

# Climate sensitivity controls uncertainty in future terrestrial carbon sink

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DOI:  
[10.1029/2018GL077528](https://doi.org/10.1029/2018GL077528)

*Document Version*  
Publisher's PDF, also known as Version of record

*Citation for published version (Harvard):*  
Schurgers, G, Ahlström, A, Arneth, A, Pugh, T & Smith, B 2018, 'Climate sensitivity controls uncertainty in future terrestrial carbon sink', *Geophysical Research Letters*. <https://doi.org/10.1029/2018GL077528>

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Published in *Geophysical Research Letters* on 23/04/2018

DOI: 10.1029/2018GL077528

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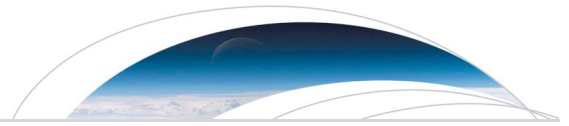
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## RESEARCH LETTER

10.1029/2018GL077528

### Key Points:

- Uncertainty in climatic response to CO<sub>2</sub> is the main cause for differences in estimates of terrestrial carbon uptake with future climate
- The terrestrial biosphere is unlikely to become a strong source of CO<sub>2</sub> in the future
- The fraction of CO<sub>2</sub> emissions taken up by the terrestrial biosphere decreases drastically with higher emissions

### Supporting Information:

- Supporting Information S1

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### Citation:



Schurgers, G., Ahlström, A., Arneth, A., Pugh, T. A. M., & Smith, B. (2018). Climate sensitivity controls uncertainty in future terrestrial carbon sink. *Geophysical Research Letters*, 45. <https://doi.org/10.1029/2018GL077528>

Received 8 FEB 2018

Accepted 12 APR 2018

Accepted article online 23 APR 2018

## Climate Sensitivity Controls Uncertainty in Future Terrestrial Carbon Sink

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**Abstract** For the 21st century, carbon cycle models typically project an increase of terrestrial carbon with increasing atmospheric CO<sub>2</sub> and a decrease with the accompanying climate change. However, these estimates are poorly constrained, primarily because they typically rely on a limited number of emission and climate scenarios. Here we explore a wide range of combinations of CO<sub>2</sub> rise and climate change and assess their likelihood with the climate change responses obtained from climate models. Our results demonstrate that the terrestrial carbon uptake depends critically on the climate sensitivity of individual climate models, representing a large uncertainty of model estimates. In our simulations, the terrestrial biosphere is unlikely to become a strong source of carbon with any likely combination of CO<sub>2</sub> and climate change in the absence of land use change, but the fraction of the emissions taken up by the terrestrial biosphere will decrease drastically with higher emissions.

**Plain Language Summary** The future uptake of carbon dioxide (CO<sub>2</sub>) by the global terrestrial biosphere impacts the atmospheric CO<sub>2</sub> concentration. The response of this uptake to a rise in CO<sub>2</sub> concentration and to climate change is explored here for a wide range of future scenarios. We conclude that a future with low CO<sub>2</sub> increase and little climate change or with high CO<sub>2</sub> increase and strong climate change does not differ greatly in the total uptake of terrestrial CO<sub>2</sub> because of the compensating effects of CO<sub>2</sub> increase and climate change. However, the response is critically determined by the magnitude of climate change for a given CO<sub>2</sub> increase (termed *climate sensitivity*), and a low climate sensitivity will result in a considerably larger terrestrial uptake of CO<sub>2</sub> than a high climate sensitivity.

## 1. Introduction

Terrestrial ecosystems remove CO<sub>2</sub> from the atmosphere, thus dampening the growth rate of the atmospheric CO<sub>2</sub> mixing ratio and thereby mitigating climate change. The large observed interannual variability in atmospheric growth rate (Keeling et al., 1995) is predominantly caused by variations in the land uptake of tropical and subtropical terrestrial ecosystems (Ahlström et al., 2015; Anderegg et al., 2015; Poulter et al., 2014). Overall, the land has been shown to act as a net sink for carbon (Le Quéré et al., 2016), with a flux that consists of two opposing components, each relatively large compared to the net sink. These are a release of CO<sub>2</sub> due to land use change of  $1.3 \pm 0.14$  Pg C/year, and a highly variable uptake of CO<sub>2</sub> in terrestrial ecosystems of, on average,  $2.6 \pm 1.0$  Pg C/year (means for 1982–2011, Le Quéré et al., 2016). The latter is inferred as the residual term in the Earth's total carbon budget and bears large uncertainties (Ballantyne et al., 2015). This terrestrial uptake results primarily from a disequilibrium between photosynthesis and plant and soil respiration.

Projected changes of future carbon uptake, obtained with terrestrial carbon cycle models, vary greatly depending on the general circulation model (GCM) and greenhouse gas emission scenarios used as forcing data (Ahlström et al., 2013; Berthelot et al., 2005; Müller et al., 2016; Schaphoff et al., 2006). In general, models project an increase of the terrestrial uptake with increasing atmospheric CO<sub>2</sub> mixing ratio and a decrease with the accompanying GCM-simulated climate change (Arora et al., 2013; Cox et al., 2000; Dufresne et al., 2002;

Friedlingstein et al., 2003, 2006; Schurgers et al., 2008). Scenario studies almost universally suggest that the land uptake due to direct effects of CO<sub>2</sub> is larger than the impact of climate change for the terrestrial carbon dynamics over the 21st century (Arora et al., 2013; Cramer et al., 2001; Friedlingstein et al., 2006; Schurgers et al., 2008; Sitch et al., 2008). However, the net response of these two effects is poorly constrained, primarily because simulated terrestrial carbon storage is sensitive to the choice of GCM used as forcing. Moreover, the number of greenhouse gas scenarios that are used in the abovementioned studies is limited, which has contributed to the difficulties in reaching conclusive statements on the likelihood of source or sink changes in the future.

