the switching point. As shown by Farzin (1996), the inclusion of stock-dependent extraction costs changes the behavior of the shadow scarcity rent and the total amount of fossil fuel extraction, which is summarized in the context of our model in the presence of a backstop technology in the following proposition.

**Proposition 1.** *If  $C(0) \geq c_y$  and Assumption 3 holds,  $R(t_b) = R_\infty \geq 0$ , and  $\lambda_R(t_b) = 0$ , with  $\dot{\lambda}_R < 0$  for  $t \in (0, t_b)$ , and  $\dot{\lambda}_R = 0$  for  $t \in (t_b, \infty)$ . If  $C(0) < c_y$  and Assumption 3 holds,  $R(t_b) = 0$ ,  $\lambda_R(t_b) = c_y - C(0)$ , with  $\dot{\lambda}_R < 0$  for  $t \in (0, t_b)$ , and  $\dot{\lambda}_R > 0$  for  $t \in (t_b, \infty)$ .*

**Proof.** At the switching point  $t_b$ , the marginal costs for extraction and the backstop technology have to be equal. Any solution including  $C(R(t_b)) + \lambda_R(t_b) = c_y$  cannot be optimal because a lower  $\lambda_R(t_b)$  would allow  $q(t_b) > \bar{y}$ , so that the objective could be raised by increasing  $t_b$ . Consequently,  $\lambda_R$  is decreasing until either  $C(R(t_b)) = c_y$  with  $\lambda_R(t_b) = 0$  or until  $R(t_b) = 0$  with  $\lambda_R(t_b) = c_y - C(0)$ . The closed form solution for  $\lambda_R$  is

$$\begin{aligned} C(0) \geq c_y \quad \lambda_R(t) &= \int_{t_b}^t C'(R(\tau))q(\tau)e^{-\rho(\tau-t)}d\tau, \\ C(0) < c_y \quad \lambda_R(t) &= (c_y - C(0))e^{-\rho(t_b-t)} + \int_{t_b}^t C'(R(\tau))q(\tau)e^{-\rho(\tau-t)}d\tau, \end{aligned} \quad (27)$$

which shows that the transversality condition  $\lim_{t \rightarrow \infty} e^{-\rho t} \lambda_R R = 0$  is fulfilled because

either  $\lambda_R(t_b) = \lambda_R(t)_{t \rightarrow \infty} = 0$  or  $R_\infty = 0$ . □

In contrast to Chakravorty et al. (2006) and Lafforgue et al. (2008), the shadow scarcity rent is declining

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<sup>12</sup>This can also be seen from the closed-form solution for  $\lambda_S$  in, e.g., the *Redux<sup>W</sup>* system:  $\lambda_S^W(t) = \lambda_{S0}e^{(\gamma+\gamma\omega+\rho)t}$ . If the initial level  $\lambda_{S0}$  is positive, the transversality condition would be violated because  $\theta_4$  is zero due to the non existent ceiling and  $\lim_{t \rightarrow \infty} \lambda_S(t) = \infty$ .

and the fossil fuel stock is not necessarily entirely extracted because extraction costs are modeled as stock-dependent. Moreover, the possibility that  $C(0) < c_y$  is more a theoretical concept, as it implies that extraction costs are still below the cost of the backstop technology when fossil fuel stocks are completely depleted. The more reasonable concept seems to be  $C(0) > c_y$  so that the amount of the economic recoverable resource is endogenously determined by  $C^{-1}(c_y) = R(t_b) = R_b > 0$  (Farzin, 1996).

The carbon emissions related to the extraction in Scenario *Ext* affect the dynamics of the global carbon cycle. According to Assumption 4, atmospheric carbon concentration is initially increasing and thereby also the net transfer into the deep ocean  $nt = \gamma S - \gamma \omega W$  because the downward flux increases by  $\gamma$ , whereas the upward flux only by  $\gamma \omega$ . Even if Assumption 4 is not fulfilled, oceanic carbon stock is monotonically increasing given the initial values fulfill  $S_0 > \omega W_0$ .<sup>13</sup> However, atmospheric carbon concentration increases at a declining rate ( $\ddot{S} < 0$ ) or might even reverse its sign ( $\dot{S} < 0$ ) because of the monotonically decreasing carbon emissions.

**Proposition 2.** *If Assumption 4 is fulfilled, atmospheric carbon concentration approaches a unique peak concentration  $S_p$  at  $t_p$  with  $0 < t_p \leq t_b$  if  $U''' > 0$ .*

**Proof.** If atmospheric carbon concentration is monotonically increasing until  $t_b$ , the peak concentration will be approached at  $t_p = t_b$  because from  $\dot{S} = q(t_b) - \gamma S(t_b) - \gamma \omega W(t_b) > 0$ , from the continuity in the state variables, and from  $q(t_b) = \bar{y} > 0$  follows that  $\dot{S} = \gamma S(t_b + \epsilon) - \gamma \omega W(t_b + \epsilon) < 0$  with  $\epsilon \rightarrow 0$ . If atmospheric carbon concentration is not monotonically increasing until  $t_b$ , the peak concentration will be approached at  $t_p < t_b$  with  $-\frac{\dot{q}}{q} > \gamma \omega$  which follows from  $\ddot{S}^R = \dot{q} - \gamma \omega \dot{R}^R < 0$ . The atmospheric carbon concentration can only once reverse its sign between  $t \in (0, t_b)$ . Observing two extrema would require

$$\begin{aligned} S_{max} : & \quad -\dot{q}/q > \gamma \omega \\ S_{min} : & \quad -\dot{q}/q < \gamma \omega, \end{aligned} \tag{28}$$

requiring an inflection point for  $q$  between  $S_{max}$  and  $S_{min}$ . From

$$\ddot{q} = \frac{\rho(U''\dot{q} + C'(R)q)U'' - \rho(U' - C(R))U'''\dot{q}}{(U'')^2} \tag{29}$$

it can be seen that  $\ddot{q} = 0$  is not feasible if  $U''' > 0$  because  $U' - C(R) < 0$  follows from the necessary optimality condition (12).  $\square$

The proposition would also be valid if Assumption 4 only required  $q_0^{Ext} > \gamma(S_0 - \omega W_0)$ , where  $q_0^{Ext}$  is

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<sup>13</sup>This can be seen from the closed-form solution for  $W(t)$  if emissions are zero:  $W(t) = e^{-(\gamma+\gamma\omega)t}(\frac{\omega W_0 - S_0}{1+\omega}) + \frac{1}{1+\omega}W_0$ , where the first term inside the parentheses is zero if the initial values constitute a carbon cycle equilibrium but is negative if initial atmospheric carbon concentration has already increased. As the parentheses are multiplied by a declining exponential term, the oceanic carbon stock is monotonically increasing. This property does not change if carbon emissions are included because these are only released into the atmosphere.

the initial amount of carbon emissions in Scenario *Ext*. From the proposition, it follows that if  $q_0^{Ext} < \gamma(S_0 - \omega W_0)$ , the atmospheric carbon concentration is either monotonically decreasing until  $t \rightarrow \infty$  or is U-shaped until  $t_b$  with  $S_p(t_b) \leq S_0$ . However, no matter when the atmospheric peak concentration is reached, the carbon cycle is in disequilibrium at  $t_b$  because  $q(t_b) = \bar{y} > 0$ . Consequently, the steady state values for atmospheric and oceanic carbon stocks are approached by the natural adjustment process, as  $t \rightarrow \infty$ , and are given by

$$S_\infty = \frac{\omega}{1+\omega}(S_0 + W_0 + R_0 - R_b), \quad W_\infty = \frac{1}{1+\omega}(S_0 + W_0 + R_0 - R_b). \quad (30)$$

