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Published in:
Geophysical Research Letters

DOI:
10.1029/2018GL077528

Publication date:
2018

Document version
Early version, also known as pre-print

Citation for published version (APA):
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*(9), 4329-4336. https://doi.org/10.1029/2018GL077528

Climate sensitivity controls uncertainty in future terrestrial carbon sink

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Key Points:

- Uncertainty in climatic response to CO_2 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_2 in the future
- The fraction of CO_2 emissions taken up by the terrestrial biosphere decreases drastically with higher emissions

Manuscript accepted for publication in *Geophysical Research Letters*
doi: 10.1029/2018GL077528

Abstract

For the 21st century, carbon cycle models typically project an increase of terrestrial carbon with increasing atmospheric CO_2, 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_2 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 or model estimates. In our simulations, the terrestrial biosphere is unlikely to become a strong source of carbon with any likely combination of CO_2 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.

1 Introduction

Terrestrial ecosystems remove CO_2 from the atmosphere, thus dampening the growth rate of the atmospheric CO_2 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 [*Poulter et al.*, 2014; *Ahlström et al.*, 2015; *Anderegg et al.*, 2015] . 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_2 due to land use change of 1.3 ± 0.14 Pg C y^{-1}, and a highly variable uptake of CO_2 in terrestrial ecosystems of, on average, 2.6 ± 1.0 Pg C y^{-1} [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 [*Berthelot et al.*, 2005; *Schaphoff et al.*, 2006; *Ahlström et al.*, 2013; *Müller et al.*, 2016]. In general, models project an increase of the terrestrial uptake with increasing atmospheric CO_2 mixing ratio, and a decrease with the accompanying general circulation model (GCM)-simulated climate change [*Cox et al.*, 2000; *Dufresne et al.*, 2002; *Friedlingstein et al.*, 2003, 2006; *Schurgers et al.*, 2008; *Arora et al.*, 2013]. Scenario studies almost universally suggest that the land uptake due to direct effects of CO_2 is larger than the impact of climate change for the terrestrial carbon dynamics over the 21st century [*Cramer et al.*, 2001; *Friedlingstein et al.*, 2006; *Schurgers et al.*, 2008; *Sitch et al.*, 2008; *Arora et al.*, 2013]. 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_2 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 CMIP5 GCMs as forcing data.

2 Materials and Methods

Terrestrial carbon storage was simulated with the dynamic vegetation model LPJ-GUESS [*Smith et al.*, 2001; *Sitch et al.*, 2003]. The model simulates the global distribution of 11 plant functional types (PFTs). Within each PFT, CO_2 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 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_2 mixing ratio was prescribed following ice core-based reconstructions and atmospheric observations [*Keeling et al.*, 1995; *Etheridge et al.*, 1996] 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_2 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_2, 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_2 increase and climate change by varying future changes in atmospheric CO_2 and global mean temperature 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_2 rise and climate change from this set. The second set of simulations follows the four representative concentration pathways (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_2 increase. By combining five levels of climate change (represented by an increase in global mean temperature between 1981-2000 and 2081-2100 of 0 K, 2 K, 4 K, 6 K or 8 K) and five levels of the atmospheric CO_2 mixing ratio (increases of 0, 250, 500, 750 or 1000 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-emission 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 Fig. 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 global mean temperature (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_2 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 (Fig. 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_2 and climate forcing in the matrix of 25 scaled simulations, an envelope of changes in CO_2 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 5^{th} and 95^{th} percentile of the confidence interval of the GMT changes reported for the four RCPs (Fig. S3) by estimating a climate sensitivity *s* (in K) that is obtained with the commonly used doubling of the CO_2 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_2. These simulations allowed us to evaluate how well the simulations forced with scaled climate and CO_2 can represent the original RCP climate and CO_2 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 3 or 4 RCP simulations for each GCM (Table S2). CO_2 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_2 mixing ratio prescribed for each simulation. The sensitivities of LPJ-GUESS to changes in CO_2 and climate were compared with those reported and computed for a set of Earth system models that simulate climate as well as carbon cycle processes. This was done using reported sensitivities in *Friedlingstein et al.* [2006] and sensitivities from five Earth system models 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 the supporting information (Text S1).