In this study, we aim to constrain the carbon cycle response by exploring a wide range of combinations of CO<sub>2</sub> rise and climate change as forcing, which we subsequently compare with the likelihood of those combinations obtained from climate models. We compare these results with a large set of simulations using different representative concentration pathways (RCPs) from a subset of the Coupled Model Intercomparison Project Phase 5 (CMIP5) GCMs as forcing data.

## 2. Materials and Methods

Terrestrial carbon storage was simulated with the dynamic vegetation model LPJ-GUESS (Sitch et al., 2003; Smith et al., 2001). The model simulates the global distribution of 11 plant functional types. Within each plant functional type, CO<sub>2</sub> fluxes from photosynthesis, autotrophic and heterotrophic respiration, along with fluxes originating from disturbance processes and fires were simulated. Litter and soil carbon were captured with one litter and two soil carbon pools.

A simulation for the 20th century was performed applying LPJ-GUESS with a simple consideration of land use (Ahlström et al., 2012), using monthly driving climate (temperature, precipitation, and cloud cover) from the Climatic Research Unit (CRU) TS3.21 data set (Harris et al., 2014) for the period 1901–2012 at a spatial resolution of 0.5° × 0.5°. The atmospheric CO<sub>2</sub> mixing ratio was prescribed following ice core-based reconstructions and atmospheric observations (Etheridge et al., 1996; Keeling et al., 1995), and land use for 1901–2000 was prescribed according to Hurtt et al. (2011). The simulation was preceded by a two-stage spin-up. For the first stage, which aims at creating the 1850 equilibrium state, a 500-year spin-up starting from bare-ground conditions was performed, for which land use and CO<sub>2</sub> were kept constant at their values for 1850 and monthly climate data were taken for 1901–1930 from the CRU data set, with a detrending of the temperatures. For the second stage, which aims at representing the period 1850–1900 dynamically, the period 1850–1900 was simulated with dynamic land use and CO<sub>2</sub>, but with the same 30-year period from the CRU data set.

Two further sets of simulations were performed to assess a wide range of future conditions for 2001–2100. The first set samples combinations of atmospheric CO<sub>2</sub> increase and climate change by varying future changes in atmospheric CO<sub>2</sub> and global mean temperature (GMT) at regular intervals that combine a wide range of plausible changes in both variables. The subsequent analysis focuses on the range of likely combinations of CO<sub>2</sub> rise and climate change from this set. The second set of simulations follows the four RCPs and uses climate anomalies obtained from multiple GCMs from the CMIP5 intercomparison (Taylor et al., 2012). Both sets are explained in more detail below. The simulations from both sets start from the simulated state of the vegetation and soil in year 2000 from the 20th-century run.

The first set of simulations created matrices of combinations of standardized levels of climate change and atmospheric CO<sub>2</sub> increase. By combining five levels of climate change (represented by an increase in GMT between 1981–2000 and 2081–2100 of 0, 2, 4, 6, or 8 K) and five levels of the atmospheric CO<sub>2</sub> mixing ratio (increases of 0, 250, 500, 750, or 1,000 ppmv in 2100 relative to 2000), a matrix of 25 simulations was formed. For representing the change in climate, we use the fact that results from climate models are largely scalable (Mitchell, 2003): The patterns of changes in key variables such as temperature and precipitation are similar between low- and high-emission scenarios but with a different magnitude. Pattern scaling maintains the spatial variability that exists in GCM outputs but scales these with global temperature, which has been suggested for application of the RCP simulations to impact assessments (Moss et al., 2010). This scaling is applied here to generate the abovementioned levels of climate change (explained in detail in the supporting information Figure S1): Grid cell mean monthly anomalies of temperature, precipitation, and incoming shortwave radiation for 2081–2100 relative to a reference period (1981–2000) were determined from a GCM simulation and

were combined with the annual mean global temperature rise between 1981–2000 and 2081–2100 to allow a linear function in monthly climate per degree GMT rise to be defined for each grid cell. This function was used to calculate a monthly anomaly for each climate variable throughout the period 2001–2100 to meet the specified target rise in 2100. To maintain interannual variability (at present-day levels), these anomalies were added to a repeated set of detrended CRU data for 1981–2000. For this scaling, physically meaningless values (negative precipitation or radiation) were suppressed, but such conditions arose only incidentally and could arise only in cases where the target GMT exceeded that of the original climate model simulation. For the atmospheric CO<sub>2</sub> mixing ratio used as forcing for LPJ-GUESS, a linear increase is imposed to obtain the five given levels of increase by 2100 relative to 2000. In all simulations, land use was kept constant at the level for 2000.

The scaling described above was applied to climate change patterns from RCP 8.5 simulations with four different GCMs, chosen to represent a wide range in key carbon cycle relevant properties (Figure S2), resulting in four matrices with 25 simulations each. For one of the GCMs, climate change patterns from three additional RCPs (2.6, 4.5, and 6.5) were tested. The GCMs and RCPs used are listed in Table S1.

To illustrate the likelihood of the combinations of CO<sub>2</sub> and climate forcing in the matrix of 25 scaled simulations, an envelope of changes in CO<sub>2</sub> and GMT from an ensemble of GCMs from CMIP5 (Taylor et al., 2012) was applied. This envelope was obtained by estimating logarithmic curves through the fifth and 95th percentile of the confidence interval of the GMT changes reported for the four RCPs (Figure S3) and accounting for the offset between pre-industrial and present-day conditions (Hartmann et al., 2013), by estimating a climate sensitivity  $s$  (in K) that is obtained with the commonly used doubling of the CO<sub>2</sub> concentration. The range obtained for  $s$  in our study (1.8–3.2 K) is smaller than the range reported for the equilibrium climate sensitivity (ECS) in IPCC AR5 (Flato et al., 2013; 2.1–4.7 K for the CMIP5 GCMs), because the RCP simulations are not in equilibrium by 2100.