I turn now to Scenario *Ceil*, where atmospheric carbon stock is limited by a ceiling  $S(t) \leq \bar{S}$ . If  $S_\infty > \bar{S}$ , the ceiling would be limiting for the total carbon accumulation in the carbon cycle and the total amount of fossil fuel extraction would decrease to

$$\int_0^{t_b^{Ceil}} q^{Ceil}(\tau) d\tau = \frac{1+\omega}{\omega} \bar{S} - S_0 - W_0 = R_0 - R_b^{Ceil} < R_0 - R_b^{Ext}. \quad (31)$$

If  $S_p < \bar{S}$  holds, the ceiling would never be binding and the optimal solution would coincide with the solution in Scenario *Ext*. With respect to the total storing capacity of the global carbon cycle but also the inertia of oceanic carbon uptake, I focus on the situation where the ceiling only limits the atmospheric peak concentration  $S_p^{Ext} > \bar{S} > S_\infty > S_0$ .  $S_p^{Ext} > \bar{S}$  implies that  $t_{cr}^{Ceil} < t_{cl}^{Ceil}$ , where  $t_{cr}$  and  $t_{cl}$  denote the points in time when the ceiling is reached and left, respectively.  $\bar{S} > S_\infty$  implies that the total amount of fossil fuel extraction is not affected ( $S_\infty^{Ext} = S_\infty^{Ceil}$ ) but that the extraction dynamics are.  $\bar{S} > S_0$  implies a period in the beginning when atmospheric carbon stock is below the ceiling. The binding ceiling requires  $\theta_4$  to be positive between  $t_{cr}^{Ceil}$  and  $t_{cl}^{Ceil}$ , resulting in positive costate variables  $\lambda_S$  and  $\lambda_W$  for  $t \in (0, t_{cl}^{Ceil})$ , where  $\lambda_S$  measures the shadow environmental scarcity rent of the atmospheric carbon storing capacity and  $\lambda_W$  measures the shadow environmental scarcity rent of the oceanic carbon storing capacity (Farzin, 1996). The overall carbon storing capacity is only scarce before and at the ceiling. Once the ceiling has been left, there is no scarcity and therefore  $\lambda_S(t) = \lambda_W(t) = 0$  for  $t \in (t_{cl}, \infty)$ . The dynamics of the costate variables can be seen from the closed form for  $\lambda_S$  in the *Redux*<sup>W</sup> system<sup>14</sup>:

$$\lambda_S^W(t) = \lambda_{S_0}^W e^{(\rho+\gamma+\gamma\omega)t} - \int_0^t \theta_4(\tau) e^{-(\rho+\gamma+\gamma\omega)(\tau-t)} d\tau \quad (32)$$

The closed form shows that the costate variables in the *Redux*<sup>W</sup> system and therefore both costate variables in the complete system are increasing on the path towards the ceiling and decreasing at the ceiling because  $\theta_4(t) = 0$  for  $t \in (0, t_{cr})$  and  $\theta_4(t) \geq 0$  for  $t \in (t_{cr}, t_{cl})$  with  $\lambda_S(t) \geq \lambda_W(t)$  for  $t \in (0, t_{cl})$ . For the

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<sup>14</sup>The costate variable associated to the atmospheric carbon stock in the *Redux*<sup>W</sup> system is equal to the tax difference in the complete system:  $\dot{\lambda}_S - \dot{\lambda}_W = (\lambda_S - \lambda_W)(\rho + \gamma + \gamma\omega) + \theta_4$ .

atmospheric carbon stock at the ceiling, the entire dynamics are exogenously determined by the two-box model description.

**Proposition 3.** *When atmospheric carbon concentration is at the ceiling, extraction is monotonically decreasing at a constant contraction rate  $-\gamma\omega$ .*

**Proof.** From  $\dot{S}^W = 0 = q - (\gamma + \gamma\omega)\bar{S} + \gamma\omega(K_0 - R(t))$  follows that  $\frac{\dot{q}}{q} = -\gamma\omega$ . □

In contrast to Chakravorty et al. (2006) and Lafforgue et al. (2008) extraction is not constant but decreasing at the ceiling because of the increasing saturation of the carbon cycle with anthropogenic carbon. This is implicitly confirmed by Farzin and Tahvonen (1996) who capture the non-renewable aspect of the global carbon cycle by artificially dividing the atmospheric carbon stock into two stock, one with decay and the other one without. However, they consider a damage function to measure the social costs of increasing atmospheric carbon concentration instead of a ceiling. They show that for certain functional forms and initial levels the situation of a stationary policy arises, where atmospheric carbon concentration is constant and extraction is decreasing at a constant contraction rate. The differences between a two-box model description versus an artificial division of the atmospheric carbon stock are further discussed in Rickels and Lontzek (2011). They show that the two-box model does not provide an advantage in itself, but becomes indispensable if options like ocean sequestration are investigated.

With the two-box model the relationship between the resource stock and the amount of extraction at the ceiling is linear:

$$q_c^{Ceil}(R) = K_1 + \gamma\omega R \quad \text{with} \quad K_1 = (\gamma + \gamma\omega)\bar{S} - \gamma\omega K_0, \quad (33)$$

which follows from  $\dot{S}^W = 0$ . Using this relation, three cases can be distinguished for switching to the backstop technology.

**Case 1:** If  $q_c^{Ceil}(R_b) > \bar{y}$  holds, the ceiling will be left before energy consumption switches to the backstop technology. The point in time when the ceiling is left  $t_{cl}^{Ceil}$  is determined by  $q_c^{Ceil}(R) = q^{Ext}(R, \lambda_R)$  and I denote the corresponding resource stock by  $R_{cl}^{Ceil}$ . From  $t_{cl}^{Ceil}$  until  $t_b$ , the dynamics are determined by Scenario *Ext*, where the initial level for the resource stock is  $R_{cl}^{Ceil}$ . Energy consumption switches to the backstop technology at  $t_b^{Ceil}$  with  $t_{cl}^{Ceil} < t_b^{Ceil}$ .

**Case 2:** If  $q_c^{Ceil}(R_b) < \bar{y}$  holds, the backstop technology will already be used at the ceiling and  $t_b^{Ceil}$  is determined by  $q_c^{Ceil}(R) = \bar{y}$  with  $R > R_b^{Ext}$ . Instead of a complete switch to the backstop technology at  $t_b^{Ceil}$ , both energy sources will be used simultaneously in this case. From  $t_b^{Ceil}$  onwards, energy consumption is fixed at  $\bar{y} = q_c^{Ceil}(R) + y(t)$ , where  $q_c^{Ceil}(R)$  is monotonically decreasing (according to Proposition 3) and in turn  $y(t)$  is monotonically increasing. Simultaneous use requires the marginal

costs for both energy sources to be equal  $c_y = C(R) + \lambda_R^{Ceil} + \lambda_S^{Ceil}$ , which holds true until  $R(t) = R_b$ , so that  $c_y = C(R_b)$  and  $\lambda_R^{Ceil} = \lambda_S^{Ceil} = 0$ . At this point in time, the ceiling is left and the consumption of the backstop technology jumps from  $\bar{y} - q_c^{Ceil}(R_b)$  up to  $\bar{y}$ , whereas consumption of fossil-fuel-based energy jumps to zero. Consequently, in this case  $t_{cl}^{Ceil} > t_b^{Ceil}$  holds.

**Case 3:** If  $q_c^{Ceil}(R_b) = \bar{y}$  holds, the ceiling will be left at the point in time when energy consumption switches to the backstop technology. Consequently, in this case  $t_{cl}^{Ceil} = t_b^{Ceil}$  holds.

