Point by point response to the reviewer comments and list of changes

Response to Steven Lade (referee #1)

We thank Steven Lade for his constructive review which will help us to improve the manuscript! We took the reviewer comments into consideration as follows:

Referee:

In this paper, the authors extend a stylised carbon cycle model to include climate engineering by terrestrial carbon dioxide removal (tCDR). The modelling is technically rigorous and the paper is clearly written. There are clear advances in including climate-society feedbacks in a dynamical model and in the methods of analysis.

My main suggestion is that I would like to see more concrete conclusions, for example about the likely effectivness of tCDR and/or about what insights this modelling approach achieved (or even why this modelling approach was chosen). Most of the statements in the abstract and the conclusion are rather empty (e.g. the results of tCDR depends on its parameters; there are trade-offs) or at best could also be obtained by simple accounting of carbon stocks or emission rates.

To my mind the main advantages of a stylised dynamical model over simple carbon stock accounting are if the system under consideration has feedbacks or time lags or non-linearities that are crucial to understanding its dynamics. Perhaps this is true in the present case but I don't see it yet, at least not in your main conclusions. Can you see any consequences of dynamics on whether tCDR is likely to succeed (in keeping the earth system within, or moving it into, the SOS)? What is the time horizon on which tCDR has to start? How likely is it that tCDR will cause at least one PB to be transgressed?

> *Reply:*
> *The transient transgression of planetary boundaries can only be simulated with a dynamic model. This is why we used the modelling approach developed by Anderies et al 2013 which was specifically developed for application in the context of planetary boundaries.*
> *The conclusions section has been changed to evaluate the chosen modelling approach (new manuscript marked up version lines 491-495) and the consequences of dynamics (new manuscript marked up version lines 497-501). The results put more emphasis on the nonlinear carbon cycle feedbacks (new manuscript marked up version lines 418, 482)*
>
> *Reliable assessments of the likely 'real-world' effectiveness of tCDR (and the required time horizon) are not achievable with this conceptual model. Our approach was rather meant to analyse the dynamic interaction of the societal feedback and carbon pools in a planetary boundaries context. However, our constrained basin stability based approach allows an estimation of tCDR effectiveness via the size of the manageable core of the SOS (MCSOS).*
> *In the abstract and conclusions of the manuscript, we put more emphasis on the fact that our conceptual modelling results suggest that tCDR could only successfully be deployed as part of a strong climate change mitigation scenario and is not likely to be effective in a business-as-usual or climate emergency scenario (new manuscript marked up version lines 17-23 and lines 504- 508). We will add the conclusion that in light of numerous economically based integrated assessment studies on tCDR, it is of special importance to note that societal focus*

on climate change only is likely to come at large costs to the biosphere. (new manuscript marked up version lines 509-515).

Minor comments

- Line 132: It's the difference in partial pressures, not the pool size, that determines atmosphere-ocean flux

> *Reply: In the model, the rate of ocean-atmosphere diffusion is approximated as being proportional to the difference in size of the atmospheric carbon pool and the maritime carbon pool. We changed this to emphasize that the dependence on carbon pool size is an assumption of the model which does not simulate carbon concentrations. (The validity of this assumption is discussed in the Appendix 4 of Anderies et al.) (new manuscript marked up version line 145).*

- Motivations of changes to Anderies et al.'s assumptions are clearly given, but what about discussing the validity of their assumptions and simplifications that haven't been changed? For example, the linear carbon-temperature relationship, and the single terrestrial and marine carbon stocks (which combine above and below ground and surface and deep ocean stocks, respectively).

> *Reply: In the methods section we will add information about existing simplifications of the model such as the single terrestrial and maritime carbon pools. Only the upper ocean carbon pool is included because the movement of carbon into the deep ocean occurs on longer timescales relative to those of interest, as discussed by Anderies et al. (new manuscript marked up version lines 115-117).*
> *The single land carbon pool is motivated by a simple proportional partitioning of aboveground and belowground carbon pools (Anderies et al.) (new manuscript marked up version lines 117-119).*
> *These simplifications have been adopted, because they reduce the number of state variables and we were able to qualitatively reproduce the dynamics of observed carbon pool evolution with the model. (new manuscript marked up version lines 119-121).*
> *Within the scope of our study, the addition of two more dimensions to include above and belowground terrestrial carbon and surface and deep ocean carbon would not have been feasible.*

- Lines 164-165: Why correct for carbon dioxide dynamics on long time scales? ("50% of the emitted carbon stays in the atmosphere")? Processes removing atmospheric carbon are already represented in the model. I would have thought temperature response to emissions on short time scales would have been more appropriate here. Long-time dynamics will emerge from the model.

> *Reply: Thank you for pointing this out, the calibration was described in a misleading way. In the model the temperature is linearly dependent on atmospheric carbon content $T(C_a)$. For the calibration, however, we used the transient response of temperature to cumulative emissions (TRCE) (i.e. a linear relationship of temperature to cumulative emissions of 2K/1000GtC). We transformed this (under the assumption that 50% of emitted carbon stay in the atmosphere) to the warming rate of 2K/(500GtC in the atmosphere) for the calibration of $T(C_a)$ instead of T(cumulative emissions). We will rewrite this in the final manuscript. (new manuscript marked up version lines 176-183).*

- I realise you probably don't have control over this, but I would have preferred Table 2 at the section of section 2.2 rather than several pages later.

Reply: We agree with the referee and moved Table 2 to the end of Section 2.2(new manuscript marked up version lines 175).

- Figure 4 is somewhat misleading. It suggests that the terrestrial biosphere will store carbon all the way to arbitrarily high atmospheric carbon concentrations. But in your model, above a certain concentration the temperature will be high enough for respiration to exceed photosynthesis and you will have zero carbon storage.

Reply: Whether the land system acts as a sink or as a source is only governed by the net flux of photosynthesis and respiration (Eq. 6). In turn, the terrestrial carbon carrying capacity (depicted Figure 4) determines the maximum capacity of the system to store carbon. We clarified this in the manuscript. (new manuscript marked up version lines 215,216).

- Line 205-6: Check grammar here.

Reply: Thank you for the hint! Changed in new manuscript, marked up version line 223-224

- Line 215: The planetary boundary is 350ppm (Steffen, 2015). The range 350-450ppm is the 'zone of uncertainty' of the threshold at which dangerous consequences may start to happen. Therefore we have already exceeded the climate change planetary boundary, unlike what is written here and is presented in the figures.

Reply: For this study, we used the mean of the uncertainty range (350-450ppm) as boundary value because critical atmospheric thresholds are likely to be located somewhere within the uncertainty range. Our results are qualitatively robust with respect to choice of the threshold values. We added to the manuscript that the actual proposed boundary is located at 350 ppm. (new manuscript marked up version lines 243-247)

- Line 222: Would appreciate being a little more explicit about how the number 0.31 is obtained.

Reply: Unfortunately, it is not possible to derive or approximate ocean acidification solely from maritime carbon content because it largely depends on chemical variables such as pH-value, ocean alkalinity, dissolved inorganic carbon, etc. that are not included in the model. Therefore we are only able to do a very simple estimation that the boundary is located at ocean carbon pools about 5% higher than current carbon pools in the upper ocean. However, the exact location and normalisation of the boundaries is not decisive for our results and slightly different sets of planetary boundaries would not qualitatively change the systemic effects reported in this study. We clarified the issue in the new manuscript (new manuscript marked up version lines 251-256 and 280-284).

- Line 225-7: I have no problem with this reasoning, but maybe be explicit about the assumptions on soil carbon. I guess the assumption is that soil carbon is unchanged by deforestation? Is this reasonable?

Reply: We clarified the assumptions this more explicily in the revised manuscript (new manuscript marked up version lines 257-264). In detail (which is not represented in the model), the global land carbon pool consists of soil and vegetation carbon of both, forests and *savannah, grasslands, croplands. For our calculation of the planetary boundary of land system change (allowing 25% vegetation carbon loss) on the one hand 'neglects' vegetation carbon of all other biomes than forest biomes, while at the same time neglecting soil carbon changes by deforestation (which would occur to some extend (Heck et al. 2016)). Thus, we do not assume zero soil carbon losses from deforestation but rather approximate that soil carbon losses are of the same order of magnitude as the 'neglected' vegetation carbon of non-forest biomes.*

- Figure 8: Interesting that in (b) and (c) the parameter on the vertical axis needs to be within a narrow parameter range. Why?

Reply: Thank you for pointing out that a discussion of this important finding was missing in this part of the manuscript. The narrow range of tCDR implementation thresholds is due to the dynamic feedbacks of the model. As explained in Section 3.3 (for a fixed tCDR rate), thresholds higher than the atmospheric carbon boundary (0.21) are not sufficient in preventing a boundary transgression in a medium emission scenario, as tCDR action would start too late to prevent a transgression. This determines the upper parameter range (around 0.21). However, 0.21 is not a clear cut-off value but tCDR thresholds allowing for the existence of the MCSOS still depend on the tCDR rate; for relatively small tCDR rates a lower threshold is required than for large tCDR rates. The lower range of the tCDR threshold can be explained by the carbon dynamics of the model. As explained in Section 3.3. the MCSOS can not be sustained if tCDR thresholds are too small because of a resulting transgression of the land system change boundary. From Fig. 8 it becomes apparent that the range of tCDR thresholds depends on the tCDR rate.

We now discuss this in the revised manuscript (new manuscript marked up version lines 472-479).