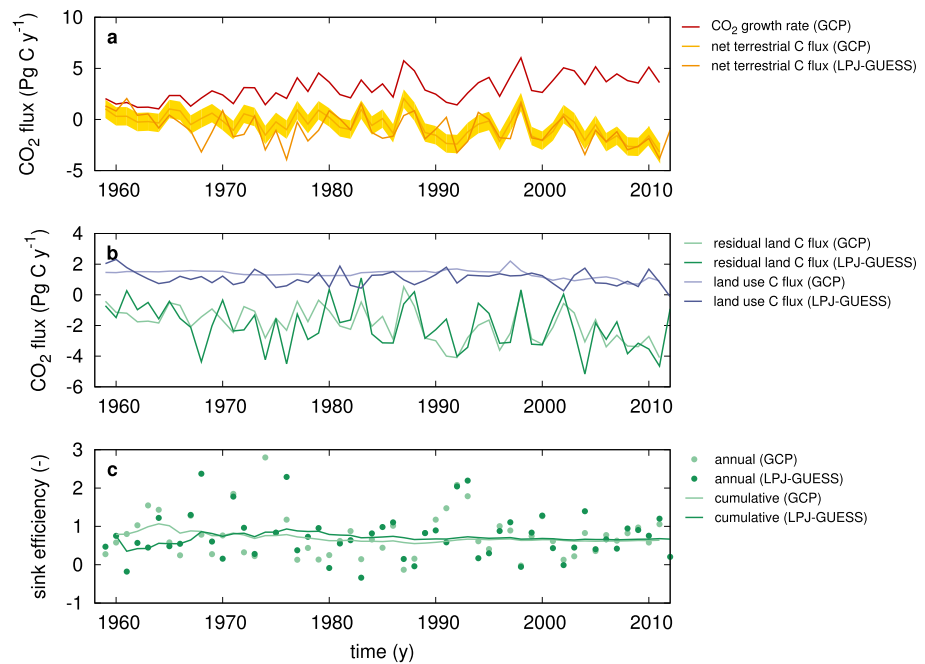
The second set of simulations followed the CMIP5 climate model scenario setup more directly to investigate the simulated carbon cycle response to projected climate change and changes in atmospheric CO<sub>2</sub>. These simulations allowed us to evaluate how well the simulations forced with scaled climate and CO<sub>2</sub> can represent the original RCP climate and CO<sub>2</sub> trajectories. In this second set of simulations, anomalies from GCM simulations relative to 1961–1990 were added to a repeated CRU data set for 1961–1990. In contrast to Ahlström et al. (2012), land use was kept at the level obtained in 2000, for comparability with the first set of simulations. Simulations were performed with data from 12 GCMs applying three or four RCP simulations for each GCM (Table S2). CO<sub>2</sub> mixing ratios were used according to the RCP (Taylor et al., 2012).

The two sets of simulations were used to quantify the carbon sink efficiency: the ratio between terrestrial carbon uptake and atmospheric carbon increase (both expressed in Pg C). This ratio was computed by applying the simulated terrestrial carbon storage difference between 1981–2000 and 2081–2100 from the two sets of simulations and the atmospheric carbon storage difference from the rise in the CO<sub>2</sub> mixing ratio prescribed for each simulation. The sensitivities of LPJ-GUESS to changes in CO<sub>2</sub> and climate were compared with those reported and computed for a set of Earth system models (ESMs) that simulate climate as well as carbon cycle processes. This was done using reported sensitivities in Friedlingstein et al. (2006) and sensitivities from five ESMs from CMIP5 (Table S3) that were computed following the same method. These simulations used different treatments of land use and land use change: Land use was ignored in the simulations in Friedlingstein et al. (2006), but land use and land use change were considered in most of the CMIP5 simulations. To assess the impact of these differences in assumptions, two additional sets of scaled simulations with LPJ-GUESS were performed (see Text S1).

Details on the computations of the sensitivities from our simulations and those from the ESMs are provided in Text S1.

### 3. Results and Discussion

The simulated carbon cycle dynamics for the 20th century capture both the magnitude and variability of the land use flux and the residual land sink over the last five decades (Figure 1; Le Quééré et al., 2016). This agreement between simulation and large-scale estimates is reassuring not only for the model but also for the large-scale estimates, as these are computed as the residual term in the carbon balance.

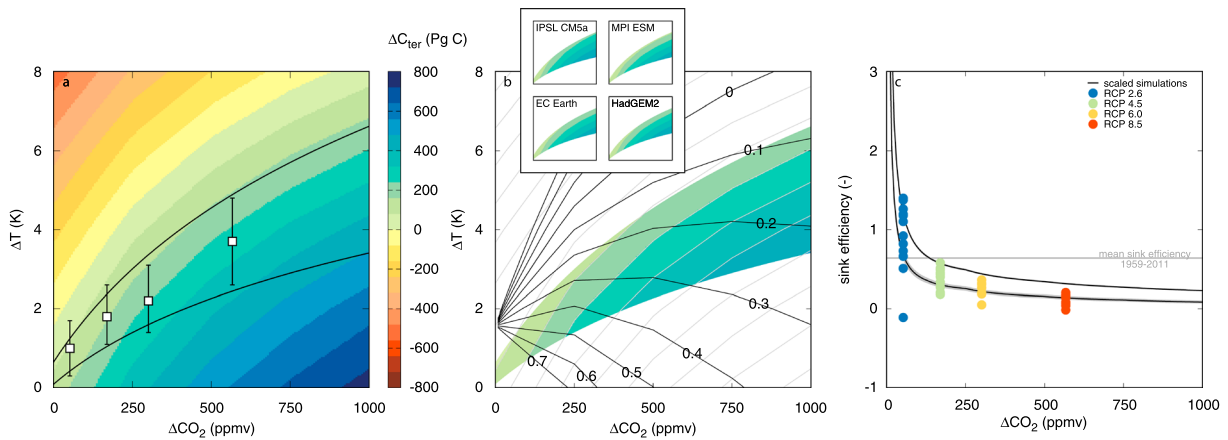


**Figure 1.** Observed and simulated terrestrial fluxes of CO<sub>2</sub>. (a) Observed CO<sub>2</sub> growth rate and estimated net terrestrial flux (mean  $\pm$  1 standard deviation) from the Global Carbon Project (GCP), and net terrestrial flux simulated by LPJ-GUESS forced with gridded station meteorology (Harris et al., 2014); (b) simulated net fluxes of natural and land use-induced CO<sub>2</sub>, together with the estimated fluxes from the Global Carbon Project (Le Quéré et al., 2016); and (c) sink efficiency (ratio between terrestrial increase and atmospheric increase; symbols: ratio of annual increase, lines: ratio of cumulative increase since 1959). Negative fluxes indicate an uptake of CO<sub>2</sub> from the atmosphere.