In Case 1 and Case 3, the marginal costs of extraction are monotonically decreasing, but in Case 2 marginal costs are constant during the simultaneous use of both energy sources, implying  $\lambda_S$  to be decreasing at a slower rate after  $t_b^{Ceil}$ . This case is investigated in more detail in Chakravorty et al. (2006) but with the carbon cycle being described by proportional decay so that extraction is constant at the ceiling,  $\bar{q}_c = \gamma_d \bar{S}$ . If  $\gamma_d \bar{S} < \bar{y}$ , backstop technology utilization will start at a level of  $y(t) = \bar{y} - \gamma_d \bar{S}$  once the ceiling is approached. Observing starting points for backstop technology utilization later at the ceiling requires the inclusion of sequestration so that energy consumption is above  $\bar{y}$  at the beginning of the binding ceiling. The two-box model description allows such a result to be observed without the inclusion of sequestration. Following Lafforgue et al. (2008), I focus on Case 1 where  $q_c^{Ceil}(R_b) > \bar{y}$ .

Obviously, the ceiling is reached later in Scenario *Ceil* than it is exceeded in Scenario *Ext*,  $t_{cr}^{Ceil} > t_{cr}^{Ext}$  because  $q^{Ext}(R_0, \lambda_{R0}) > q^{Ceil}(R_0, \lambda_{R0}, \lambda_{S0})$  and  $q^{Ext}(t_{cr}^{Ext}) > q^{Ceil}(t_{cr}^{Ext})$ . Accordingly, the resource stock  $R(t_{cr}) = R_{cr}$  also changes.

**Proposition 4.** *The ceiling is approached with a lower fossil fuel resource stock in Scenario Ceil than in Scenario Ext:  $R_{cr}^{Ceil} < R_{cr}^{Ext}$ .*

**Proof.** This can be seen from the closed-form solution for  $S(t)$  in the *Redux*<sup>W</sup> system:

$$S(t) = e^{-(\gamma+\gamma\omega)t} \left( \int_0^t ((q(\tau) - \gamma\omega R(\tau))e^{(\gamma+\gamma\omega)\tau} d\tau + \frac{S_0}{1+\omega} - \frac{\omega(R_0 + W_0)}{1+\omega} \right) + \frac{\omega K_0}{1+\omega}. \quad (34)$$

By taking the derivative with respect to time at  $t_{cr}$  where  $S(t_{cr}) = \bar{S}$  one obtains

$$\frac{\gamma\omega R(t_{cr}) - q(t_{cr})}{\gamma + \gamma\omega} = \bar{S} - \frac{\omega K_0}{1 + \omega}, \quad (35)$$

from which follows that a lower amount of extraction in Scenario *Ceil* at  $t_{cr}$  also implies a lower fossil fuel resource stock.  $\square$

The ceiling is not just approached later due to the lower extraction rate in Scenario *Ceil* but also to the higher cumulative oceanic carbon uptake compared to Scenario *Ext*:  $W^{Ceil}(t_{cr}) = K_0 - \bar{S} - R_{cr}^{Ceil} > W^{Ext}(t_{cr}) = K_0 - \bar{S} - R_{cr}^{Ext}$ .



Note that the cumulative oceanic uptake with the two-box model at  $t_{cr}$ , does not necessarily differ from the cumulative uptake obtained with the proportional decay assumption,  $W(t) = \gamma_d \int_0^t S(t) + W_0$ , if the decay parameter  $\gamma_d$  is chosen appropriately:

$$\gamma_d = \frac{e^{-\gamma\omega t} \gamma \int_0^t S^{Ceil}(\tau) e^{\gamma\omega\tau} d\tau + W_0(e^{-\gamma\omega t} - 1)}{\int_0^t S_d^{Ceil}(\tau) d\tau}. \quad (36)$$

Obviously,  $\gamma_d$  varies with time, so that the endogenous oceanic carbon uptake in the two-box model description also alters the optimal extraction path before the ceiling has been approached compared to the proportional decay description. If the ceiling is approached at the same point in time with both the proportional decay and the two-box model description, then the initial extraction must be larger with the latter description as the net transfer into the deep ocean is not only influenced by the atmospheric carbon stock but also by the saturation of the ocean with anthropogenic carbon. Therefore, the dynamics of  $\lambda_S$  are influenced by the oceanic saturation, as it can be seen from (16) and (17). The initial level of  $\lambda_S$  is not only influenced by  $S_0$  but also by  $W_0$ , where an initial lower oceanic saturation level implies a lower value for  $\lambda_S$  for a given value of  $S_0$ .

### 3.3. Convex sequestration costs and oceanic carbon storage

We include now the option of capturing carbon and injecting it into the deep ocean. The implications for the optimal solution depend crucially on the behavior of the costs associated with such an activity. According to Assumption 6, we distinguish between  $A' = a_c$ , as is assumed in Chakravorty et al. (2006) and Lafforgue et al. (2008) and  $A' > 0$  with  $A'' > 0$ . To clarify the difference, we apply first the proportional decay description for the global carbon cycle without endogenous oceanic carbon uptake as is done in those papers and investigate the Scenarios *AC* and *AX*.<sup>15</sup> Note that with the proportional decay description,  $W(t)$  does not affect the objective function so that it does not have to be included in the Hamiltonian function. Consequently, the necessary conditions for an optimal solution are only described by (12) to (16) and (18) to (22), where  $\lambda_W$  vanishes in conditions (13), (15), and (22). Considering ocean sequestration with a proportional decay description is equivalent to considering geological storage without scarcity with respect to storage volume. Furthermore, we presuppose that the Scenarios *Ext* and *Ceil* can be accordingly defined for the proportional decay description.

In Scenario *AC*, it follows from conditions (12) and (13) that only the total amount of fossil fuel energy consumption  $x^{AC} = q^{AC} + a^{AC}$  is determined and that positive sequestration requires  $\lambda_S = a_c$ . However, even if the latter condition were fulfilled, it would be beneficial to provide total energy consumption only by  $q^{AC}$  because  $a^{AC} > 0$  would imply additional costs in the objective function. This changes if  $q^{AC}$  is

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<sup>15</sup>From Assumption 4 follows that the initial value  $S_0$  has to be normalized to be zero for the proportional decay description.

determined by the binding ceiling to be  $q^{AC} = \gamma_d \bar{S}$ , implying that  $a^{AC} = x - \gamma_d \bar{S}$ , as pointed out by Chakravorty et al. (2006) and Lafforgue et al. (2008). From  $a_c > 0$  and  $U'(\gamma_d \bar{S}) - C(R(t_{cl}) - \lambda_R(t_{cl})) = 0$  follows that there exists a point in time  $t_a^{AC} < t_{cl}^{AC}$  where  $U'(\gamma_d \bar{S}) - C(R) - \lambda_R - \lambda_S - a_c = 0$ , so that sequestration does not take place over the entire period at the ceiling. The price continuity condition implied by (12) requires that  $q^{AC}(t_{cr}^{AC}) = \gamma_d \bar{S} + a^{AC}(t_{cr}^{AC})$ .<sup>16</sup> Consequently, at  $t_{cr}^{AC}$ ,  $q^{AC}$  jumps down from  $x^{AC}$  to  $\gamma_d \bar{S}$  and  $a^{AC}$  jumps up from zero to  $x^{AC} - \gamma_d \bar{S}$ . The costate variable  $\lambda_S^{AC}$  is increasing, constant, decreasing, and zero for  $t \in (0, t_{cr}^{AC})$ ,  $(t_{cr}^{AC}, t_a^{AT})$ ,  $(t_a^{AC}, t_{cl}^{AC})$ , and  $(t_{cl}^{AC}, \infty)$ , respectively, implying that  $\lambda_S^{AC}$  stays at its maximum value for  $t \in (t_{cr}^{AC}, t_a^{AC})$ , which is equal to  $a_c$  (Chakravorty et al., 2006; Lafforgue et al., 2008).