- Line 423: The success of a climate intervention "nonlinearly depends" on tCDR effectiveness. This is not surprising; when the aim is to avoid a threshold (a planetary boundary), of course success will be very sensitive to parameters in the vicinity of the threshold. Or is there some other effect you're referring to?

Reply: Yes, on the one hand there is the obvious nonlinearity in the vicinity of the planetary boundary but as explained in the reply to the previous comment there is also the nonlinear feedback of the terrestrial carbon pool transgression. We changed the conclusions (new manuscript marked up version line 501) and results accordingly (new manuscript marked up version lines 418, 482).

Response to anonymous referee #2

We thank the reviewer for the constructive review! We took the reviewer comments into consideration as follows:

Referee:

General comment

I very much agree with the approach taken in this paper. We have long known that interactions among the 9 planetary boundaries (PBs) are important, but have only made qualitative assessment of these interactions so far. Applying a conceptual modelling approach to exploring a small set of PB interactions around a specific question is an excellent way to approach the interactions problem. And I fully agree that a conceptual modelling approach is an important step, as it allows one to better understand how he model is behaving – providing insights into how the system might be operating. The outcomes of this modelling study show how effective conceptual modelling can be in elucidating system-level constraints and trade-offs in a broad sense. The authors are to be congratulating for taking such an important and convincing step forward in developing the PB framework.

> *Reply: Thank you very much!*

Specific comments:

1. Figure 1 is an excellent visual description of the model but it leaves one interesting carbon cycle-climate question a bit unanswered. In many countries, storage of carbon in land systems via reforestation and afforestation (and avoided deforestation) is being used to “offset” fossil fuel emissions. In Figure 1, these activities would be part of the loop “Land-human offtake-land use emissions-atmosphere”. These activities could be considered as “negative” human offtake, or human uptake. But the point – clearly made in Figure 1 – is that such activities clearly remain in the active carbon cycle and can in no way “offset” fossil fuel emissions. It is only when tCDR activities are undertaken, and the transfer of carbon is from Land to CE sink, can carbon originating in land truly offset emissions of carbon from the geological reservoir. Although this issue is not a part of the simulation, it might be worth including a paragraph that discusses this fundamental difference between carbon stored in above-ground vegetation (and thus in the active carbon cycle) and carbon stored in geological formations.

> *Reply: This is an excellent observation! Afforestation activities for offsetting fossil fuels would be a negative human offtake flux, i.e. adding carbon to the land system which is then included in the active carbon cycle. As this study focuses on the implications of climate engineering (not afforestation), we did not explicitly include a positive and a negative human offtake flux, rather the net flux of human offtake. We now discuss this difference between afforestation and biomass extraction into a geological reservoir in the introduction. (new manuscript marked up version lines 51-55).*

2. The PB for land system change is actually not based on the carbon storage on the three major forest biomes (boreal, temperate, tropical) but rather on the biogeophysical feedbacks of these three biomes to the physical climate system via changes in albedo and evapotranspiration. In the 2015 PB paper we noted that the land carbon issue, which in principle affects all terrestrial biomes (although the bulk of the above-ground biomass in land systems is in the major forest biomes), would be dealt

with the climate PB, given than atmospheric CO2, a feature of the active carbon cycle, was the control variable for the climate boundary. An interesting off-line calculation might be to fix the land system boundary at 75% of the carbon storage for the three major forest biomes (based on potential areas), and then see what this means for carbon offtake for the rest of the terrestrial biosphere. This, of course, would only be interesting for those scenarios in which the land-system boundary is transgressed.

Reply: Due to the lack of biogeophysical feedbacks in the model, we used the land carbon content as a proxy for deforestation by measuring the loss of vegetation carbon with deforestation. We are aware that the global land carbon pool consists of soil and vegetation carbon of both, forest and non forest biomes. Our calculation of the planetary boundary of land system change (allowing 25% vegetation carbon loss) on the one hand 'neglects' vegetation carbon of all non-forest biomes, while at the same time neglecting soil carbon changes by deforestation (which would occur to some extend (Heck et al. 2016)). By assuming that soil carbon losses are of the same order of magnitude as the 'neglected' vegetation carbon of non-forest biomes, we implicitly accounted for the discrepancy of global and forest carbon storage. This is now included in the revised manuscript (new manuscript marked up version lines 256-264).

3. Just to follow on from point 2, there is an interesting further nuance to the tradeoff between the climate and land-system change PBs for very high tCDR rates – the scenarios that shrink the MCSOS due to transgression of the land-system PB in order to meet the climate PB. This may actually be counterproductive for the climate system, given that the land system PB is configured around biogeophysical feedbacks to the climate system. If these are disrupted due to transgression of the land-system PB, we may see significant changes in atmospheric circulation, monsoon systems, rainfall patterns more generally, even though the carbon aspect of the climate PB is respected via very high tCDR rates. So there is another interesting trade-off at play here!

Reply: Thank you for pointing this out. We included this in the discussion (new manuscript marked up version lines 373-377) and conclusion (new manuscript marked up version line 514)!

4. The biosphere integrity PB (along with climate one of the two core PBs) was only mentioned once, I think, in the manuscript. This is OK, as it is beyond the scope of the study. However, the 2015 PB paper noted that this boundary was more likely to be a bigger constraint on the use of land systems for carbon management than the land-system PB itself (which is rather narrowly focused on biogeophysical feedbacks to climate). There isn't much that can be done yet in a modelling framework with the biosphere integrity boundary, but there are some promising approaches such as the Biodiversity Intactness Index (BII) or MSA (Mean Species Abundance) that are quantitative and could eventually be useful in conceptual modelling frameworks. So this is just a note to say "watch this space", with no action required on the present manuscript.

Reply: Yes, we agree that it would be very interesting to include some biodiversity index in future works.

5. The issue of baseline emission trajectories was a bit confusing in the paper. This is especially important since, according to the conclusions section, managing an SOS depends, in addition to the anticipation of climate change and the potential maximum tCDR, on the baseline emissions pathway.

For example, RCP8.5 was used early in the analysis as the emissions pathway (cf. Figure 5), but then Figure 6 switches to a low baseline emission pathway, while Figure 7 uses an emissions baseline of ~1600 Gt C cumulative emissions. It is only when we get to Figure 8 that we see the profound importance of the baseline emission pathway for the entire analysis! I think this problem could be rather easily fixed by putting a paragraph upfront in the paper foreshadowing that different baseline emission pathways are used in various points of the paper, and that there are good reasons for this. The para could also foreshadow the important of baseline emission pathway, but that this will be dealt with near the end of the paper.

> *Reply: Thank you for pointing this out! We added a section on fossil fuel emissions as part of the model description, foreshadowing the importance of the baseline emissions. (new manuscript marked up version lines 225-234)*

6. I think the trade-off analyses in this paper are excellent, and are certainly a strong point of the paper. Even though this is a rather simple conceptual model, it yields some fascinating tradeoffs involving anticipation and timing of actions, as well as magnitudes of interventions. In particular, I really liked the statements in lines 394-398 and 427- 429. These really show the value of this approach.

> *Reply: Thank you very much!*

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Collateral transgression of planetary boundaries due to climate engineering by terrestrial carbon dioxide removal

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Abstract. The planetary boundaries framework ~~as proposed by Rockström et al. (2009)~~ provides guidelines for defining thresholds in environmental variables. Their transgression is likely to result in a shift in Earth system functioning away from the relatively stable Holocene state. As the climate ~~change boundary is already transgressed,~~ system is approaching critical thresholds of atmospheric carbon, several climate engineering methods are discussed, aiming at a reduction of atmospheric carbon concentrations to control the Earth's energy balance. Terrestrial carbon dioxide removal (tCDR) via afforestation or bioenergy production with carbon capture and storage are part of most climate change mitigation scenarios that limit global warming to less than 2°C.

We analyse the co-evolutionary interaction of societal interventions via tCDR and the natural dynamics of the Earth's carbon cycle. Applying a conceptual modelling framework, we analyse how ~~societal monitoring and management of atmospheric CO_2 concentrations~~ the degree of anticipation of the climate problem and the intensity of tCDR efforts with the aim of staying within a 'safe' level of global warming might influence the state of the Earth system with respect to other carbon-related planetary boundaries.

Within the scope of our approach, we show that societal management of atmospheric carbon via tCDR can lead to a collateral transgression of the planetary ~~boundaries~~ boundary of land system change~~and ocean acidification~~. Our analysis indicates that the opportunities to remain in a desirable region within carbon-related planetary boundaries only exist for a small range of anticipation levels and depend critically on the ~~sensitivity and strength of the tCDR management system, as well as underlying emission pathways~~underlying emission pathway. While tCDR has the potential to ensure the Earth system's persistence within a carbon safe operating space under low emission pathways, ~~this potential decreases rapidly for medium to high emission pathways.~~ it is unlikely to succeed in a business-as-usual scenario.

1 Introduction

Rockström et al. (2009) introduced the concept of a safe operating space (SOS) for humanity, delineated by nine global planetary boundaries, some of which take into account the existence of tipping points or nonlinear thresholds in the Earth system (Lenton et al., 2008; Schellnhuber, 2009; Kriegler et al., 2009) and may frame sustainable development. Particularly, the state of the Earth system with respect to climate change has received strong political attention, as atmospheric carbon concentrations have already entered the uncertainty zone of the planetary boundary of climate change, set at an atmospheric CO_2 concentration of 350 ppmv to 450 ppmv (Steffen et al., 2015).