3 Results and Discussion

The simulated carbon cycle dynamics for the 20th century captures both the magnitude and variability of the land use flux and the residual land sink over the last five decades (Fig. 1; *Le Quéré et al.* [2016]). This agreement between simulation and large-scale estimates is reassuring for the model, but also for the large-scale estimates, as these are computed as the residual term in the carbon balance.

The set of future simulations with scaled GCM patterns presents a wide range of changes in climate and CO_2. For the future, the terrestrial carbon cycle response to climate change is nearly linear with global mean temperature change, but the response to CO_2 has a logarithmic shape, with the CO_2 fertilization effect saturating at higher CO_2 mixing ratios (Fig. 2a, colored contours). The response of the global mean temperature change to CO_2 is known to also respond logarithmically, as seen e.g. for the different RCPs (Fig. 2a, squares), and had a rather similar logarithm base. Because of this similarity, the terrestrial uptake obtained for the combinations of CO_2 change and mean temperature change for the ensemble mean of the RCPs used in CMIP5 [*Collins et al.*, 2013] (Fig. 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 (Fig. 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_2 (Fig. 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 (Fig. S2). The response obtained with climate change patterns from four different Representative Concentration Pathway (RCP) simulations with one GCM resulted in even smaller differences when scaled with global mean temperature (Fig. S4).

In contrast, the uncertainty of future scenario estimates originating from the climate sensitivities of the GCMs in CMIP5 (Fig. 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 (Fig. 2b). For an increase of 1000 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 (Fig. 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 471-504 Pg C, Fig. 2b). Hence, the climate sensitivity-induced difference is of similar magnitude as the inter-scenario 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_2 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_2 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 global mean temperature 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 (Fig. 3a). Small releases of CO_2 were simulated with climate forcing from a GCM that combines a generally strong temperature response to CO_2 with a relatively large warming of the Northern Hemisphere high latitudes. The equilibrium climate sensitivity of the GCM used as forcing (ECS, which describes the GCM's response to a doubling of the atmospheric CO_2 mixing ratio [*Flato et al.*, 2013]) is the primary factor explaining the difference in carbon storage between these simulations (Fig. 3b). The range of responses between GCMs is considerably larger than the trends between the RCPs obtained for each GCM separately (Fig. 3c), where the models with a relatively small ECS tend to have a slight increase in carbon storage with larger CO_2 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 (Fig. 3a), whereas the low RCPs are more similar. The difference between the scaled simulations and the RCP simulations at high CO_2 forcing results from the difference between the linearly increasing CO_2 mixing ratio in the former and the convex increase in the latter for the high RCPs (Fig. 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 γ in Fig. 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 ratio between terrestrial and atmospheric carbon increase), which is approximately 0.64 for the period 1959-2010 (Fig. 1c), decreases drastically in the future with both climate change and CO_2 rise (Fig. 2b). It is thus clearly linked to the magnitude of climate change in the future climate change scenario considered.

The combinations of changes in global mean temperature and atmospheric CO_2 content that allow for the sink efficiency to remain nearly unchanged (Fig. 2b, c) are obtained only at very low 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 CO_2 fertilization causes the sink efficiency to decrease quickly at elevated CO_2 mixing ratios (Fig. 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 CO_2 for the high RCPs in particular [*Jones et al.*, 2013; *Arora and Boer*, 2014], 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 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 CO_2 mixing ratio, with saturation at higher CO_2 (Fig. S6c). By 2100, NPP increases between 5-10% for RCP 2.6 and 20-35% for RCP 8.5 (Fig. S6a). Climate change has a relatively small impact on NPP (Fig. 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 (Fig. S6d).