In Scenario AX, the regularity condition for  $q$  and  $a$  is fulfilled, so that the control variables are continuous apart from the switch to the backstop technology that is assumed to take place after the ceiling has been left. Conditions (12) and (13) determine not only the total optimal amount of energy consumption but also its composition because  $A'(a^{AX}) = \lambda_S$ . From the continuity in the control variables follows that  $q^{AX}(t_{cr}^{AX}) = \gamma \bar{S}$ . The costate variable  $\lambda_S^{AX}$  is increasing, decreasing, and zero for  $t \in (0, t_{cr}^{AX})$ ,  $(t_{cr}^{AX}, t_{cl}^{AX})$ , and  $(t_{cl}^{AX}, \infty)$ , respectively, implying that  $\lambda_S^{AX}$  approaches its maximum value at  $t_{cr}^{AX}$ . If  $A'(0) = 0$ , sequestration will be used for  $t \in (0, t_{cl}^{AX})$ ; if  $A'(0) > 0$ , sequestration will be used for  $t \in (t_{as}^{AX}, t_{ae}^{AX})$  with  $0 \leq t_{as}^{AX} < t_{cr}^{AX} < t_{ae}^{AX} < t_{cl}^{AX}$ . From  $\lambda_{S0}^{AX} > 0$  follows that even if  $A'(0) > 0$  holds, sequestration can start at  $t = 0$ , but must end before  $t_{cl}^{AX}$  because  $\lambda_S^{AX}(t_{cl}^{AX}) = 0$ .

**Proposition 5.** *If sequestration costs are constant, sequestration is used only at the ceiling and the ceiling is approached earlier than without sequestration. If sequestration costs are convex, sequestration is also used before the ceiling is approached and the ceiling can also be approached later than without sequestration.*

**Proof.** In both scenarios, AC and AX, energy consumption  $x$  is larger at  $t_{cr}$  than in Scenario Ceil if sequestration is used, requiring the right hand side in (12) to be smaller. If  $t_{cr}^{AC} = t_{cr}^{AX} = t_{cr}^{Ceil}$ ,  $\lambda_S(t_{cr})$  is lower in scenario AC and AX. From  $\lambda_S(t) = \lambda_0 e^{(\rho+\gamma)t}$  follows for both scenarios that also the initial values are lower, so that then  $x(t) > x^{Ceil}(t)$  for  $t \in (0, t_{cr})$  extraction is monotonically decreasing. Consequently, in Scenario AC  $x^{AC} = q^{AC}(t) > x^{Ceil} = q^{Ceil}(t)$  holds for  $t \in (0, t_{cr})$ . From  $S(t_{cr}) = \bar{S} = \int_0^{t_{cr}} q(\tau) e^{-\gamma(t_{cr}-\tau)} d\tau$  follows that  $t_{cr}^{AC} < t_{cr}^{Ceil}$ . In Scenario AX, it follows from

$$q^{AX}(t) = U'^{-1}(C(R) + \lambda_R + \lambda_S) - A'^{-1}(\lambda_S) \quad (37)$$

that  $q^{AX}(t) \leq q^{Ceil}(t)$  for  $t \in (0, t_{cr})$  is possible because  $\frac{\partial q^{AX}}{\partial \lambda_S} = (U'^{-1})'_{\lambda_S} - (A'^{-1})'_{\lambda_S} < 0$ . Even though  $\int_0^{t_{cr}} x^{AX}(\tau) d\tau = \int_0^{t_{cr}} q^{AX}(\tau) + a^{AX}(\tau) d\tau > \int_0^{t_{cr}} q^{Ceil}(\tau) d\tau$  needs to be fulfilled, it is possible that  $\int_0^{t_{cr}} q^{AX}(\tau) d\tau \leq \int_0^{t_{cr}} q^{Ceil}(\tau) d\tau$ , so that from  $S(t_{cr}) = \bar{S} = \int_0^{t_{cr}} q(\tau) e^{-\gamma(t_{cr}-\tau)} d\tau$  follows  $t_{cr}^{AX} \leq t_{cr}^{Ceil}$ .  $\square$

<sup>16</sup>This can also be seen by the carbon balance equation:  $\int_0^{t_{cr}} q^{AC}(\tau) d\tau + \gamma \bar{S} (t_{cl} - t_{cr}) + \int_{t_{cr}}^{t_a} a^{AC}(\tau) d\tau + \int_{t_{cl}}^{t_b} q^{AC}(\tau) d\tau = R_0 - R_b$ . From derivation with respect to  $t_{cr}$  follows  $q^{AC}(t_{cr}) = a^{AC}(t_{cr}) + \gamma_d \bar{S}$ .

With respect to the point in time when the ceiling is reached, Chakravorty et al. (2006) argue that if sequestration is costless, the energy consumption from Scenario *Ext* is realized and therefore the ceiling is approached earlier than in Scenario *Ceil*, while  $q^{Ext}(t) - \gamma\bar{S}$  is sequestered once the ceiling is reached with  $\lambda_S^{AC}(t) = 0$  for  $t \in (0, \infty)$ . But one could also argue that if sequestration is costless, Condition (12) and (13) coincide and only total energy consumption  $x$  is determined to be equal to  $q^{Ext}$ . Consequently, it is also possible to use sequestration for total energy consumption so that the atmospheric carbon stock would remain unchanged and never reach the ceiling. Assuming very small sequestration costs, then in both Scenarios *AC* and *AX*, almost the energy consumption of Scenario *Ext* would be realized. However, in Scenario *AC*, sequestration is only realized at the ceiling, which is approached only slightly later than in Scenario *Ext*, whereas in Scenario *AX*, a substantial fraction of energy consumption involves sequestration before and at the ceiling, so that the ceiling is approached substantially later than in Scenario *Ext* and probably also later than in Scenario *Ceil*.<sup>17</sup>

In Scenarios *AC* and *AX*, it is assumed that sequestration is determined only by the associated costs and not by the availability of appropriate storage sides. The case where a scarcity of the carbon storing capacity of geological reservoirs exists, is investigated for constant sequestration costs by Lafforgue et al. (2008). If the cumulative stored amount of carbon for Scenario *AC* or *AX*, denoted by, e.g.,  $A(t) = \int_0^t a(\tau)d\tau$ , exceeds the capacity of the geological reservoir, denoted by, e.g.,  $\bar{A}$ , an additional costate variable measuring this scarcity, e.g.,  $\lambda_A$ , has to be included in the optimization problem. The amount of sequestration is determined not only by the sequestration costs and the scarcity of atmospheric storing capacity with respect to the ceiling but also by the scarcity of the storing capacity:  $A'(a) = \lambda_S - \lambda_A$ . Irrespective of whether sequestration takes place before the atmospheric ceiling has been reached, as in Scenario *AX*, or once the ceiling has been reached, as in Scenario *AC*, the overall period of sequestration shrinks, so that  $\int_{t_1}^{t_2} a(\tau)d\tau = \bar{A}$ . Even if  $A'(0) = 0$  holds in Scenario *AX*, sequestration ends before  $t_{cl}$  because  $\lambda_S$  is decreasing at the ceiling whereas  $\lambda_A(t) = \lambda_{A0}e^{\rho t}$  is monotonically increasing until the storing limit has been reached. Obviously, even if sequestration is costless, the extraction path of Scenario *Ext* is not regained. Lafforgue et al. (2008) distinguish between the case where only one or the case where many geological reservoirs exists. The former case implies that sequestration cost are equal for all geological reservoirs and only the overall storing capacity has to be considered. The latter case requires that sequestration costs differ with respect to the geological reservoirs. They show that the reservoirs are used for sequestration in ascending order with respect to their costs without the simultaneous use of two reservoirs. This results requires, apart from the sequestration unit cost being constant, that there is no kind of regeneration of the reservoirs, e.g., due to chemical processes or leakage. This can easily be seen by thinking about the overall optimization problem of storing carbon