The Paris climate agreement (**?**) aims at limiting global temperature increase to well below 2°C above pre-industrial levels, while currently greenhouse gas emissions are still growing. Fuss et al. (2014) have highlighted that more than 85 % of IPCC scenarios that are consistent with the 2° goal require net negative emissions before 2100. Particularly, terrestrial carbon dioxide removal (tCDR) via afforestation or large-scale cultivation of biomass plantations for the purpose of bioenergy production has been included in recent IPCC scenarios (Vuuren et al., 2011; Kirtman et al., 2013). Furthermore, tCDR has been proposed as a climate engineering (CE) method that could be applied in case global efforts in mitigating anthropogenic greenhouse gas emissions fail to prevent dangerous climate change (Caldeira and Keith, 2010).

In the context of the SOS framework, tCDR via large scale biomass plantations could on the one hand extract carbon from the atmosphere via the natural process of photosynthesis (Shepherd et al., 2009). If the carbon accumulated in biomass is harvested and stored in deep reservoirs or used for bioenergy production in combination with carbon capture and storage (Caldeira et al., 2013), further transgression of the climate change boundary and initial transgression of the ocean acidification boundary could be prevented. On the other hand, tCDR is likely to have unintended impacts on other Earth system components besides atmospheric carbon concentrations that is mediated by the global cycles of carbon, water and other biogeochemical compounds (Vaughan and Lenton, 2011). For example, large-scale biomass plantations would require substantial amounts of fertilizer, irrigation water and land area, driving the Earth system closer to the planetary boundaries for biogeochemical flows, freshwater use and land system change, respectively (Heck et al., 2016). TCDR in the form of afforestation would not be accompanied by most of these negative trade-offs. However, afforestation only has a limited potential to increase the terrestrial carbon storage while all emitted fossil carbon remains a part of the active carbon cycle. Thus, the potentials of tCDR via afforestation are small and afforestation is not included as a tCDR method in this study.

Social and political actions are important drivers of tCDR. The willingness to engage in CE or mitigation is based on monitoring of the climate system and can be expected to increase as the climate system approaches the normatively assigned climate change boundary. A holistic assessment and systemic understanding of CE therefore requires an analysis of the social and ecological co-evolutionary system.

A dynamic integration of complex interactions between the social and ecological components of the Earth system to simulate in detail the co-evolution of societies and the environment is currently unfeasible due to fundamental conceptual problems and high computational demands on both modelling sides (Van Vuuren et al., 2012; van Vuuren et al., 2015). An emerging field of low-complexity models explores new pathways for understanding social-ecological Earth system dynamics (e.g. Brander and Taylor, 1998; Kellie-Smith and Cox, 2011; Jarvis et al., 2012; Anderies et al., 2013; Motesharrei et al., 2014). For example, first simulation approaches have been reported using such conceptual models to simulate the interaction between human climate monitoring and societal action in the form of transitions to renewable energy (Jarvis et al., 2012) or climate engineering (MacMartin et al., 2013) While not aiming for realism in their quantitative evaluations, the low complexity of such conceptual models allows to understand the structure and effects of dominating feedbacks and their leading interactions, which are otherwise often hidden in the complexity of state-of-the-art full complexity Earth system models.

In this paper, we provide a conceptual but systematic analysis of the nonlinear system response to using tCDR for steering the Earth system within the SOS defined by planetary boundaries as quantified by Rockström et al. (2009) and Steffen et al. (2015). Specifically, we analyse how the trade-offs between tCDR and other planetary boundaries depend on the achievable rate and threshold of tCDR implementation; and whether particular combinations of climate and management parametrisations can safeguard a persistence within the SOS. As a starting point, we focus on a subset of the nine proposed planetary boundaries that are most important in the context of tCDR. These are the carbon-related boundaries on climate change, ocean acidification and land-system change.

We utilise a conceptual model of the carbon cycle and expand it to explore feedbacks within and between societal and ecological spheres, while being sufficiently simple to permit an analysis of its state and parameter spaces in the form of constrained stability analysis similar to van Kan et al. (2016). We do not aim to provide a quantitative assessment because in this exploratory study we choose to use a computationally efficient conceptual model to shed light onto the qualitative structure of co-evolutionary dynamics. The approach proposed here can be transferred to models of higher complexity to the extent that this is computationally feasible.

This paper is structured as follows: following the introduction (Sect. 1) we present a co-evolutionary model of societal monitoring and tCDR intervention in the Earth's carbon cycle and related parameter calibration procedures (Sect. 2). Subsequently, we present and discuss our results (Sect. 3) and finish with conclusions (Sect. 4).

2 Methods

In social-ecological systems modelling, societal influences and ecological responses are recognized as equally important (Berkes et al., 2000). Therefore, it can be considered essential that representations of social and ecological systems are of the same order of complexity. Increasing complexity of only one model component would not increase the accuracy of information generated by the full coupled model, but would greatly increase computational demand. In view of our objective, we require a sufficiently simple model that conceptually captures the most important processes of global carbon dynamics with respect to planetary boundaries, as well as a stylised societal management loop consisting of tCDR interventions and monitoring of the climate system.

2.1 Co-evolutionary model of societal monitoring and tCDR intervention in the carbon cycle

The basis of our co-evolutionary model is the conceptual carbon cycle model by Anderies et al. (2013),. The model covers the most basic interactions between terrestrial, atmospheric, and marine carbon pools and was developed specifically to enable a bifurcation analysis of carbon-related planetary boundaries and their interactions. We modified atmosphere-land interactions for a better representation of empirically observed Earth system carbon dynamics and extended the model by a stylized social management loop mimicking the current focus of international policy processes on climate change. We calibrated the model in order to represent global carbon cycle dynamics consistent with observational data and simulations from detailed high-resolution Earth system models (Sect. 2.2). In the following, we provide an overview of the fundamental model equations. A detailed motivation of the model design and underlying assumptions is given in Anderies et al. (2013).

The adapted model consists of five interacting carbon pools: land $C_t(t)$, atmosphere $C_a(t)$, upper ocean $C_m(t)$, geologic fossil reservoirs $C_f(t)$ and a potential CE carbon sink $C_{CE}(t)$ (Fig. 1). All model equations are summarised in Table 1. Note that only the upper ocean carbon pool is included because the movement of carbon into the deep ocean occurs on longer timescales relative to those of interest, as discussed by (Anderies et al., 2013). The land carbon pool combines soil and vegetation carbon pools, implying a simple proportional partitioning of aboveground and belowground carbon pools (Anderies et al., 2013). These simplifications have been adopted because they reduce the number of state variables and we were able to qualitatively reproduce the dynamics of observed carbon pool evolution with the adapted model.

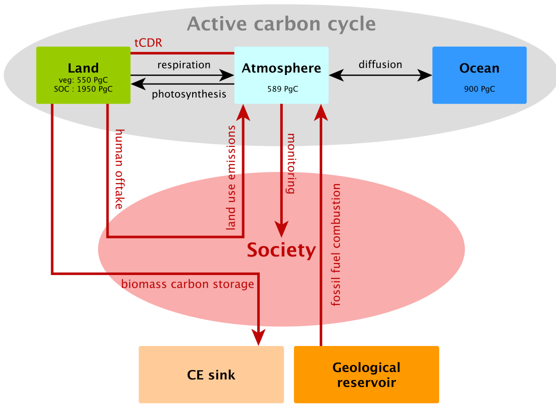

Figure 1. Structure of the co-evolutionary model of societal monitoring and tCDR intervention in the carbon cycle including simulated components of the carbon cycle as well as a societal management loop and their interactions. Carbon values in the boxes indicate estimates of preindustrial carbon pools in the year 1750 AD (Batjes, 1996; Ciais et al., 2013)).

Process	Equation	
conservation of mass	$C_t(t)+C_a(t)+C_m(t)=C_0+C_r(t)-C_{CE}(t)$	(1)
fossil carbon release	$\dot{C}_r(t)=r_iC_r(t)(1-\frac{C_r(t)}{c_{max}})$	(2)
CE carbon storage	$\dot{C}_{CE}(t)=H_{CE}(C_t(t),C_a(t))$	(3)
ocean-atmosphere diffusion	$\dot{C}_m(t)=a_m(C_a(t)-\beta C_m(t))$	(4)
terrestrial carbon flux	$\dot{C}_t(t)=NEP(C_a(t),C_t(t))-H(C_t(t))-H_{CE}(C_t(t),C_a(t))$	(5)
net ecosystem productivity	$NEP(C_a(t),C_t(t),T(t))=r_{tc}\left[P(T(t))-R(T(t))\right]C_t(t)\left[1-\frac{C_t(t)}{K(C_a(t))}\right]$	(6)
terrestrial carbon carrying capacity	$K(C_a(t))=a_ke^{-b_kC_a(t)}+c_k$	(7)
photosynthesis	$P(T(t))=a_pT(t)^{b_p}e^{-c_pT(t)}$	(8)
respiration	$R(T(t))=a_rT(t)^{b_r}e^{-c_rT(t)}$	(9)
temperature	$T(C_a(t))=a_TC_a(t)+b_T$	(10)
tCDR offtake flux	$H_{CE}(C_t(t),C_a(t))=\alpha_{CE}(C_a(t))\;C_t(t)$	(11)
societal tCDR offtake rate	$\alpha_{CE}(C_a(t))=\alpha_{max}\left(1+\exp(-s_{CE}\;(C_a(t)-\tilde{C}_a)\right)^{-1}$	(12)
other human biomass offtake flux	$H(C_t(t))=\alpha C_t(t)$	(13)

Table 1. Summary of equations describing the co-evolutionary model of societal monitoring and tCDR intervention in the carbon cycle building upon Anderies et al. (2013).