The set of future simulations with scaled GCM patterns presents a wide range of changes in climate and CO<sub>2</sub>. For the future, the terrestrial carbon cycle response to climate change is nearly linear with GMT change, but the response to CO<sub>2</sub> has a logarithmic shape, with the CO<sub>2</sub> fertilization effect saturating at higher CO<sub>2</sub> mixing ratios (Figure 2a, colored contours). The response of the GMT change to CO<sub>2</sub> is known to also respond logarithmically, as seen, for example, for the different RCPs (Figure 2a, squares) and had a rather similar logarithm base. Because of this similarity, the terrestrial uptake obtained for the combinations of CO<sub>2</sub> change and mean temperature change for the ensemble mean of the RCPs used in CMIP5 (Collins et al., 2013; Figure 2a, squares) increases only moderately between the low-emission scenarios with little climate change and the high-emission scenarios with large climate change (cumulative uptake ranging from, on average, 100 Pg C for RCP 2.6 to 270 Pg C for RCP 8.5).

These results are insensitive to the GCM used to derive the climate patterns for scaling the forcing data with (Figure 2b, inset): A large proportion of the differences in carbon cycle responses between simulations applying either patterns from different GCMs or patterns from different climate scenarios disappears when the forcing data are scaled to equal changes in annual mean global temperature and CO<sub>2</sub> (Figure S4). This relatively low sensitivity to GCM pattern is remarkable, given the wide range in warming patterns and precipitation changes simulated by the four GCMs that were applied (Figure S2). The response obtained with climate change patterns from four different RCP simulations with one GCM resulted in even smaller differences when scaled with GMT (Figure S4).

In contrast, the uncertainty of future scenario estimates originating from the climate sensitivities of the GCMs in CMIP5 (Figure 2a, whiskers) causes a considerable uncertainty in the terrestrial carbon uptake estimates (up to several hundreds of Pg C) and does so irrespective of the GCM that was used to obtain the scaled climate change scenarios (Figure 2b). For an increase of 1,000 ppmv by 2100, patterns for the four different GCMs resulted in a variation of the estimated lower boundary (at the highest T response) of the uptake of 145–224 Pg C (Figure 2b). This variation is small compared to the difference between the lower boundary and the higher boundary (variation of the estimated higher boundary at the lowest T response of

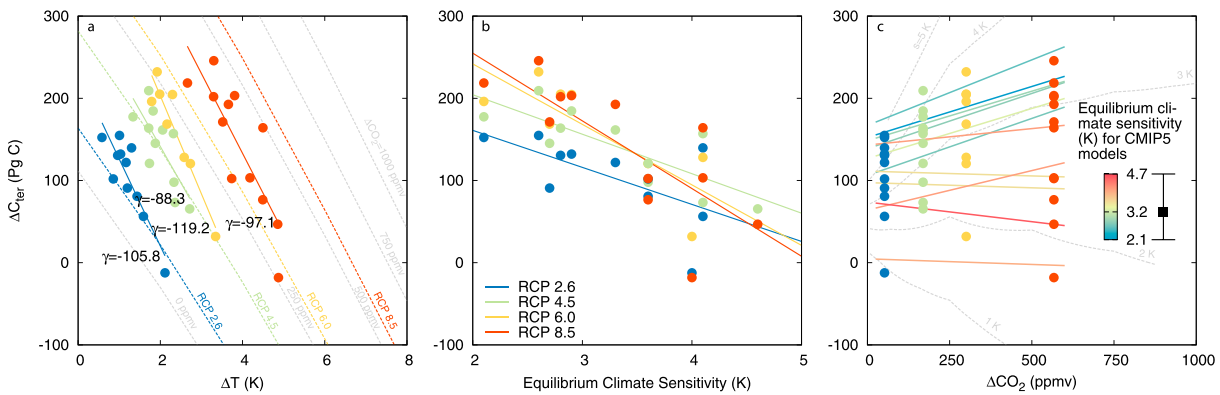


**Figure 2.** Change in terrestrial carbon storage between 1981–2000 and 2081–2100. (a) Average response obtained from four sets of simulations with different general circulation model (GCM) climate change patterns (contour colors), together with the mean global temperature rise from an ensemble of GCMs and the corresponding 5–95% uncertainty range (boxes and whiskers) for the representative concentration pathway (RCP) scenarios in IPCC AR5 (Collins et al., 2013). Lines indicate fitted curves through the fifth and 95th percentiles of the responses (see section 2); (b) same as in (a), highlighting the fitted 5–95% uncertainty range (contour colors). Black contour lines indicate the sink efficiency, for comparison with Figure 1c. Individual response patterns (contour colors) for the four sets of GCM climate change patterns are provided in the inset figures and in Figure S4; (c) sink efficiency as a function of CO<sub>2</sub> increase obtained from interpolation of the simulations shown in (a) and (b) for the minimum and maximum responses (fitted curves from (a), gray shading indicates the range obtained with four different GCM climate change patterns) and the RCP simulations with LPJ-GUESS using multiple GCMs as forcing.