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<sup>17</sup>The fraction of total energy consumption that involves sequestration in Scenario *AX* is relative to  $\frac{\lambda_S^{AX}}{C(R) + \lambda_R^{AX} + \lambda_S^{AX}}$ , so that the share of sequestration is largest at  $t_{cr}^{AX}$ .

in reservoirs with limited capacity, where the atmosphere is the cheapest storing reservoir that regenerates naturally. The case of multiple reservoirs  $n$  with different costs shows that even if overall storing capacity is not limited, e.g.,  $\int_0^{t_{cl}} a(\tau) d\tau < \bar{A} = \sum_1^n \bar{A}_n$ , a shadow value must be associated with the  $n - 1$  reservoirs, where the storing capacity of the  $n$ th reservoir will not entirely be used (Lafforgue et al., 2008).

We also consider possible scarcity issues related to the storage side, but with respect to ocean sequestration instead of geological sequestration (Scenario *SeqC* and *SeqX*). In contrast to the scenarios *AC* and *AX*, sequestration is determined not only by the scarcity of the atmospheric storing capacity but by the difference between this scarcity and the scarcity of oceanic storing capacity:

$$A'(a) = \lambda_S - \lambda_W = \lambda_S^W, \quad (38)$$

As explained in Section 3.2 and above, the difference between both scarcities increases until  $t_{cr}$ , is constant until  $t_a$ , and then decreases until  $t_{cl}$ , to zero, if sequestration unit costs are constant, or it directly decreases to zero from  $t_{cr}$  onwards if sequestration costs are convex, whereby  $\lambda_S(t) \geq 0$  and  $\lambda_W(t) \geq 0$  for  $t \in (0, t_{cl})$ . Note neither the storing capacity of the atmosphere nor that of the ocean is scarce by itself if the ceiling is such that  $\bar{S} > S_\infty$  so that  $\bar{S}/\omega > W_\infty$ . Nevertheless, scarcity arises if the inertia of the carbon cycle to move carbon into the deep ocean and the decreasing oceanic buffer capacity result in an atmospheric peak concentration with  $S_p > \bar{S}$ . The benefit of ocean sequestration arises from overcoming this inertia and using the oceanic buffer capacity. This can be understood by considering instantaneous equilibration between atmospheric and oceanic carbon stocks without including oceanic buffer capacity ( $\gamma = \omega = 1$ ), implying that both carbon stocks would be monotonically increasing to their steady state values ( $S_\infty = W_\infty$ ). If the ceiling is binding with respect to the steady state values ( $\bar{S} < S_\infty$ ), both costate variables are almost equal and ocean sequestration is nearly of no benefit, as it increases both stocks equally. Factoring in either the inertia ( $\gamma < 1$ ) or the oceanic buffer capacity ( $\omega < 1$ ) implies that ocean sequestration causes the atmospheric carbon stock to increase by only  $\gamma a$  or  $\omega a$ , respectively. As a result, the difference between the scarcities becomes positive and ocean sequestration is of benefit if  $A'(0) < \lambda_S - \lambda_W$ . With both the inertia and the buffer capacity included, ocean sequestration causes the atmospheric carbon stock to increase by only  $\gamma\omega a$  so that the difference between the scarcities increases further.

Because the two-box model description includes the oceanic buffer capacity, it is able to demonstrate that ocean sequestration does not only economically but also physically influence the amount of extraction. In the two-box model, extraction at the ceiling is given by  $q^{Seq} = \gamma(\bar{S} - \omega W)$ , where  $W$  is influenced by ocean sequestration. Therefore, Proposition 3 needs to be modified:

**Proposition 6.** *When atmospheric carbon concentration is at the ceiling, extraction must be monotonically decreasing at a faster rate if sequestration is used.*

**Proof.** From  $\dot{S}^W = 0 = q - (\gamma + \gamma\omega)\bar{S} + \gamma\omega(K_0 - R(t))$  follows that  $\frac{\dot{q}}{q+a} = -\gamma\omega$ , whereas without sequestration  $\frac{\dot{q}}{q} = -\gamma\omega$  holds.  $\square$

Proposition 6 implies that we observe a kink in the extraction path at the ceiling at the point in time when extraction ends in Scenario *SeqC* and in Scenario *SeqX* given  $A'(0) > 0$ . For a given value of the resource stock and therefore also the oceanic carbon stock at  $t_{cr}$  ( $K_0 - \bar{S} - R(t_{cr}) = W(t_{cr})$ ), the period at the ceiling is shorter for Scenario *SeqC* and *SeqX* than for Scenario *Ceil* because from (33) follows that the oceanic carbon stock is unique for all three scenarios at  $t_{cl}$ . Consequently, the path from  $t_{cl}$  onwards until the switching point  $t_b$  is the same for all three scenarios. However, as implied by Proposition 4 and 5, the initial values at  $t_{cr}$  are not unique for the three scenarios. In Scenario *SeqC*, the ceiling is approached earlier and therefore with a higher resource stock and a lower oceanic carbon stock than in Scenario *Ceil*. If in Scenario *SeqX* the ceiling is approached later than in Scenario *Ceil*, the resource stock is lower and the oceanic carbon stock is higher, so that initial extraction at the ceiling is lower than in Scenario *Ceil*. Note, even if the ceiling is reached at the same point in time or earlier than in Scenario *Ceil*, the oceanic carbon stock can be higher due to positive sequestration. However, that would again imply lower initial extraction at the ceiling, so that it seems more likely that in an optimal solution the ceiling is approached later than in Scenario *Ceil*.

To illustrate the implications of the various scenarios, we provide a numerical example.<sup>18</sup> Figure 1 shows the optimal paths for extraction, sequestration, total energy consumption by fossil fuels, and backstop technology in the left column and the atmospheric carbon concentration in the right column for the scenarios *Ext*, *Ceil*, *SeqC*, and *SeqX*. The parameter values are chosen so that assumptions 3 to 6 are fulfilled. In the unconstrained Scenario *Ext*, atmospheric carbon stock approaches its peak concentration before energy consumption switches to the backstop technology, whereby the ceiling is crossed twice. Accordingly, in Scenario *Ext*,  $t_{cr}$  and  $t_{cl}$ , denote when the ceiling is crossed, whereas in the other scenarios they denote the start and end of the ceiling period. In Scenario *Ext*, the amount of extraction at  $t_{cl}$  is actually lower than in the other scenarios. This can be seen from the shorter period between  $t_{cl}^{Ext}$  and  $t_b^{Ext}$ , compared to other scenarios where this period is equal for Scenario *Ceil*, *SeqC*, and *SeqX*, as explained above. However, the period at the ceiling varies between these three latter scenarios. In line with Proposition 5, the ceiling is approached earlier in Scenario *SeqC* than in Scenario *Ceil* due to sequestration. Even though the ceiling is left earlier in Scenario *SeqC*, the overall period at the ceiling is extended. Consequently, the effect of approaching the ceiling earlier because of higher initial extraction overcompensates the faster decline in fossil fuel energy consumption at the ceiling. For the chosen parameter values, the ceiling is reached later and left

<sup>18</sup>The utility function is  $U(q) = b_1 * q - b_2 * q^2$ , the stock-dependent extraction cost function is  $c_1 - c_2 R$ , the ocean sequestration cost function for Scenario *SeqX* is  $A(a) = a_x * a^2$  and for Scenario *SeqC*  $A(a) = a_c * a$ . The parameter values are  $b_1 = 6$ ,  $b_2 = 6/20$ ,  $c_1 = 6$ ,  $c_2 = 1/10$ ,  $a_x = a_c = 2/10$ ,  $c_y = 5.6$ ,  $\gamma = 1/10$ ,  $\omega = 1/10$ ,  $\rho = 3/100$ , and the initial values are  $R_0 = 50$ ,  $S_0 = 20$ , and  $W_0 = 200$ . The ceiling is  $\bar{S} = \frac{45}{28} S_0 = 32.1429$  where 280 ppm is the preindustrial atmospheric carbon stabilization level and 450 ppm is a ceiling that could possibly be used to comply with the 2°C temperature limit discussed above.