The co-evolutionary dynamics of the system is determined by Equations (1)–(5). Conservation of mass (Eq. 1) dictates that the active carbon in the system, i.e. the sum of terrestrial, atmospheric and maritime carbon, is equal to the active carbon at preindustrial times (C_0) plus carbon released from
125 fossil reservoirs ($C_r(t)$) minus carbon extracted via tCDR ($C_{CE}(t)$) to permanent stores. Fossil

carbon release (Eq. 2) is approximated by a logistic function parametrised by the maximum emitted carbon c_{max} and rate of carbon release r_i.

The social management loop is motivated by proposals of CE as a management intervention in response to intolerable levels of global warming. It comprises atmospheric carbon monitoring and tCDR action conditional on the proximity to a critical threshold of atmospheric carbon content (Eq. 3). CE action is implemented via a tCDR carbon offtake from terrestrial carbon ($H_{CE}(t)$) and storage in a permanent (geological) sink C_{CE}. Carbon offtake for tCDR (Eq. 11) is defined analogous to human offtake for agriculture or land use change (Eq. 13), however, with a dynamic offtake rate $\alpha_{CE}(C_a(t))$ (Eq. 12).

TCDR characteristics are governed by three parameters: (i) implementation threshold ($\tilde{C_a}$) in terms of atmospheric carbon content, representing societal foresightedness, (ii) maximally achievable rate of tCDR (α_{max}), a measure of societies' efforts, as well as biogeochemical constraints and (iii) the slope of tCDR implementation (s_{CE}), parametrising social and economic implementation capacities. Figure 2 depicts an exemplary tCDR trajectory for constant terrestrial carbon in Eq. (11) for two values of s_{CE}. The implementation time can be computed from the slope of tCDR-implementation by using current increase rates of atmospheric carbon as a conversion factor. With current increase rates of approximately 2 ppmv a^{-1} (Tans and Keeling, 2015), the two depicted values of s_{CE} correspond to tCDR ramp-up times of approximately 20 years and 40 years (from 10 % to 90 % capacity) for $s_{CE} = 0.1$ ppmv^{-1} (solid) and $s_{CE} = 0.05$ ppmv^{-1} (dashed), respectively.

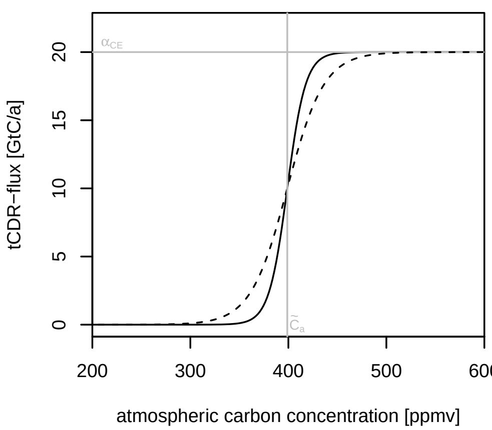

Figure 2. Sigmoidal dependence of the tCDR-flux on atmospheric carbon concentrations for two values of the tCDR implementation capacity parameter (slope): $s_{CE} = 0.1$ ppmv^{-1} (solid line) and $s_{CE} = 0.05$ ppmv^{-1} (dashed line). The threshold parameter ($\tilde{C_a}$) is set at 400 ppmv atmospheric carbon concentration and the potentially achievable tCDR-flux is parametrised with $\alpha_{max} = 20$ GtC a^{-1}.

The atmosphere and ocean carbon feedback (Eq. 4) is governed by diffusion, ~~depending~~ which in the model is assumed to depend on the difference between atmospheric and maritime carbon pools.

Land-atmosphere interaction is determined by both ecological and social processes: the net ecosystem productivity (Eq. 6), tCDR offtake (Eq. 11) and other human offtake for agriculture and other land use (Eq. 13), respectively.

Net ecosystem productivity is given by the net carbon flux of photosynthesis (Eq. 8) and respiration (Eq. 9), multiplied with the terrestrial carbon pool and a logistic dampening function which represents competition for space, sunlight, water or nutrients. Both photosynthesis and respiration are continuous functions of global land temperature ($T(t)$, Eq. 10), which in turn depends linearly on atmospheric carbon content. It is important to note that in our model respiration exceeds photosynthesis for higher temperatures (Fig. 3). The state of equilibrium of the terrestrial carbon pool is thus determined by the land surface temperature, as well as the terrestrial carbon carrying capacity (Eq. 7) in the density function. In contrast to Anderies et al. (2013), we implement a dynamic terrestrial carbon carrying capacity as a function of atmospheric carbon content. This is motivated by a number of factors such as CO_2 fertilisation and a higher water use efficiency under higher atmospheric carbon concentrations, as well as higher average vegetation density in a warmer world (e.g. Drake et al., 1997; Keenan et al., 2013). For low atmospheric carbon we assume a rapid increase of terrestrial carbon storage capacity as a function of atmospheric carbon concentration and a saturation of storage capacity for high atmospheric carbon, in line with assessments of coupled carbon-cycle climate models (Heimann and Reichstein, 2008). The functional relationship in (Eq. 7) follows these constraints for chosen parameter values (Sect. 2.2).

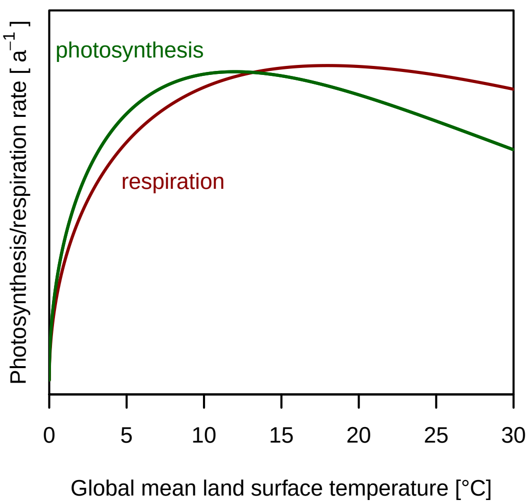

Figure 3. Modelled photosynthesis and respiration rates as a function of global mean land surface temperature.

2.2 Calibration of model parameters

A sufficiently suitable application of a conceptual model in the context of the planetary boundaries as in Steffen et al. (2015) requires the model's ability to simulate credible transients of global carbon dynamics. In order to achieve this, we calibrated model parameters to observed carbon fluxes and pools, as well as simulation results of detailed high-resolution Earth system models.

Because we simulate relative dynamics between the different carbon compartments and do not aim at prognostics of actual time evolution of carbon pools, all carbon fluxes and pools are normalised to the the active carbon at preindustrial times, i.e. the total sum of preindustrial carbon in the year 1750 AD (3989 GtC, Fig. 1). All normalised parameter values are summarised in Table 2.

Parameter	Symbol	Value	Unit
ecosystem-dependent conversion factor	r_{tc}	2.5	a^{-1}
scaling factor for photosynthesis $P(T)$	a_p	0.48	$(20\mathrm{K})^{-\mathrm{b_p}}$
scaling factor for respiration $R(T)$	a_r	0.40	$(20\mathrm{K})^{-\mathrm{b_r}}$
power law exponent for increase in $P(T)$ for low T	b_p	0.5	1
power law exponent for increase in $R(T)$ for low T	b_r	0.5	1
rate of exp. decrease in $P(T)$ for high T	c_p	0.556	$(20\mathrm{K})^{-1}$
rate of exp. decrease in $R(T)$ for high T	c_r	0.833	$(20\mathrm{K})^{-1}$
scaling factor for terrestrial carbon carrying capacity	a_k	-0.6	1
rate of exp. increase for terrestrial carbon carrying capacity	b_k	13.0	1
offset for terrestrial carbon carrying capacity	c_k	0.75	1
human terrestrial carbon offtake rate	α	0.0004	a^{-1}
slope of $T-C_a$ relationship	a_T	1.06	20K
intercept of $T-C_a$ relationship	b_T	0.227	20K
carbon solubility in sea water factor	β	0.654	1
atmosphere ocean diffusion coefficient	a_m	0.0166	20K
(*) atmospheric carbon threshold of tCDR implementation	$\tilde{C}_a$	0 – 0.3	1
rapidity of tCDR ramp-up (tCDR implementation capacity)	s_{CE}	200	1
(*) maximum tCDR rate	α_{max}	0 – 0.03	a^{-1}
(*) size of geological fossil carbon stock	c_{max}	0 – 0.51	1
industrialization rate	r_i	0.03	a^{-1}
climate change boundary	b_a	0.21	1
land system change boundary	b_l	0.59	1
ocean acidification boundary	b_m	0.31	1

Table 2. Calibrated model parameters. After normalization to preindustrial carbon pools, remaining units are years (a) and temperature (20K). Parameters marked with an asterisk (*) are varied during the analysis and the parameter range is stated.

2.2.1 Temperature

The linear relationship For the calibration of the linear relationship between temperature and atmospheric carbon content (Eq. 10) was calibrated to reported long-term we used the transient response of cumulative emissions (TRCE) with a reported global mean surface temperature increase per emitted carbon of 2K/1000GtC (Joos et al., 2013; Gillett et al., 2013). On timescales of a few hundred years, approximately 50 % of the emitted carbon stays in the atmosphere (Archer et al., 2009; Joos et al., 2013).