The outcome of this study depends on the model's sensitivities to 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 eleven coupled climate-carbon cycle models in C4MIP [*Friedlingstein et al.*, 2006] as well as five coupled models in CMIP5 [*Taylor et al.*, 2012] reveals that LPJ-GUESS' sensitivities to climate and CO_2 changes are comparable to those of other models, but that a large spread in sensitivities exists between models (Fig. 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 Fig. 4), but a considerable variability in sensitivities and simulated carbon cycle changes between Earth system models remains [*Friedlingstein et al.*, 2006; *Anav et al.*, 2013]. The fact that LPJ-GUESS captures the mean residual land flux over the last decades (Fig. 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_2 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 [*Wårlind 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_2 increase have largely counterbalancing impacts over a wide range of CO_2 mixing ratios, and that climate sensitivity is more important than the actual CO_2 scenario for determining future changes. A possible reduction of this uncertainty [*Myhre et al.*, 2015; *Cox et al.*, 2018] would therefore not only reduce uncertainties in climate estimates, but also constrain carbon cycle feedbacks. In all except for very low CO_2 emission scenarios, the ability of the terrestrial carbon cycle to take up carbon loses pace with the emission-driven enhancement of atmospheric CO_2 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_2 in the atmosphere.

Acknowledgments and Data

GS was funded by the Swedish Research Council VR, grant number 2009-4290. AAhl acknowledges support from The Royal Physiographic Society in Lund (Birgit and Hellmuth Hertz' Foundation) and the Swedish Research Council VR, grant number 637-2014-6895. AAr and TAMP acknowledge support from the EU FP7 grant numbers 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 Modelling, which is responsible for CMIP, and we thank the climate modelling groups (listed in the Supporting information 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.erda.dk/public/archives/YXJjaGl2ZS1waW5Obk4=/published-archive.html

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Figures

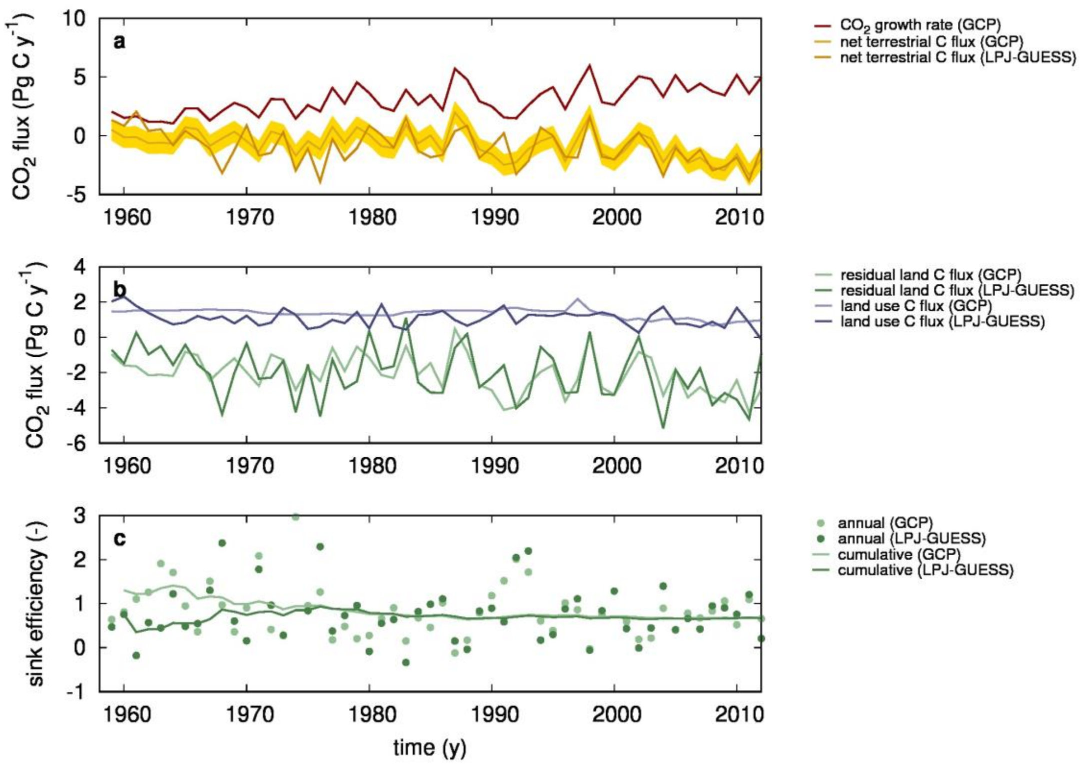

Figure 1. Observed and simulated terrestrial fluxes of CO_2. (a) Observed CO_2 growth rate and estimated net terrestrial flux (mean ± 1 standard deviation) from the Global Carbon Project, and net terrestrial flux simulated by LPJ-GUESS forced with gridded station meteorology [*Harris et al.*, 2014]; (b) simulated net fluxes of natural and land use-induced CO_2, 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_2 from the atmosphere.