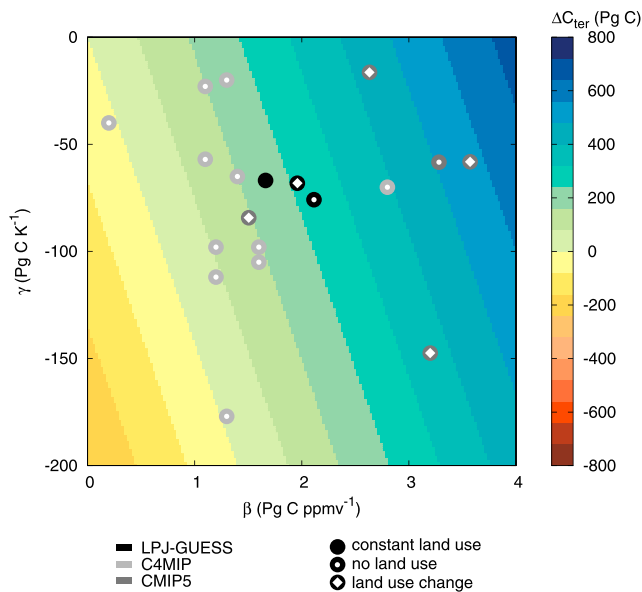
471–504 Pg C, Figure 2b). Hence, the climate sensitivity-induced difference is of similar magnitude as the interscenario differences for the lower RCPs and outweighs these differences for the higher RCPs. This implies that it is not primarily the future emissions that determine the terrestrial response but rather the sensitivity of the climate system to CO<sub>2</sub> changes. This is in line with earlier studies investigating the impact of climate sensitivity from individual climate models on simulated terrestrial carbon storage (Govindasamy et al., 2005; Müller et al., 2016), but we can show here that it also represents the main factor explaining differences between GCM forcing data sets. A reduction of the uncertainty on the climate sensitivity is hence of crucial importance to constrain the terrestrial response.

The strong response to climate sensitivity rather than to the CO<sub>2</sub> mixing ratio is confirmed by a second set of simulations with the LPJ-GUESS vegetation model, in which the simulated climate from three or four scenarios with different emission pathways (RCPs) for 12 GCMs was applied as forcing to the vegetation model. Within individual RCPs, the GCMs with a high GMT response result in negligible changes in terrestrial carbon storage, whereas the GCMs with a low temperature rise result in an increase of 150–250 Pg by the end of the 21st century (Figure 3a). Small releases of CO<sub>2</sub> were simulated with climate forcing from a GCM that combines a generally strong temperature response to CO<sub>2</sub> with a relatively large warming of the Northern Hemisphere high latitudes. The ECS of the GCM used as forcing (which describes the GCM's response to a doubling of the atmospheric CO<sub>2</sub> mixing ratio; Flato et al., 2013) is the primary factor explaining the difference in carbon storage between these simulations (Figure 3b). The range of responses between GCMs is considerably larger than the trends between the RCPs obtained for each GCM separately (Figure 3c), where the models with a relatively small ECS tend to have a slight increase in carbon storage with larger CO<sub>2</sub> mixing ratios, and the models with larger ECS show a near-constant carbon storage. These model simulations forced with RCP climate directly show a smaller change in terrestrial carbon storage in the high-emission RCPs compared with the scaled simulations (Figure 3a), whereas the low RCPs are more similar. The difference between the scaled simulations and the RCP simulations at high CO<sub>2</sub> forcing results from the difference between the linearly increasing CO<sub>2</sub> mixing ratio in the former and the convex increase in the latter for the high RCPs (Figure S5), which causes an offset in the total change of terrestrial carbon that was simulated. However, the sensitivity to climate change (depicted as the slope  $\gamma$  in Figure 3a) is similar between the scaled simulations and the RCP simulations.

Despite an increase of absolute uptake over the last decades, the relative ability of the terrestrial biosphere to take up carbon has been reported to decrease (Raupach et al., 2014). The sink efficiency (Gloor et al., 2010; the



**Figure 3.** Change in terrestrial carbon storage for scaled and representative concentration pathway (RCP) simulations. (a) Change in terrestrial carbon storage between 1981–2000 and 2081–2100 as a function of temperature rise for RCP simulations (dots and regression lines) and interpolation of scaled simulations (gray and colored dashed lines for annotated  $\Delta\text{CO}_2$ ). (b) Results from (a) sorted by the model’s equilibrium climate sensitivity (Flato et al., 2013). (c) Change in terrestrial carbon storage between 1981–2000 and 2081–2100 as a function of atmospheric  $\text{CO}_2$  increase for RCP simulations (dots and regression lines colored by equilibrium climate sensitivity) and interpolation of scaled simulations (gray contours for annotated climate sensitivity  $s$ , see section 2). CMIP5 = Coupled Model Intercomparison Project Phase 5.



**Figure 4.** Model sensitivities to changes in atmospheric  $\text{CO}_2$  and climate change. Sensitivity of simulated terrestrial carbon storage to changes in  $\text{CO}_2$  ( $\beta$ ) and global mean temperature ( $\gamma$ ), determined for LPJ-GUESS from the scaled simulations using the climate change pattern from IPSL-CM5A-MR (Figure 2b) assuming a mean  $\text{CO}_2$  increase and global mean temperature rise for representative concentration pathway (RCP) 4.5, and using a constant 2000 CE land use (setup as described in section 2) as well as using no land use (natural vegetation only) or an RCP 4.5 land use change scenario. The sensitivities are compared with values reported for the C4MIP intercomparison (11 models, none with land use) for the SRES A2 scenario (Friedlingstein et al., 2006) and with values computed from for RCP 4.5 simulations with only climate change or only  $\text{CO}_2$  change in Coupled Model Intercomparison Project Phase 5 (CMIP5; five models, of which four apply the RCP 4.5 land use change scenario; Table S3). A computed response for RCP 4.5 conditions with the values for  $\beta$  and  $\gamma$  ( $\Delta C_{\text{ter}} = \beta \Delta \text{CO}_2 + \gamma \Delta T$ ) is given in the color contours.

ratio between terrestrial and atmospheric carbon increase), which is approximately 0.64 for the period 1959–2010 (Figure 1c), decreases drastically in the future with both climate change and  $\text{CO}_2$  rise (Figure 2b). It is thus clearly linked to the magnitude of climate change in the future climate change scenario considered.