~~Thus,~~ Assuming an airborne fraction of 0.5 (Knorr, 2009; Gloor et al., 2010), the global mean temperature increase rate per atmospheric carbon increase (Eq. 10) is approximately twice the temperature increase rate of emitted carbon (TRCE), i.e. 2K/~~500 GtC~~ 500GtC in the atmosphere~~)~~. From this global surface temperature increase rate (2/3 ocean and 1/3 land surface), the global land surface temperature increase can be inferred via the global land/sea warming ratio of approximately 1.6 (Sutton et al., 2007). Thus, we approximate a global land surface warming rate of 5.3K/1000GtC remaining in the atmosphere. The y-offset (b_T in Eq. 10) was inferred via global land surface temperature anomalies from 1880–2000 (Jones et al., 2012), a global average (1880–2000) land temperature of 8.5 °C (NOAA, 2015) and observed monthly mean CO_2 concentrations (Mauna Loa, 1959–2000) (Tans and Keeling, 2015).

2.2.2 Ocean-atmosphere dynamics

The carbon solubility in sea water factor (β) is directly determined by the assumption of pre-industrial equilibrium between upper-ocean and atmospheric carbon ($\dot{C_m}(0) = 0$). From this and a present carbon flux from the atmosphere to the ocean of $\dot{C_m}(t_{tod}) = 2.3$ GtC a^{-1} (Ciais et al., 2013) follows the atmosphere-ocean diffusion coefficient a_m.

2.2.3 Terrestrial dynamics

Photosynthesis and respiration are calibrated according to temperature relationships reported in the literature. However, literature generally specifies temperature relationships at small temporal and spatial scales in controlled environments, whereas our model equations refer to a global average of day and night-time temperature. Thus, only a rough estimation of the relationship between temperature and photosynthesis/respiration for model calibration is possible. As in Anderies et al. (2013), we assume a maximum of respiration at a global land surface temperature of 18 °C (supported by Yuan et al. (2011)), determining the ratio of parameters $b_r/c_r = 18$ °C (Fig. 3). We choose a maximum of photosynthesis at 12 °C, incorporating a CO_2 fertilisation feedback indirectly via the dependence of temperature on atmospheric carbon ($b_p/c_p = 12$ °C). The amplitudes of photosynthesis and respiration functions (a_r and a_p, respectively) are approximated for agreement with carbon fluxes reported in Ciais et al. (2013). Note that the functional form of carbon fluxes is not decisive for the model dynamics, however, it is important that the curves of photosynthesis and respiration intersect at some temperature limit where ecosystem respiration exceeds photosynthesis. With our parametrisation this is the case at a global mean land surface temperature of approximately 13 °C, which is 4.5 °C warmer than the 20th century average global mean land surface temperature (NOAA, 2015). This is in line with multi-model assessments in carbon reversal studies (e.g. Heimann and Reichstein, 2008; Friend et al., 2013).

The terrestrial carbon carrying capacity $K(C_a(t))$ in $\dot{C}_t(t)$ determines how much carbon can be accumulated in the terrestrial system ~~.~~ at maximum, as long as photosynthesis exceeds respiration (refer to Eq. 6). $K(C_a(t))$ was calibrated to represent both, past long term climatic and terrestrial carbon changes (last glacial maximum to Holocene) (Crowley, 1995; François et al., 1998; Kaplan et al., 2002; Joos et al., 2004) and prognostics of climate change impacts on terrestrial carbon storage (Joos et al., 2001; Lucht et al., 2006; Friend et al., 2013), to capture terrestrial changes due to climate variability (Fig. 4).

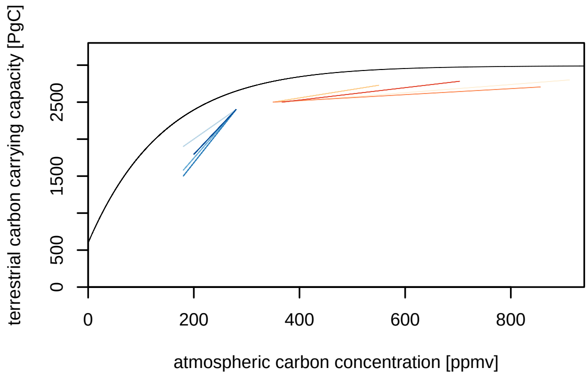

Figure 4. Approximated terrestrial carbon carrying capacity (black line). Blue lines represent approximate changes in terrestrial carbon storage published in Crowley (1995); François et al. (1998); Kaplan et al. (2002); Joos et al. (2004). Red lines represent simulated changes in terrestrial carbon storage due to climate change reported by Joos et al. (2001); Lucht et al. (2006); Friend et al. (2013)

Human activities such as fires, deforestation and agricultural land use that affect terrestrial carbon stocks are summarised as human offtake of biomass and are presently estimated at ~~1.1~~ $H(t_{tod}) = 1.1$ GtC a^{-1} (Ciais et al., 2013). With a present terrestrial carbon pool of ~~2470 GtC follows~~ $C_t(t_{tod}) = 2470$ GtC we calculate the human offtake rate $\alpha = H(t_{tod})/C_t(t_{tod})$.

2.2.4 Fossil fuel emissions

The size of the geological fossil carbon stock c_{max} determines the carbon released from fossil reservoirs (Eq. 2) and plays an important role for carbon dynamics (Sec. 3.4). In the scope of this study, c_{max} is varied to assess different baseline emissions following the cumulative emissions of the representative concentration pathways (RCPs). RCP2.6 is a low-emission scenario with cumulative emissions of approximately 880 GtC ($c_{max} = 0.2$) (Vuuren et al., 2011). The two medium emission scenarios RCP4.5 and RCP6.0 have cumulative emissions of approximately 1200 GtC ($c_{max} = 0.31$) (Thomson et al., 2011) and 1400 GtC ($c_{max} = 0.36$) (Masui et al., 2011), respectively. RCP8.5 represents a business as usual scenario with cumulative emissions of approximately 2000 GtC ($c_{max} = 0.51$) (Riahi et al., 2011).

2.3 Planetary Boundaries

We use the carbon-related planetary boundaries (climate change, ocean acidification and land system change) to define the desirability of given trajectories of carbon pool evolution. The proposed locations of these boundaries are normalised to match the normalisation of our model. ~~Note that the exact location and normalisation of the boundaries is not decisive for our results because we qualitatively analyse the influence of tCDR management on the existence of desirable trajectories. Slightly different sets of planetary boundaries would not qualitatively change the systemic effects reported in this study.~~

The planetary boundary for climate change is proposed at ~~350–450~~ 350 ppmv CO_2 equivalents in the atmosphere ~~(Steffen et al., 2015). Taking the mean,~~ with an uncertainty range to 450 ppmv (Steffen et al., 2015). For our study we take the middle of the uncertainty range (400 ppmv~~, the~~) because critical atmospheric thresholds are likely to be located somewhere within the uncertainty range and obtain a normalised climate change boundary is at 0.21 atmospheric carbon. Ocean acidification is measured via the saturation state of aragonite and its boundary is set at 80 % of the preindustrial average annual global saturation state of aragonite (Steffen et al., 2015). Since chemical processes are not explicitly represented in our model, this measure is not directly transferable to maritime carbon content. ~~However, at the~~ This measure is not directly transferable to maritime carbon content because it largely depends on chemical variables such as pH-value, ocean alkalinity and dissolved inorganic carbon that are not included in the model. At the current carbon content (1150 GtC), the saturation state of aragonite is at 84 % of the preindustrial value (Guinotte and Fabry, 2008). We therefore estimate the normalised ocean acidification boundary at 0.31, ~~slightly~~ about 5 % higher than the current value of the marine carbon stock (0.29). The land system change boundary is defined in terms of the amount of remaining forest cover~~and~~, motivated by critical biogeophysical feedbacks of forest biomes to the physical climate system (Steffen et al., 2015). The global boundary has been specified as 75 % of global forest cover remaining (Steffen et al., 2015). ~~As an estimate~~Due to the lack of biogeophysical feedbacks in the model, we translate deforestation into carbon content by measuring the loss of vegetation carbon with deforestation. We thereby neglect vegetation carbon of all non-forest biomes, while at the same time neglecting soil carbon changes by deforestation (Heck et al., 2016), thus approximating that soil carbon changes by deforestation are of the same order of magnitude as vegetation carbon pools of non-forest biomes. With vegetation carbon of 550 GtC (Ciais et al., 2013), we obtain a normalised land system change boundary at 0.59.