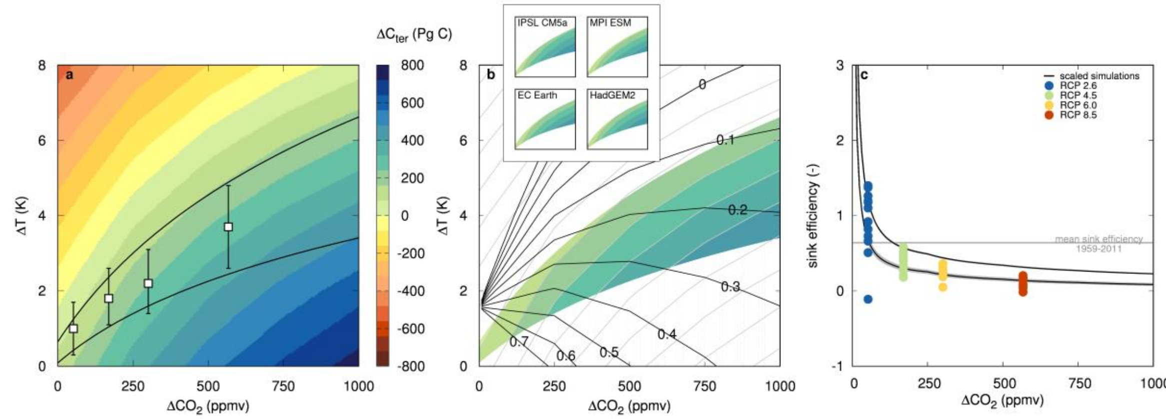

Figure 2. Change in terrestrial carbon storage between 1981-2000 and 2081-2100. (a) Average response obtained from four sets of simulations with different GCM climate change patterns (contour colors), together with the mean global temperature rise from an ensemble of GCMs and the corresponding 5-95% uncertainty range (boxes and whiskers) for the RCP scenarios in IPCC AR5 [*Collins et al.*, 2013]. Dashed lines indicate fitted curves through the 5th and 95th percentiles of the responses (see Methods); (b) Same as in (a), highlighting the fitted 5-95% uncertainty range (contour colors). Black contour lines indicate the sink efficiency, for comparison with Fig. 1c. Individual response patterns (contour colors) for the four sets of GCM climate change patterns are provided in the inset figures and in Fig. S4; (c) Sink efficiency as a function of CO_2 increase obtained from interpolation of the simulations shown in (a) and (b) for the minimum and maximum responses (fitted curves from (a), dashed lines; grey shading indicates the range obtained with four different GCM climate change patterns) and the RCP simulations with LPJ-GUESS using multiple GCMs as forcing.