The combinations of changes in GMT and atmospheric  $\text{CO}_2$  content that allow for the sink efficiency to remain nearly unchanged (Figures 2b and 2c) are obtained only at very low  $\text{CO}_2$  emissions, such as those conforming to RCP 2.6. For the future, even in the case of a low climate sensitivity, the saturation of  $\text{CO}_2$  fertilization causes the sink efficiency to decrease quickly at elevated  $\text{CO}_2$  mixing ratios (Figure 2c). Other studies have found a similar decrease in the relative uptake: Analysis of the ESM simulations from the CMIP5 set has shown a declining trend in the land-borne fraction of emitted  $\text{CO}_2$  for the high RCPs in particular (Arora & Boer, 2014; Jones et al., 2013), but these CMIP5 simulations included future land use change, which complicates comparison with our results.

The response of the terrestrial carbon cycle to changes in climate and  $\text{CO}_2$  can be explained from the simultaneous changes in carbon uptake and release. Net primary production (NPP), which determines the uptake of carbon, is primarily affected by the  $\text{CO}_2$  mixing ratio, with saturation at higher  $\text{CO}_2$  (Figure S6c). By 2100, NPP increases between 5% and 10% for RCP 2.6 and between 20% and 35% for RCP 8.5 (Figure S6a). Climate change has a relatively small impact on NPP (Figure S6c) but instead determines the processes that govern the time carbon resides in the biosphere, primarily through the response of heterotrophic respiration to temperature rise (Figure S6d).

The outcome of this study depends on the model’s sensitivities to  $\text{CO}_2$  and climate changes, which represent key uncertainties for future climate-carbon cycle projections (Huntzinger et al., 2017), and may hence be subject to the choice of the terrestrial carbon cycle model. A comparison of these sensitivities with results from 11 coupled climate-carbon cycle models in the Coupled Climate-Carbon Cycle Model Intercomparison (C4MIP, Friedlingstein et al., 2006). As well as five

coupled models in CMIP5 (Taylor et al., 2012) reveals that LPJ-GUESS's sensitivities to climate and CO<sub>2</sub> changes are comparable to those of other models but that a large spread in sensitivities exists between models (Figure 4). This large spread can be attributed to some extent to different treatments of land use between different studies (see different responses of LPJ-GUESS in Figure 4), but a considerable variability in sensitivities and simulated carbon cycle changes between ESMs remains (Anav et al., 2013; Friedlingstein et al., 2006). The fact that LPJ-GUESS captures the mean residual land flux over the last decades (Figure 1b) gives us confidence in the model's response.

Representing the uncertainty in future response by a set of ensemble simulations for a few emission scenarios, as is currently practiced in most studies, does not provide enough information about the likelihood for the future. Uncertainty is exacerbated if not only CO<sub>2</sub> and climate are altered but also other anthropogenic drivers such as land use change, which varies between the RCPs (Hurtt et al., 2011), and is not considered here for the 21st century. The outcome of this study may be affected by a lack of representation of processes such as carbon-nitrogen interactions (Wieder et al., 2015), which have been shown to cause a slight enhancement of future carbon uptake for this model (Wärmland et al., 2014), or permafrost melting, which has potential to enhance the climate-induced offset even further (Zimov et al., 2006). Changes in nitrogen deposition may affect the ability of terrestrial ecosystems to sequester carbon (Wang et al., 2017). Despite these uncertainties, the wide range of forcings studied strengthens our expectation that a strong climate change-induced terrestrial source of carbon in the future is unlikely in absence of considerable land use changes, even with a high climate sensitivity.

## 4. Conclusions

Our analysis demonstrates that climate change and atmospheric CO<sub>2</sub> increase have largely counterbalancing impacts over a wide range of CO<sub>2</sub> mixing ratios and that climate sensitivity is more important than the actual CO<sub>2</sub> scenario for determining future changes. A possible reduction of this uncertainty (Cox et al., 2018; Myhre et al., 2015) would therefore not only reduce uncertainties in climate estimates but also constrain carbon cycle feedbacks. In all except for very low CO<sub>2</sub> emission scenarios, the ability of the terrestrial carbon cycle to take up carbon loses pace with the emission-driven enhancement of atmospheric CO<sub>2</sub> in the Earth system, reducing the importance of the terrestrial biosphere for mitigating climate change and leaving a larger part of the anthropogenic emissions of CO<sub>2</sub> in the atmosphere.

## References

- Ahlström, A., Raupach, M. R., Schurgers, G., Smith, B., Arneeth, A., Jung, M., et al. (2015). The dominant role of semi-arid ecosystems in the trend and variability of the land CO<sub>2</sub> sink. *Science*, *320*(6), 4503–4518. <https://doi.org/10.1002/2015JA021022>
- Ahlström, A., Schurgers, G., Arneeth, A., & Smith, B. (2012). Robustness and uncertainty in terrestrial ecosystem carbon response to CMIP5 climate change projections. *Environmental Research Letters*, *7*, 44008. <https://doi.org/10.1088/1748-9326/7/4/044008>
- Ahlström, A., Smith, B., Lindström, J., Rummukainen, M., & Uvo, C. B. (2013). GCM characteristics explain the majority of uncertainty in projected 21st century terrestrial ecosystem carbon balance. *Biogeosciences*, *10*(3), 1517–1528. <https://doi.org/10.5194/bg-10-1517-2013>
- Anav, A., Friedlingstein, P., Kidston, M., Bopp, L., Ciais, P., Cox, P., et al. (2013). Evaluating the land and ocean components of the global carbon cycle in the CMIP5 earth system models. *Journal of Climate*, *26*(18), 6801–6843. <https://doi.org/10.1175/JCLI-D-12-00417.1>
- Anderegg, W. R. L., Ballantyne, A. P., Smith, W. K., Majkut, J., Rabin, S., Beaulieu, C., et al. (2015). Tropical nighttime warming as a dominant driver of variability in the terrestrial carbon sink. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(51), 15,591–15,596. <https://doi.org/10.1073/pnas.1521479112>
- Arora, V. K., & Boer, G. J. (2014). Terrestrial ecosystems response to future changes in climate and atmospheric CO<sub>2</sub> concentration. *Biogeosciences*, *11*(15), 4157–4171. <https://doi.org/10.5194/bg-11-4157-2014>
- Arora, V. K., Boer, G. J., Friedlingstein, P., Eby, M., Jones, C. D., Christian, J. R., et al. (2013). Carbon-concentration and carbon-climate feedbacks in CMIP5 Earth system models. *Journal of Climate*, *26*(15), 5289–5314. <https://doi.org/10.1175/JCLI-D-12-00494.1>
- Ballantyne, A. P., Andres, R., Houghton, R., Stocker, B. D., Wanninkhof, R., Anderegg, W., et al. (2015). Audit of the Global Carbon Budget: Estimate errors and their impact on uptake uncertainty. *Biogeosciences*, *12*(8), 2565–2584. <https://doi.org/10.5194/bg-12-2565-2015>
- Berthelot, M., Friedlingstein, P., Ciais, P., Dufresne, J.-L., & Monfray, P. (2005). How uncertainties in future climate change predictions translate into future terrestrial carbon fluxes. *Global Change Biology*, *11*(6), 959–970. <https://doi.org/10.1111/j.1365-2486.2005.00957.x>
- Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., et al. (2013). Long-term climate change: Projections, commitments and irreversibility. In T. F. Stocker, et al. (Eds.), *Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change* (pp. 1029–1136). Cambridge, UK: Cambridge University Press.
- Cox, P. M., Betts, R. A., Jones, C. D., Spall, S. A., & Totterdell, I. J. (2000). Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature*, *408*(6809), 184–187. <https://doi.org/10.1038/35041539>
- Cox, P. M., Huntingford, C., & Williamson, M. S. (2018). Emergent constraint on equilibrium climate sensitivity from global temperature variability. *Nature*, *553*(7688), 319–322. <https://doi.org/10.1038/nature25450>