~~Parameter Symbol Value Unitecosystem-dependent conversion factorr_{tc}2.5scaling factor for photosynthesis $P(T)$ a_p0.48 scaling factor for respiration $R(T)$ a_r0.40 power law exponent for increase in $P(T)$ for low $T b_p$0.5 power law exponent for increase in $R(T)$ for low T b_r 0.5rate of exp. decrease in $P(T)$ for high $T c_p$0.556 rate of exp. decrease in $R(T)$ for high $T c_r$0.833scaling factor for terrestrial carbon carrying capacitya_k -0.6rate of exp. increase for terrestrial carbon carrying capacityb_k13.0offset for terrestrial carbon carrying capacityc_k0.75human terrestrial carbon offtake rateα0.0004 slope of T~~

$- C_a$ relationshipa_T1.06 intercept of $T - C_a$ relationshipb_T0.227carbon solubility in sea water factorβ0.654 atmosphere ocean diffusion coefficient a_m0.0166 (*) atmospheric carbon threshold of tCDR implementation$\tilde{C}_a 0 - 0.3$rapidity of tCDR ramp-up (tCDR implementation capacity) s_{CE}200(*) maximum tCDR rate $\alpha_{max} 0 - 0.03$(*) size of geological fossil carbon stock $c_{max} 0 - 0.51$ industrialization rate r_i0.03 climate change boundary b_a0.21 land system change boundary b_l0.59ocean acidification boundary b_m0.31 Calibrated model parameters. After normalization to preindustrial carbon pools, remaining units are years (a) and temperature (20K). Parameters marked with an asterisk (*) are varied during the analysis and the parameter range is stated.

Note that the exact location and normalisation of the boundaries is not decisive for our results because we qualitatively analyse the influence of tCDR management on the existence of desirable trajectories. Slightly different sets of planetary boundaries would not qualitatively change the systemic effects reported in this study.

2.4 Model analysis and terminology

Our analysis of the co-evolutionary system aims at assessing transient dynamics of carbon pools with respect to planetary boundaries. First (Sect. 3.1), we run the model and exemplarily show the influence of socially controlled parameters of tCDR implementation on the transient carbon pool evolution. It is of particular relevance under what circumstances the simulated carbon pool trajectories (atmosphere, ocean and land) do not cross their respective planetary boundaries. We refer to the regions on the safe side of the planetary boundaries as *safe regions*. All carbon pool trajectories remaining in the respective safe region at all times are considered *safe trajectories*. For example, all atmospheric carbon trajectories that do not cross the planetary boundary for climate change (i.e. trajectories that are in the safe region of atmospheric carbon) are safe atmospheric carbon trajectories. System states with each carbon pool remaining in its respective safe region are referred to as carbon system states in the safe operating space, i.e. *safe states*.

In a nonlinear dynamical system, trajectories can be sensitive to initial conditions. The preindustrial distribution of carbon pools, as well as carbon dynamics in the Earth system are relatively well assessed, while still subject to high uncertainty (Ciais et al., 2013). Furthermore, considerable uncertainty remains with respect to our conceptual model structure and the exact values of planetary boundaries. Bearing in mind these inherent uncertainties, we explore how robust the existence of safe trajectories is under a variation of the initial conditions, i.e. the initial carbon pool distribution, and different tCDR characteristics (Sect. 3.2).

Such a variation of initial conditions is also a common approach to conceptualising and measuring resilience of social-ecological systems as the ability to return to an attracting state after a perturbation (Holling, 1973; Scheffer et al., 2001). A suitable approach to quantifying the likelihood of a complex system to return to an attracting state under finite perturbations is basin stability analysis (Menck et al., 2013).

In the context of planetary boundaries, not necessarily all trajectories that approach a *safe attractor* (i.e. an attractor within the SOS associated to all three planetary boundaries) would be considered safe, because they could temporarily leave the safe region. The concept of constrained basin stability (van Kan et al., 2016) and related methods (Hellmann et al., 2015) provide generalisations of basin stability that allow taking transient phenomena into account. Similarly to the constrained basin stability approach, we classify different domains in state space based on transient dynamics of carbon pools. The set of initial conditions resulting in safe carbon trajectories form the *safe domain*. We refer to this domain as the *manageable core of the SOS (MCSOS)*, as it depends on the tCDR management characteristics and the emission pathway. The *undesirable domain* is formed by all initial conditions resulting in a transgression of all three carbon boundaries at some point in time. Remaining state space domains are formed by initial conditions leading to a transgression of a subset of planetary boundaries. They are referred to as the respective *partially manageable domains (MD)* (e.g. the land manageable domain is the state space domain of initial conditions with trajectories without a transgression of the land boundary).

The computational efficiency of our model allows for a systematic analysis of the MCSOS and other domains under variation of societal parameters (tCDR management and fossil fuel emissions). We analyse how the size of all domains (MCSOS, partially MDs and the undesirable domain) varies with different tCDR characteristics (Sect. 3.3) and emission pathways (Sect. 3.4). In the spirit of van Kan et al. (2016), the size of (partially) manageable domains can be interpreted as a resilience-like measure of the opportunities to stay within the carbon related SOS, taking into account inherent structural uncertainties of our model, the location of planetary boundaries, and the preindustrial carbon pool distribution. Note that the maximum extent of the MCSOS is constrained by the planetary boundaries, but it may differ from the SOS (i.e. the *safe* region), as the safety of the domain is determined by transient system dynamics, whereas the SOS is defined within static planetary boundaries.

3 Results and Discussion

3.1 Carbon system trajectories subject to societal tCDR management loop

To illustrate how the co-evolutionary social-environmental system evolves with respect to carbon-related planetary boundaries, Figure 5 depicts trajectories of the major carbon pools with tCDR adhering to different management characteristics. All trajectories start at their respective normalised preindustrial state. The normalised planetary boundaries (Sect. 2.3) are indicated as dotted lines and the safe region of each boundary (refer to Sect. 2.4) is shaded in the respective colours. Variation of tCDR characteristics reflects uncertainty about possible tCDR rates related to overall biomass harvesting potentials and societies' implementation capacities (Sect. 2.1).

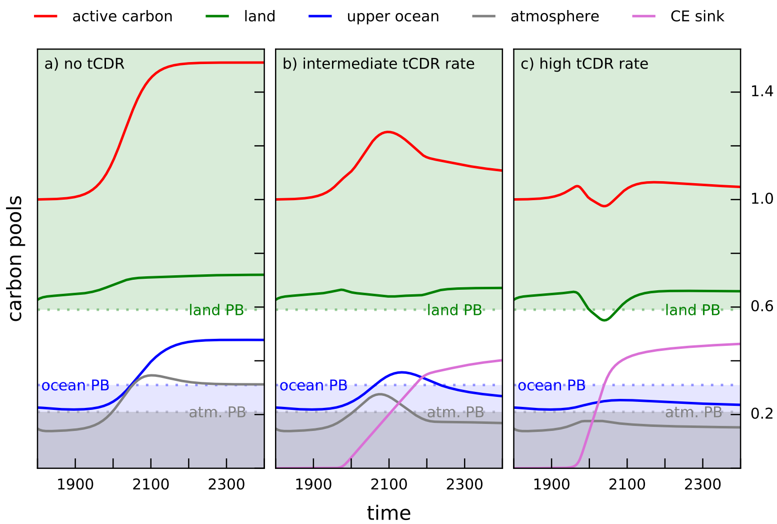

Figure 5. Time evolution of the normalised carbon pools in our model of the carbon system for three tCDR configurations with a high emission baseline (cumulative emissions as in RCP8.5 (Riahi et al., 2011)): a) without tCDR (α_{max} = 0), b) intermediate tCDR rate (α_{max} = 0.0025) and c) high tCDR rate (α_{max}= 0.025). Total active carbon (red) is increased by fossil fuel emissions (c_{max} = 0.51) with dynamic response of the terrestrial carbon pool (green), maritime carbon pool (blue) and atmospheric carbon pool (grey). The tCDR sink (purple) stores carbon extracted from the active system. Shaded areas represent the respective safe regions of land, ocean and atmosphere in green, blue and grey. Dotted lines indicate the location of the associated planetary boundaries.

The emission baseline used for all results displayed in Figure 5 is a business-as-usual scenario with cumulative emissions as in RCP8.5 (Riahi et al., 2011). Without tCDR (Fig. 5a), all fossil carbon societies emit into the atmosphere is distributed to ocean, land and atmosphere. This results in more active carbon (red), leading to carbon accumulation in all pools and a transgression of the atmosphere and ocean boundaries. In this emission scenario, the land system accumulates carbon and, thus, moves away from its planetary boundary in our model setting (note that the actual control variable of the planetary boundary of land-system change as defined by Steffen et al. (2015) is the remaining forest cover, which would not be directly modified by changing atmospheric carbon concentrations). Moreover, higher emission baselines (results not shown here) can lead to decreasing terrestrial carbon stocks when respiration dominates over photosynthesis due to strong global warming.

In Figures 5b) and c), the societal tCDR response via harvesting from the terrestrial carbon stock and subsequent storage starts just before the atmospheric boundary is reached ($\tilde{C}_a = 0.18 \sim 340$ ppmv). With a low tCDR rate (maximal storage flux of about 7 GtC a^{-1}, α_{max} = 0.0025), the CE sink is filled relatively slowly (Fig. 5b). Thus, a transient transgression of the atmosphere and ocean boundaries cannot be prevented. However, all trajectories re-enter their respective *safe* region after about 150 years. A higher tCDR rate (α_{max} = 0.025, corresponding to very high potential storage fluxes of 26 $\mathrm{GtC\ a^{-1}}$ or 5 % of global biomass per year) can prevent a large increase in active carbon and thus prevents the transgression of both, atmosphere and ocean boundaries (Fig. 5c). However, extensive harvest from the land carbon pool then leads to a temporary transgression of the land boundary. The implementation of tCDR was thus effective in its purpose of preventing entry into a dangerous region of climate change, but at the cost of exploiting the land system to an extent that crossed the land system change boundary.