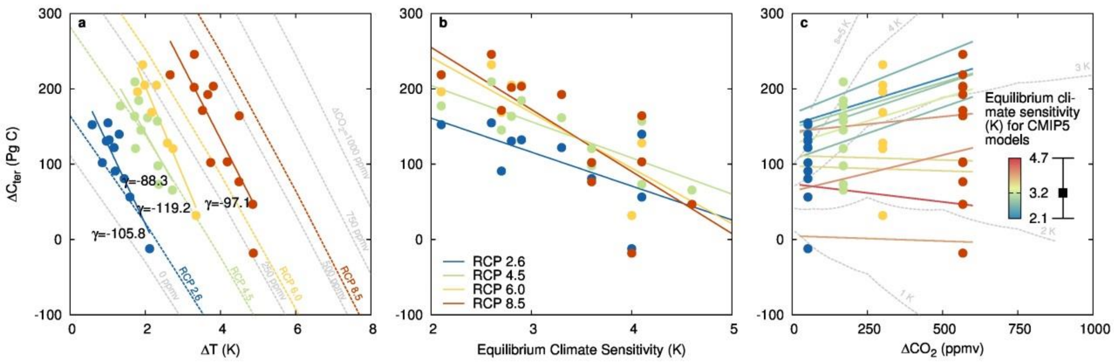

Figure 3. Change in terrestrial carbon storage for scaled and RCP simulations. (a) Change in terrestrial carbon storage between 1981-2000 and 2081-2100 as a function of temperature rise for RCP simulations (dots and regression lines) and interpolation of scaled simulations (grey and colored dashed lines for annotated ΔCO_2). (b) Results from (a) sorted by the model's Equilibrium Climate Sensitivity (ECS) [*Flato et al.*, 2013]. (c) Change in terrestrial carbon storage between 1981-2000 and 2081-2100 as a function of atmospheric CO_2 increase for RCP simulations (dots and regression lines colored by ECS) and interpolation of scaled simulations (grey contours for annotated climate sensitivity *s*, see Methods).

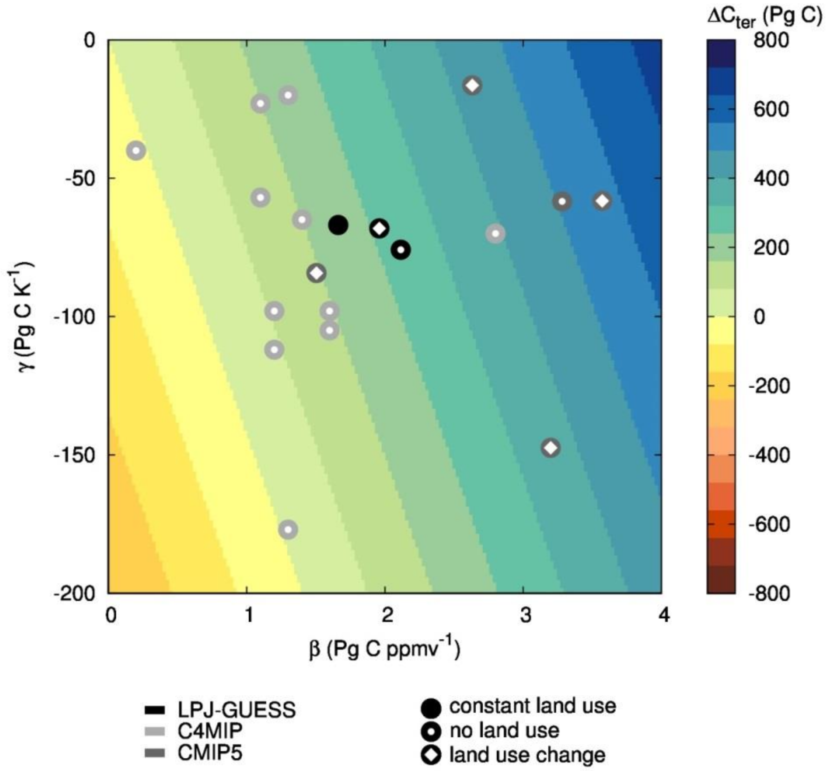

Figure 4. Model sensitivities to changes in atmospheric CO_2 and climate change. Sensitivity of simulated terrestrial carbon storage to changes in CO_2 (β) and global mean temperature (γ), determined for LPJ-GUESS from the scaled simulations using the climate change pattern from IPSL-CM5A-MR (Fig. 2b) assuming a mean CO_2 increase and global mean temperature rise for RCP 4.5, and using a constant 2000 A.D. land use (setup as described in Methods) 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 CO_2 change in CMIP5 (5 models, of which 4 apply the RCP 4.5 land use change scenario, Table S3). A computed response for RCP 4.5 conditions with the values for β and γ ($\Delta C_{ter}=\beta\Delta CO_2+ \gamma\Delta T$) is given in the color contours.