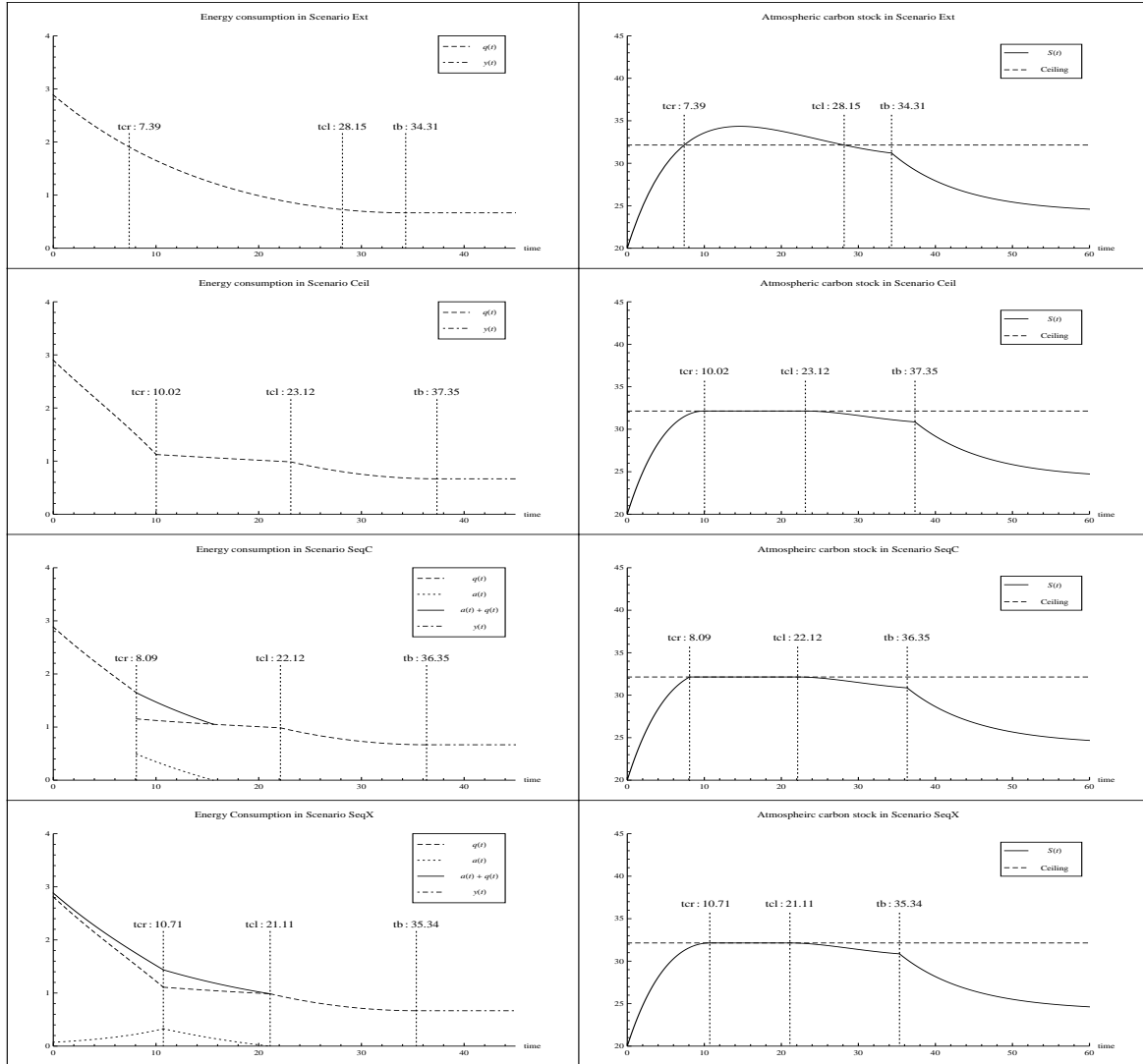


Figure 1: Energy consumption and atmospheric carbon stock in scenarios *Ext*, *Ceil*, *SeqC*, and *SeqX*

earlier in Scenario *SeqX* than in Scenario *Ceil* because of continuous sequestration. Scenario *SeqX* has the shortest period at the ceiling, Scenario *SeqC* the longest period. In both scenarios *SeqC* and *SeqX*, the option of sequestration allows an path of energy consumption to be reached which looks more like the energy consumption path in Scenario *Ext*. Note if the initial values  $S_0$  and  $W_0$  are chosen such that Assumption 4 is violated but such that  $S_0 > \omega W_0$  and Assumption 5 are still satisfied, the period until the ceiling is reached shrinks and the path for atmospheric carbon concentration until the ceiling could be U-shaped.

It remains to briefly discuss the implications of the change in path of the oceanic carbon stock caused by ocean sequestration. As explained above, the oceanic carbon stock  $W(t_{cl})$  is unique for the scenarios *Ceil*, *SeqX*, and *SeqC*. Leaving the ceiling earlier with ocean sequestration implies that the oceanic carbon

stock has increased faster than without ocean sequestration. Consequently, ocean sequestration influences the rate of ocean acidification even though the total level of ocean acidification is not affected, as it follows from the unaffected steady state values ( $\bar{S} > S_\infty$ ). A ceiling for the oceanic carbon stock or a damage function capturing the social costs of an increasing oceanic carbon stock could be included in the objective function. Both of these possibilities would have a similar effect as the oceanic carbon stock is monotonically increasing to its steady state value. Therefore,  $\lambda_W$  and, in turn  $\lambda_S$ , would be positive for  $t \in (0, \infty)$  and total fossil fuel consumption would shrink.<sup>19</sup> The amount of ocean sequestration would also shrink or even become zero in the period until  $t_{cl}$ , as the tax difference decreases. After the ceiling has been left, the tax difference would become negative, implying that it would be beneficial to “pump” carbon back from the ocean to atmosphere ( $\theta_2 > 0$ ). Furthermore, the positive costate variable  $\lambda_S$  for  $t \rightarrow \infty$  implies that fossil fuels and the backstop technology would be used simultaneously from  $t_b$  onwards.

#### 4. Conclusion

In this paper I investigate the optimal role of carbon sequestration from a social planner’s perspective while the atmospheric carbon concentration is constrained by a ceiling. In contrast to existing analyses, we include stock-dependent extraction costs, describe the carbon cycle using a two-box model, assume carbon sequestration costs to be convex, and consider oceanic instead of geological carbon storage.