These results show that small tCDR rates (Fig. 5b) (or too late implementation, results not shown here) do not necessarily keep the system in the SOS. High tCDR rates (Fig. 5c) could seem successful when focusing on the climate change boundary, but might in fact not be feasible if other components of the carbon system are taken into account. In light of ongoing deforestation for the purpose of bioenergy production (Gao et al., 2011), this simulated ~~co-transgression~~ collateral transgression of the land system change boundary with large-scale tCDR is an important and plausible feature of the model.

In the actual Earth system, a transgression of the land system change boundary might evoke additional trade-offs to the biogeophysical climate system (Foley et al., 2003), which are not represented in the model. For example, large tCDR rates can only be achieved by large-scale land-use change that could alter atmospheric circulations and rainfall patterns (Snyder et al., 2004) even though the carbon related climate change boundary might not be transgressed with high tCDR rates.

The carbon values stated here are primarily given as an orientation for the reader, and should not be directly interpreted with respect to tCDR feasibility assessments. However, tCDR rates of 7 $\mathrm{GtC\ a^{-1}}$ are in line with more conservative biomass harvest potentials considering biodiversity conservation and agricultural limits (Dornburg et al., 2010; Beringer et al., 2011). More idealistic assessments of tCDR rates of more than 35 $\mathrm{GtC\ a^{-1}}$ – assuming high biomass yields on more than 1/4 of global land area – have been reported as well (Smeets et al., 2007). In this context, the range of tCDR rates studied in this paper reflects both conservative and highly optimistic tCDR potentials reported in the literature.

3.2 State space domain structure of the Earth's carbon system subject to societal tCDR management loop

We compute the state space domain structure (refer to Sect. 2.4) from a sample of initial conditions around the preindustrial carbon state. We sample approximately 66,000 initial conditions from a regular grid by variation of each carbon pool by ± 0.2 around the preindustrial conditions. This range is a pragmatic choice which does not influence the following qualitative analysis. To compute the existing domains, we evolve each initial condition for 600 years in time and colour it according to the domains following from the transient properties of the trajectories of land, atmosphere and ocean carbon, as described above. The mapping of initial conditions sheds light on possible domains in the carbon system and potential transitions into other state space domains in our model of the carbon cycle. In this context, the vicinity of the preindustrial and current Earth system states to such domain boundaries in the model's carbon state space is of particular relevance.

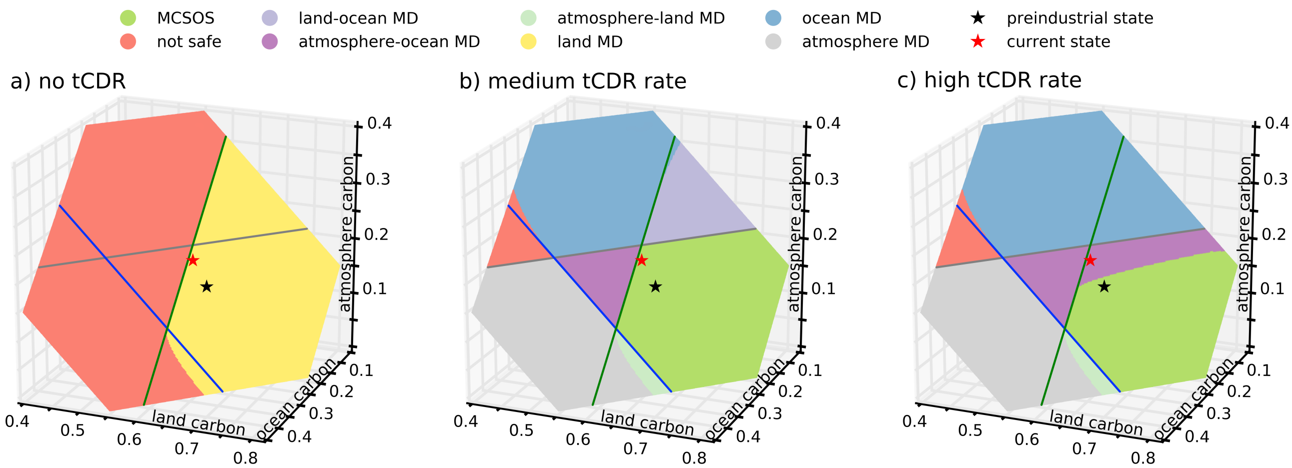

Figure 6. Charting of normalised carbon system state space in our model for three tCDR management characteristics with identical, relatively low emission baseline ($c_{max} = 0.2$): a) without tCDR ($\alpha_{max} = 0$), b) intermediate tCDR rates ($\alpha_{max} = 0.004$) and c) high tCDR rates ($\alpha_{max} = 0.04$). The two-dimensional plane is formed by sampling initial conditions around the preindustrial state (variation of carbon stocks by ± 0.2 while conserving total carbon in the system). Each domain is coloured according to transient properties of trajectories starting in different state space regions. For example, the MCSOS (i.e. safe domain) is formed by the initial conditions of *safe* trajectories, whereas red indicates the initial conditions of trajectories crossing all respective planetary boundaries at some point of the simulation. Lines indicate the associated planetary boundaries of atmosphere, land and ocean in grey, green and blue, respectively.

Figure 6 shows the existing domains without tCDR (a), with intermediate tCDR rates (b) and with very high tCDR rates (c). The emission baseline is the same for all variations of tCDR characteristics, with cumulative emissions of approximately 880 GtC, which is comparable to RCP2.6 cumulative emissions (Vuuren et al., 2011). The current state of the carbon cycle is located in proximity to domain borders, highlighting that it is close to a transgression of the land system and climate change boundaries. Historical emissions and land system changes have moved the state of the carbon cycle closer towards the undesirable domain, and remaining on an emission trajectory similar to RCP2.6 without tCDR results in the non-existence of the MCSOS (Fig. 6a). Thus, the manageable core does not exist if the implementation of tCDR management is not considered by society, even in a relatively low emission scenario.

Figures 6b) and c) serve as an example of how human intervention and management by tCDR can influence the size and even the existence of the MCSOS and other domains. With an implementation of tCDR, the MCSOS can be re-established, potentially to its full extent, which is directly determined by the three planetary boundaries (Fig. 6b). Even for a relatively low emission scenario, the tCDR threshold needs to be at sufficiently low atmospheric carbon contents ($\tilde{C_a}$=0.16) to prevent potential boundary transgressions. Nevertheless, because of past land use change, the current Earth system state is approaching domains with unsafe land system and climate change. If tCDR is applied under the same conditions but with a ten times higher potential tCDR rate (α_{max}=0.04), the MCSOS shrinks due to over-exploitation of the land system for tCDR (Fig. 6c). The current state of the carbon cycle of the Earth system is out of the MCSOS. In this case, large societal commitment to avoid a transgression of the climate change boundary leads to a nonlinear feedback on the land system, resulting in a transgression of the land system change boundary in our model.

3.3 Size of manageable domains under variation of tCDR characteristics

The size and existence of the MCSOS and other state space domains depends on tCDR characteristics (refer to Sect. 2.4). We compute the size of the different state space domains depending on the most decisive management parameters, i.e. on the implementation threshold $\tilde{C_a}$ and on the potential maximum tCDR rate α_{max}. The size of all domains is measured in relation to the size of the considered state space section as depicted in Figure 6, which is given by a variation of preindustrial conditions by ± 0.2.

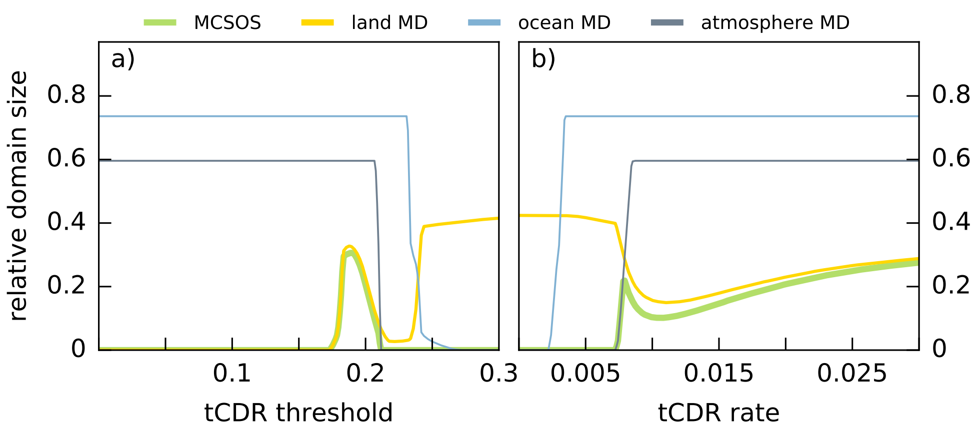

Figure 7. Relative size of domains in modelled carbon system state space for normalised parameter variation of a) tCDR threshold (with $\alpha_{max} = 0.02$) and b) tCDR rate (with $\tilde{C_a} = 0.2$) for a medium emission scenario ($c_{max} = 0.4 \sim 1600$ GtC cumulative emissions). All domain sizes are given as shares of the state space region defined by a variation of the preindustrial conditions by ± 0.2.

Figure 7 depicts the relative size of the MCSOS and the partially manageable domains under baseline emissions of $c_{max} = 0.4$, corresponding to cumulative emissions on the order of RCP6.0.