### Acknowledgments

G. S. was funded by the Swedish Research Council VR, grant 2009-4290. A. Ahl. acknowledges support from The Royal Physiographic Society in Lund (Birgit and Hellmuth Hertz' Foundation) and the Swedish Research Council VR, grant 637-2014-6895. A. Ar. and T. A. M. P. acknowledge support from the EU FP7, grants 603542 (LUC4C) and 282672 (EMBRACE), and were supported, in part, by the German Federal Ministry of Education and Research (BMBF), through the Helmholtz Association and its research program ATMO. The simulations were performed on resources provided by the Swedish National Infrastructure for Computing (SNIC) at LUNARC and the Danish e-Infrastructure Cooperation (DeIC) at the national HPC Centre, SDU. We acknowledge the World Climate Research Programme's Working Group on coupled modeling, which is responsible for CMIP, and we thank the climate modeling groups (listed in Tables S1–S3) for producing and making available their model output. For CMIP, the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. The simulation results are available at the Electronic Research Data Archive (ERDA) of the University of Copenhagen (<http://www.erd.dk/public/archives/YXJJaG12Z51waW5Obk4=/published-archive.html>).



- Cramer, W., Bondeau, A., Woodward, F. I., Prentice, I. C., Betts, R. A., Brovkin, V., et al. (2001). Global response of terrestrial ecosystem structure and function to CO<sub>2</sub> and climate change: Results from six dynamic global vegetation models. *Global Change Biology*, 7(4), 357–373. <https://doi.org/10.1046/j.1365-2486.2001.00383.x>
- Dufresne, J.-L., Friedlingstein, P., Berthelot, M., Bopp, L., Ciais, P., Fairhead, L., et al. (2002). On the magnitude of positive feedback between future climate change and the carbon cycle. *Geophysical Research Letters*, 29(10), 1405. <https://doi.org/10.1029/2001GL013777>
- Etheridge, D. M., Steele, L. P., Langenfelds, R. L., Francey, R. J., Barnola, J. M., & Morgan, V. I. (1996). Natural and anthropogenic changes in atmospheric CO<sub>2</sub> over the last 1000 years from air in Antarctic ice and firn. *Journal of Geophysical Research*, 101(D2), 4115–4128. <https://doi.org/10.1029/95JD03410>
- Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S. C., Collins, W., et al. (2013). Evaluation of climate models. In T. F. Stocker, et al. (Eds.), *Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change* (pp. 741–866). Cambridge, UK: Cambridge University Press.
- Friedlingstein, P., Cox, P., Betts, R., Bopp, L., von Bloh, W., Brovkin, V., et al. (2006). Climate-carbon cycle feedback analysis: Results from the C4MIP model intercomparison. *Journal of Climate*, 19(14), 3337–3353. <https://doi.org/10.1175/JCLI3800.1>
- Friedlingstein, P., Dufresne, J., Cox, P. M., & Rayner, P. (2003). How positive is the feedback between climate change and the carbon cycle? *Tellus*, 55B, 692–700.
- Gloor, M., Sarmiento, J. L., & Gruber, N. (2010). What can be learned about carbon cycle climate feedbacks from the CO<sub>2</sub> airborne fraction? *Atmospheric Chemistry and Physics*, 10(16), 7739–7751. <https://doi.org/10.5194/acp-10-7739-2010>
- Govindasamy, B., Thompson, S., Mirin, A., Wickert, M., Caldeira, K., & Delire, C. (2005). Increase of carbon cycle feedback with climate sensitivity: Results from a coupled climate and carbon cycle model. *Tellus Series B: Chemical and Physical Meteorology*, 57, 153–163.
- Harris, I., Jones, P. D., Osborn, T. J., & Lister, D. H. (2014). Updated high-resolution grids of monthly climatic observations—The CRU TS3.10 dataset. *International Journal of Climatology*, 34(3), 623–642. <https://doi.org/10.1002/joc.3711>
- Hartmann, D. L., Klein Tank, A. M. G., Ruscicucci, M., Alexander, L. V., Broenniman, B., Charabi, Y., et al. (2013). Observations: Atmosphere and surface. In T. F. Stocker, et al. (Eds.), *Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change* (pp. 159–254). Cambridge, UK: Cambridge University Press.
- Huntzinger, D. N., Michalak, A. M., Schwalm, C., Ciais, P., King, A. W., Fang, Y., et al. (2017). Uncertainty in the response of terrestrial carbon sink to environmental drivers undermines carbon-climate feedback predictions. *Scientific Reports*, 7(1), 4765. <https://doi.org/10.1038/s41598-017-03818-2>
- Hurttt, G. C., Chini, L. P., Frolking, S., Betts, R. A., Feddema, J., & Fischer, G. (2011). Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. *Climatic Change*, 109(1–2), 117–161. <https://doi.org/10.1007/s10584-011-0153-2>