The inclusion of stock-dependent extraction costs does not influence the optimal sequestration decision as discussed in the literature. However, their inclusion can imply that not the entire stock of fossil resources is extracted, as is shown by Dasgupta and Heal (e.g., 1979) and Tahvonen (1997). The description of the carbon cycle using a two-box model allows the ongoing saturation of the ocean with anthropogenic carbon to be taken into account. Consequently, extraction at the ceiling is not constant, as is the case with a proportional decay description, but is monotonically decreasing. This implies that the simultaneous use of fossil fuels and a backstop technology could start at some point at the ceiling which is not possible with the proportional decay description without also using sequestration. The non renewable description of the carbon cycle provided by the two-box model implies positive atmospheric and oceanic carbon stock stabilization values that have to be larger in sum than the initial values as a consequence of the anthropogenic release of carbon into the cycle. Therefore, it is possible that the ceiling limits total carbon accumulation in the cycle, where with the proportional decay description, the ceiling is a temporary problem per definition. When the ceiling is permanently binding in the two-box model, the stock of fossil resources left in the ground must increase, compared to a when a ceiling is only temporarily binding regardless of whether extraction costs are stock-dependent or not.

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<sup>19</sup>In the case of a damage function instead of a ceiling the steady state values for  $\lambda_S$  and  $\lambda_W$  are:  $\lambda_S(\infty) = \frac{D'(W)\gamma}{\rho(\gamma+\rho+\gamma\omega)}$  and  $\lambda_W(\infty) = \frac{D'(W)(\gamma+\rho)}{\rho(\gamma+\rho+\gamma\omega)}$ .

Convex carbon sequestration costs imply that sequestration is used in a continuous manner, increasing on the path towards the ceiling and decreasing at the ceiling. Constant sequestration costs imply that sequestration is used in a discontinuous manner, jumping from zero to its maximum value and decreasing at the ceiling (Chakravorty et al., 2006; Lafforgue et al., 2008). Both cost assumptions result in a total energy consumption path that looks more like the one observed in the unconstrained solution. However, the path resulting from convex sequestration costs seems to be more realistic with respect to physical and investment requirements related to the implementation of such a technology. This is confirmed by simulation results that project an increasing share of carbon sequestration for various temperature stabilization targets (e.g., IEA, 2010). Furthermore, constant sequestration costs imply that in an optimal solution, the atmospheric ceiling will be approached earlier if sequestration is used at the ceiling. Convex sequestration also allows the atmospheric ceiling to be approached later. Our ability to profoundly determine a ceiling on atmospheric carbon concentration that can be regarded as safe with respect to climate change is restricted by our still limited understanding of the earth's climate system, in particular with respect to tipping points. Accordingly, at the meeting of the parties in Cancun, it was recognized that the limit for temperature increase to 2°C need to revised to a limit of 1.5°C because of new scientific knowledge (UNFCCC, 2010). Therefore, technologies allowing society to approach an agreed ceiling later and to gain time to learn more about the consequences of climate change can be regarded as preferable. Results based on linear sequestration costs, suggest that carbon sequestration would not be a recommend option to deal with the atmospheric carbon accumulation problem, whereas results based on convex sequestration costs suggest that such technology could be an important option.

Ocean sequestration and therefore oceanic carbon storage allows the kinetic constraints of natural oceanic carbon uptake to be overcome. The atmospheric carbon accumulation problem is crucially influenced by the inertia of the global and in particular the marine carbon cycle in balancing anthropogenic disturbances to the carbon cycle. About 80 percent of the anthropogenic carbon emitted to the atmosphere is expected to be taken up by the ocean on timescales of several hundred years (e.g., Archer et al., 1997; Körtzinger and Wallace, 2002; Sarmiento and Gruber, 2006). Ocean sequestration takes advantage of the oceanic buffer capacity and the slow turnover speed of the natural adjustment process. Therefore, the optimal amount of ocean sequestration is determined by the difference between the scarcities of the atmospheric carbon storing capacity and of the oceanic carbon storing capacity. Whereas the former results from the temporarily binding ceiling, the latter results from its negative feedback effect on natural oceanic carbon uptake. Ocean sequestration contributes to the saturation of the ocean with anthropogenic carbon, implying that emissions released into the atmosphere at the ceiling have to decline at a faster rate than without ocean sequestration. If the oceanic carbon storing capacity becomes scarce by itself, e.g., by accounting for ocean acidification, ocean sequestration is less beneficial. Furthermore, after the ceiling has been left, the optimal amount of fossil fuel extraction would no longer be limited by the atmospheric carbon stock but rather by the ongoing



ocean acidification. With respect to ocean acidification, geological storage would be more beneficial, as it allows overall atmospheric and oceanic stabilization levels to be decreased, whereas ocean sequestration does not. Apart from ocean acidification, geological storage does not affect the buffer capacity of the ocean, so that, if costs for geological and oceanic carbon sequestration are equal, the geological storage capacity will be fully used, irrespective of whether simultaneous use is implied by convex sequestration costs or successive use is implied by linear sequestration costs. However, if carbon sequestration is applied on a large scale, it will be probably more expensive to inject carbon into suitable geological storage sites which each require specific investments with respect to pipelines and injection facilities, than to inject carbon into the ocean. Therefore, the interesting case for future research arises from considering various storage options that can be ranked according to the associated injection costs but also according to the associated environmental costs, which would probably result in different ranking orders.

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### A. Necessary and sufficient optimality conditions

For the three control variable constraints,  $g_1(q, a, y) = -q \leq 0$ ,  $g_2(q, a, y) = -a \leq 0$ , and  $g_3(q, a, y) = -y \leq 0$ , and the state variable constraint,  $h(S(t)) = S(t) - \bar{S} \leq 0$ , the constraint qualification is fulfilled if the matrix

$$m = \begin{pmatrix} \frac{\partial g_1}{\partial q} & \frac{\partial g_1}{\partial a} & \frac{\partial g_1}{\partial y} & g_1 & 0 & 0 & 0 \\ \frac{\partial g_2}{\partial q} & \frac{\partial g_2}{\partial a} & \frac{\partial g_2}{\partial y} & 0 & g_2 & 0 & 0 \\ \frac{\partial g_3}{\partial q} & \frac{\partial g_3}{\partial a} & \frac{\partial g_3}{\partial y} & 0 & 0 & g_3 & 0 \\ \frac{\partial \frac{\partial h}{\partial t}}{\partial q} & \frac{\partial \frac{\partial h}{\partial t}}{\partial a} & \frac{\partial \frac{\partial h}{\partial t}}{\partial y} & 0 & 0 & 0 & h \end{pmatrix} \quad (\text{A.1})$$

has the full row rank (Feichtinger and Hartl, 1986, p.165, 6.17), which can be seen to be fulfilled from

$$m = \begin{pmatrix} -1 & 0 & 0 & -q & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & -a & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & -y & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & S(t) - \bar{S} \end{pmatrix} \quad (\text{A.2})$$

The concavity of the maximized Hamiltonian can be shown by proving that the Hessian Matrix of the Hamiltonian is at least negative semi-definite (Feichtinger and Hartl, 1986, p.37, Remark 2.4). To do so, we use the *Redux*<sup>W</sup> system, where the oceanic carbon stock is dropped. The corresponding Current Value Hamiltonian is  $H^c = U(q + a + y) - A(a) - C(R)(q + a) - c_y y + \lambda_R \dot{R} + \lambda_S \dot{S}$ , so that the corresponding Hessian matrix is:

$$\begin{pmatrix} H_{SS} & H_{SR} & H_{Sq} & H_{Sa} & H_{Sy} \\ H_{RS} & H_{RR} & H_{Rq} & H_{Ra} & H_{Ry} \\ H_{qS} & H_{qR} & H_{qq} & H_{qa} & H_{qy} \\ H_{aS} & H_{aR} & H_{aq} & H_{aa} & H_{ay} \\ H_{yS} & H_{yR} & H_{yq} & H_{ya} & H_{yy} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & -C''(R)(q+a) & -C'(R) & -C'(R) & 0 \\ 0 & -C'(R) & U'' & U'' & U'' \\ 0 & -C'(R) & U'' & U'' - A'' & U'' \\ 0 & 0 & U'' & U'' & U'' \end{pmatrix}. \quad (\text{A.3})$$

The negative semi definiteness can easily be seen by checking whether all the leading principal minors are zero.