The size of the MCSOS or partially MDs can be interpreted as a form of resilience of the system (i.e. the likelihood that the system stays within the carbon related SOS). Thus, we measure the resilience of the carbon cycle by the size of MCSOS (i.e. the opportunity of success of tCDR to maintain safe trajectories). This strongly depends on the atmospheric carbon threshold at which tCDR is implemented. Obviously, only the anticipation of an approaching planetary boundary can prevent a transgression thereof. Thresholds higher than the atmospheric carbon boundary ($b_l = 0.21$) are not sufficient in sustaining a MCSOS, because the atmosphere MD disappears by definition at $\tilde{C}_a = 0.21$ (grey line in Fig. 7a).

However, strong anticipation coupled with too early tCDR implementation does not necessarily maintain the system within the SOS. If tCDR is initialized at relatively low atmospheric carbon contents ($\tilde{C}_a = 0.13$ (approx.~~330~~. 330 ppmv) in Fig. 7a), the MCSOS is diminished due to a transgression of the land system change boundary at some point in time. Hence, the window of opportunity for using tCDR as a means of staying in the SOS under this exemplary fossil fuel emission scenario is limited to a relatively narrow range of tCDR implementation thresholds.

Similar to the tCDR threshold, the parameter governing the maximal achievable rate of tCDR plays a decisive role for the existence of the MCSOS. With a tCDR implementation threshold not far below the atmospheric carbon boundary ($\tilde{C}_a = 0.2$), high tCDR rates are required in order to maintain a MCSOS. TCDR starts being effective in maintaining a MCSOS at a rate of $\alpha_{max} > 0.007$ (corresponding to approx. 16.5 GtC a^{-1} with a fixed land carbon pool of 0.6). Rates smaller than that are not sufficient because of a lacking atmospheric MD (grey line in Fig. 7b). The carbon cycle in our model shows nonlinear behaviour for higher tCDR rates to decrease atmospheric carbon via tCDR. Higher tCDR rates result in a smaller land MD due to over-exploitation of the photosynthetic productivity of the system until $\alpha_{max} = 0.01$. Higher rates, however, lead to overall smaller reductions of the land MD. This nonlinearity is evoked by the co-evolutionary feedbacks between society and the carbon cycle, which lead to a deceasing tCDR flux if the system is in the atmosphere MD. Thus, sufficiently high tCDR rates lead to fast atmospheric carbon decrease and tCDR is switched off before the land system boundary is transgressed.

This analysis of the size of state space domains suggests that the success of tCDR in sustaining the Earth system's persistence in the carbon SOS nonlinearly depends on the characteristics of tCDR implementation. On the one hand, foresightedness and anticipation of planetary boundaries are required to maintain the MCSOS, while on the other hand, too early or too intensive management could trigger co-transgressions of other planetary boundaries.

3.4 Opportunities and limitations of tCDR

While anticipation and appropriate management are necessary, the underlying emission scenario plays a major role in the resulting carbon dynamics. Figure 8 exemplarily depicts the relative MCSOS size for variations of tCDR characteristics (threshold and potential maximum rate) for emission pathways in accordance with RCP cumulative emission scenarios. The window of opportunity for successful tCDR decreases with increasing emission baselines. In the case of the low emission RCP2.6 scenario ($c_{max} = 0.2$), the MCSOS can be sustained for a broad range of parameter values (Fig. 8a). The medium emission scenarios RCP4.5 ($c_{max} = 0.31$, Thomson et al. (2011)) and RCP6.0 ($c_{max} = 0.36$, Masui et al. (2011)) show a more narrow range of tCDR characteristics that have the potential to sustain a MCSOS (Fig. 8b and c). In a business-as-usual RCP8.5 scenario, the room for manoeuvring to maintain a MCSOS is very small (Fig. 8d).

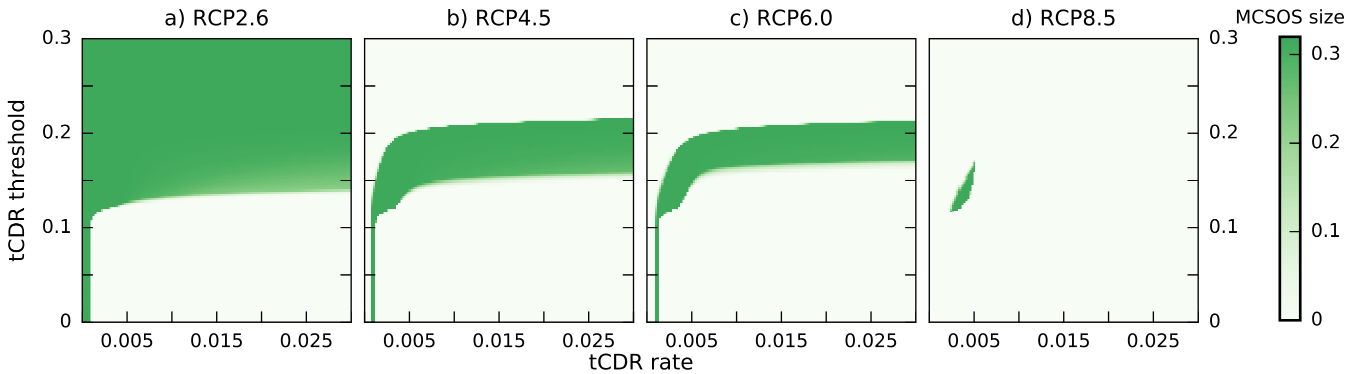

Figure 8. Relative size of the MCSOS for normalised parameter variation of potential maximum tCDR rate (x-axis) and tCDR threshold (y-axis) for different underlying emission scenarios: a) RCP2.6 ($c_{max} = 0.2$), b) RCP4.5 ($c_{max} = 0.31$), c) RCP6.0 ($c_{max} = 0.36$) and d) RCP8.5 ($c_{max} = 0.51$)).

Besides the dependence on the emission scenario, Fig. 8 highlights that for most emission scenarios the range of tCDR thresholds sustaining the MCSOS is narrow and depends on the tCDR rate. As discussed in Section 3.3 (for a fixed tCDR rate), tCDR thresholds higher than the atmospheric carbon boundary (0.21) are not sufficient in preventing a boundary transgression in the medium to high emission scenarios (Fig. 8b-d), whereas small tCDR thresholds lead to a transgression of the land system change boundary. The variation of both, the tCDR rate and threshold, shows that smaller tCDR rates require a smaller minimal tCDR threshold as well as a smaller maximal threshold (Fig. 8b-d).

This dependence of the success of tCDR on both, the tCDR characteristics and the underlying emission scenarios, highlights that any intervention into the climate system triggers a dynamic system response based on the implementation characteristics of tCDR and nonlinear carbon cycle feedbacks. In our conceptual framework, tCDR can be effective in complementing climate change mitigation strategies as employed in low emission scenarios. However, already an RCP4.5 emission scenario narrows the range of potentially successful management options significantly in comparison to RCP2.6 emissions. Under a business-as-usual pathway, tCDR cannot be applied to maintain a MCSOS in a resilient way. In contrast to prevailing reasoning of CE as an emergency action in case of dangerous climate change (Caldeira and Keith, 2010), tCDR would most likely not function as an emergency option under high emission scenarios when additional sustainability dimensions reflected by other planetary boundaries are taken into account.

4 Conclusions

The introduced conceptual modelling approach – combining carbon cycle dynamics with a societal feedback loop of carbon monitoring and terrestrial carbon dioxide removal (tCDR) action – provides valuable insights into system-level constraints to navigating within the carbon-related safe operating space defined by several interlinked planetary boundaries. Despite the fact that the reported results cannot be taken as exact quantitative prognostics of carbon pool evolution, our analysis has shown that ~~an intervention into the climate system by climate engineering nonlinearly depends on the characteristics of terrestrial carbon dioxide removal (tCDR) implementation. TCDR~~ employing tCDR for managing the atmospheric carbon pool does not necessarily safeguard the carbon cycle in ~~a~~ the safe operating space ~~defined by several interlinked planetary boundaries because of potential trade-offs with land and ocean carbon pools.~~ because of nonlinear carbon cycle feedbacks.

The success of maintaining a manageable core of the safe operating space depends on the degree of anticipation of climate change, the potential maximum tCDR rate, as well as the underlying emission pathway. While tCDR might be successfully deployed as part of a strong climate change mitigation scenario, it is not likely to be effective in a business-as-usual scenario. Particularly, the focus on one planetary boundary alone (e.g. climate change), may lead to navigating the Earth system out of the carbon-related safe operating space due to collateral transgression of other boundaries (e.g. land system change). ~~This highlights the importance of an integrated sustainability assessment in the context of~~ In light of numerous (economically based) integrated assessment studies proposing tCDR to counteract anthropogenic emissions, our conceptual results highlight that it is vital to include integrated sustainability assessments of more advanced models to the debate on climate engineering (CE) and climate change mitigation via tCDR~~employing more advanced models.~~ . In the case of tCDR, the consequences for biosphere integrity, as well as trade-offs with agricultural land use and the biogeophysical climate system must be taken into account among other sustainability dimensions reflected by planetary boundaries and beyond.

In analogy to our analysis for tCDR, the approach followed in this paper could be transferred to other CE proposals such as ocean fertilization or solar radiation management. Additionally, it would be of interest to extend the analysis provided here and study Earth system dynamics under CE with more detailed models in line with the framework proposed by ~~(Heitzig et al., 2016)~~Heitzig et al. (2016), including a full topological analysis of the system with respect to the possibility of avoiding or leaving undesired domains, the reachability of desirable domains and the various management dilemmas induced by this accessibility structure.

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