- Jones, C., Robertson, E., Arora, V., Friedlingstein, P., Shevliakova, E., Bopp, L., et al. (2013). Twenty-first-century compatible CO<sub>2</sub> emissions and airborne fraction simulated by CMIP5 earth system models under four representative concentration pathways. *Journal of Climate*, 26(13), 4398–4413. <https://doi.org/10.1175/JCLI-D-12-00554.1>
- Keeling, C. D., Whorf, T. P., Wahlen, M., & Vanderpligt, J. (1995). Interannual extremes in the rate of rise of atmospheric carbon-dioxide since 1980. *Nature*, 375(6533), 666–670. <https://doi.org/10.1038/375666a0>
- Le Quéré, C., Andrew, R. M., Canadell, J. G., Sitch, S., Korsbakken, J. I., Peters, G. P., et al. (2016). Global Carbon Budget 2016. *Earth System Science Data*, 8(2), 605–649. <https://doi.org/10.5194/essd-8-605-2016>
- Mitchell, T. D. (2003). Pattern scaling: An examination of the accuracy of the technique for describing future climates. *Climatic Change*, 60(3), 217–242. <https://doi.org/10.1023/A:1026035305597>
- Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., et al. (2010). The next generation of scenarios for climate change research and assessment. *Nature*, 463(7282), 747–756. <https://doi.org/10.1038/nature08823>
- Müller, C., Stehfest, E., van Minnen, J. G., Strengers, B., von Bloh, W., Beusen, A. H. W., et al. (2016). Drivers and patterns of land biosphere carbon balance reversal. *Environmental Research Letters*, 11(4), 44002. <https://doi.org/10.1088/1748-9326/11/4/044002>
- Myhre, G., Boucher, O., Bréon, F.-M., Forster, P., & Shindell, D. (2015). Declining uncertainty in transient climate response as CO<sub>2</sub> forcing dominates future climate change. *Nature Geoscience*, 8(3), 181–185. <https://doi.org/10.1038/ngeo2371>
- Poulter, B., Frank, D., Ciais, P., Myneni, R. B., Andela, N., Bi, J., et al. (2014). Contribution of semi-arid ecosystems to interannual variability of the global carbon cycle. *Nature*, 509(7502), 600–603. <https://doi.org/10.1038/nature13376>
- Raupach, M. R., Gloor, M., Sarmiento, J. L., Canadell, J. G., Frölicher, T. L., Gasser, T., et al. (2014). The declining uptake rate of atmospheric CO<sub>2</sub> by land and ocean sinks. *Biogeosciences*, 11(13), 3453–3475. <https://doi.org/10.5194/bg-11-3453-2014>
- Schaphoff, S., Lucht, W., Gerten, D., Sitch, S., Cramer, W., & Prentice, I. C. (2006). Terrestrial biosphere carbon storage under alternative climate projections. *Climatic Change*, 74(1–3), 97–122. <https://doi.org/10.1007/s10584-005-9002-5>
- Schurgers, G., Mikolajewicz, U., Gröger, M., Maier-Reimer, E., Vizza'ino, M., & Winguth, A. (2008). Long-term effects of biogeophysical and biogeochemical interactions between terrestrial biosphere and climate under anthropogenic climate change. *Global and Planetary Change*, 64(1–2), 26–37. <https://doi.org/10.1016/j.gloplacha.2008.01.009>
- Sitch, S., Huntingford, C., Gedney, N., Levy, P. E., Lomas, M., Piao, S. L., et al. (2008). Evaluation of the terrestrial carbon cycle, future plant geography and climate-carbon cycle feedbacks using five Dynamic Global Vegetation Models (DGVMs). *Global Change Biology*, 14(9), 2015–2039. <https://doi.org/10.1111/j.1365-2486.2008.01626.x>
- Sitch, S., Smith, B., Prentice, I. C., Arneth, A., Bondeau, A., Cramer, W., et al. (2003). Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. *Global Change Biology*, 9(2), 161–185. <https://doi.org/10.1046/j.1365-2486.2003.00569.x>
- Smith, B., Prentice, I. C., & Sykes, M. (2001). Representation of vegetation dynamics in the modelling of terrestrial ecosystems: Comparing two contrasting approaches within European climate space. *Global Ecology and Biogeography*, 10(6), 621–637. <https://doi.org/10.1046/j.1466-822X.2001.00256.x>
- Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012). An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*, 93(4), 485–498. <https://doi.org/10.1175/BAMS-D-11-00094.1>
- Wang, R., Goll, D., Balkanski, Y., Hauglustaine, D., Boucher, O., Ciais, P., et al. (2017). Global forest carbon uptake due to nitrogen and phosphorus deposition from 1850 to 2100. *Global Change Biology*, 23(11), 4854–4872. <https://doi.org/10.1111/gcb.13766>
- Wärnlind, D., Smith, B., Hickler, T., & Arneth, A. (2014). Nitrogen feedbacks increase future terrestrial ecosystem carbon uptake in an individual-based dynamic vegetation model. *Biogeosciences*, 11(21), 6131–6146. <https://doi.org/10.5194/bg-11-6131-2014>
- Wieder, W. R., Cleveland, C. C., Smith, W. K., & Todd-Brown, K. (2015). Future productivity and carbon storage limited by terrestrial nutrient availability. *Nature Geoscience*, 8(6), 441–444. <https://doi.org/10.1038/ngeo2413>
- Zimov, S. A., Schuur, E. A. G., & Chapin, F. S. I. (2006). Permafrost and the Global Carbon Budget. *Science*, 312, 1612–1613. <https://doi.org/10.1007/BF02508825>