The regularity of the Hamiltonian follows from the strict concavity of the Hamiltonian in the control variables (Feichtinger and Hartl, 1986, p.167). If the optimization problem is restricted to the control variables  $q$  and  $a$  and sequestration costs are defined by Case  $X$  in Assumption 6, this strict concavity is

fulfilled:

$$\text{Det} \begin{pmatrix} H_{qq} & H_{qa} \\ H_{aq} & H_{aa} \end{pmatrix} = -U''A'' > 0. \quad (\text{A.4})$$

If sequestration costs are defined by Case *C* in Assumption 6 and/or the backstop technology is included, we see from (A.4) and the lower right  $3 \times 3$  matrix in the Hesse matrix (A.3) that the regularity condition is not fulfilled because the Hamiltonian is not strictly concave in the control variables anymore.

# Eidesstattliche Erklärung

Hiermit erkläre ich an Eides statt, dass ich meine Doktorarbeit ‘Optimal global carbon management with ocean sequestration’ selbständig und ohne fremde Hilfe angefertigt habe und dass ich alle von anderen Autoren wörtlich übernommenen Stellen, wie auch die sich an die Gedanken anderer Autoren eng anlehrenden Ausführungen meiner Arbeit, besonders gekennzeichnet und die Quellen nach den mir angegebenen Richtlinien zitiert habe.

Kiel, den 08.06.2011

## Curriculum Vitae

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|                   |   |
|-------------------|---|
| 01/2008-08/2011   | ISOS PhD program, Kiel Cluster of Excellence                                |
| 10/2006-08/2011   | Postgraduate study 'Quantitative Economics', CAU Kiel                       |
| 02/2006           | German Master of Business Studies, CAU Kiel                                 |
| 07/2004           | German Master of Economics, CAU Kiel  |
| 08/2002 – 05/2003 | Erasmus Exchange at University of Bergen, Norway                            |
| 10/1998 – 05/2006 | Study of Economics and Business Studies, CAU Kiel                           |
| 7/1997            | Abitur  |
| 07/1994 - 08/1994 | Commercial high school, BBS Leer  |
| 08/1984 - 08/1994 | Elementary school, orientation stage, and secondary modern school in Remels |

### Professional experience

|                   |   |
|-------------------|---|
| Since 01/2008     | Member of the Future Ocean Cluster Junior Research Group 'Valuing the ocean', Kiel Institute for the World Economy      |
| Since 04/2006     | Research assistant at the Kiel Institute for the World Economics, research area 'The Environment and Natural Resources' |
| 03/2005 – 12/2008 | Junior-Consultant (full- and part time), HSH N Financial Markets Advisory, Kiel   |
| 02/2005 – 01/2004 | Student employee sailing centre CAU Kiel, Kiel  |
| 01/2002 – 07/2002 | Student employee 'schiff-gmbh', Kiel  |
| 08/2001 – 09/2001 | Internship Agency for Economy and Labor, Department Harbor Economy, Hamburg   |
| 10/1999 – 06/2001 | Student employee KSK Kai Service Kiel, Port of Kiel   |
| 07/1997 – 08/1998 | Civilian service children's cure home, Spiekeroog   |

## **Papers & Publications**

### **Journal articles**

Rickels, W., Rehdanz, K., Oschlies, A. (2011). Economics prospects of ocean iron fertilization in an international carbon market, *Resource and Energy Economics* (in press), doi:10.1016/j.reseneeco.2011.04.003.

Rickels, W., Lontzek, T. (2011): Optimal global carbon management with ocean sequestration, *Oxford Economic Papers* (in press), doi: 10.1093/oep/GPR027.

Rickels, W., Rehdanz, K., Oschlies, A. (2010): Methods for greenhouse gas offset accounting: A case study of ocean iron fertilization, *Ecological Economics*, 69, 2495-2509.

Oschlies, A., Koeve, W., Rickels, W., Rehdanz, K. (2010): Side effects and accounting aspects of hypothetical large-scale Southern Ocean iron fertilization, *Biogeosciences*, 7, 4017-4035.

Güssow, K., Proelß, A., Oschlies, A., Rehdanz, K., Rickels, W. (2010): Ocean iron fertilization. Why further research is necessary, *Marine Policy*, 34, 911-918.

Rickels, W., Kleemann, L., Klepper, G., Peterson, S., Petrick, S. (2010): Konjunktur für den Klimaschutz? Klima- und Wachstumswirkung weltweiter Konjunkturprogramme, *Aussenwirtschaft*, 2010 II, Universität St. Gallen.

### **Policy papers**

Khadjavi, M., Peterson, S., Petrick, S., Rickels, W. (2009): No money left for climate protection? Climate policy after the crisis, *Kiel Policy Brief*.

Bencek, D., Klodt, H., Rickels, W. (2011): Vorratslager für Seltene Erden: Eine Aufgabe für die Wirtschaftspolitik? *Wirtschaftsdienst*, 91 (3).

### **Assessment reports**

Klepper, G., Peterson, S., Rickels, W., Kopmann, A., Weitzel, M. (2009): Gutachten zu Perspektiven der wirtschaftswissenschaftlichen Forschung zum Klimawandel on behalf of the German Federal Ministry of Education and Research.

Klepper G., Rickels, W. (2011): Sondierungsstudie: Wirtschaftliche und ökonomische Aspekte des Climate Engineerings, under the authority of the Federal Ministry of Education and Research in Germany.

Klepper G., Rickels, W. (2011): Sondierungsstudie: Wirtschaftliche und ökonomische Aspekte des Climate Engineerings, under the authority of the Federal Ministry of Education and Research in Germany.

Rickels, W.; Klepper, G.; Doern, J.; Betz, G.; Brachatzek, N.; Cacean, S.; Güssow, K.; Heintzenberg J.; Hiller, S.; Hoose, C.; Leisner, T.; Oschlies, A.; Platt, U.; Proelß, A.; Renn, O.;



Schäfer, S.; Zürn M. (2011): Gezielte Eingriffe in das Klima? Eine Bestandsaufnahme der Debatte zu Climate Engineering. Sondierungsstudie für das Bundesministerium für Bildung und Forschung.

### **Working papers**

Rickels, W., Duscha, V., Keller, A., Peterson, S. (2007): The determinants of allowance prices in the European Emissions Trading Scheme - Can we expect an efficient allowance market 2008?

Rickels, W., Görlich, D., Oberst, G. (2010): Explaining European Emission Allowance Price Dynamics: Evidence from Phase II.

Rickels, W. (2011): The role of sequestration costs with a ceiling on atmospheric carbon.

Klepper, G. and Rickels, W. (2011): The Real Economics of Climate Engineering.

### **Selected conferences and presentations**

2008, EAERE Göteborg: The determinants of allowance prices in the European ETS (poster)

2009, EEA Barcelona: Optimal global carbon management with ocean sequestration (presentation)

2010, EER Talented Economist Clinic (EERTEC3): Optimal global carbon management with ocean Sequestration (presentation)

2010, EEA Glasgow: Economic prospects of ocean iron fertilization (presentation)

2010, 4th Meeting of the Scientific Advisory Board (Future Ocean): Economic prospects of ocean iron fertilization in an international carbon market (presentation)

### **Summer Schools**

Governing Climate Engineering – A Transdisciplinary Summer School, Heidelberg, July 12-16, 2010.

NBER Summer Institute, Boston, July 29-30, 2011

Climate Engineering – Second Transdisciplinary Summer School, Banff, Canada, August 1-7, 2011.