

Examining soil carbon uncertainty in a global model

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Examining soil carbon uncertainty in a global model: response of microbial decomposition to temperature, moisture and nutrient limitation

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Abstract

Reliable projections of future climate require land–atmosphere carbon (C) fluxes to be represented realistically in Earth System Models. There are several sources of uncertainty in how carbon is parameterized in these models. First, while interactions between the C, nitrogen (N) and phosphorus (P) cycles have been implemented in some models, these lead to diverse changes in land–atmosphere fluxes. Second, while the parameterization of soil organic matter decomposition is similar between models, formulations of the control of the soil physical state on microbial activity vary widely. We address these sources uncertainty by implementing three soil moisture (SMRF) and three soil temperature (STRF) respiration functions in an Earth System Model that can be run with three degrees of biogeochemical nutrient limitation (C-only, C and N, and C and N and P). All 27 possible combinations of a SMRF with a STRF and a biogeochemical mode are equilibrated before transient historical (1850–2005) simulations are performed. As expected, implementing N and P limitation reduces the land carbon sink, transforming some regions from net sinks to net sources over the historical period (1850–2005). Differences in the soil C balance implied by the various SMRFs and STRFs also change the sign of some regional sinks. Further, although the absolute uncertainty in global carbon uptake is reduced, the uncertainty due to the SMRFs and STRFs grows relative to the inter-annual variability in net uptake when N and P limitations are added. We also demonstrate that the equilibrated soil C also depend on the shape of the SMRF and STRF. Equilibration using different STRFs and SMRFs and nutrient limitation generates a six-fold range of global soil C that largely mirrors the range in available (17) CMIP5 models. Simulating the historical change in soil carbon therefore critically depends on the choice of STRF, SMRF and nutrient limitation, as it controls the equilibrated state to which transient conditions are applied. This direct effect of the representation of microbial decomposition in Earth System Models adds to recent concerns on the adequacy of these simple representations of very complex soil carbon processes.

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1 Introduction

A major step in the transition from Climate System Models to Earth System Models is the addition of biological processes and biogeochemical cycles. If the carbon (C) cycle was in equilibrium this would be an academic exercise, but how terrestrial C stores respond to warming resulting from human-emissions of atmospheric carbon dioxide (CO₂) is of critical importance. Vegetation stores around 450–650 Pg C (Prentice et al., 2001) while soils store 1500–2400 Pg C (Batjes, 1996) with additional carbon stored in wetland soils (200–450 Pg C) and in permafrost (~ 1670 Pg C; Tarnocai et al., 2009). If vegetation and soil processes respond to global warming by increasing the terrestrial C sink this could help offset human emissions. Conversely, any decrease in the magnitude of the terrestrial sink, or any progressive loss of stored C would provide a positive feedback on global warming.

Our current understanding is that human-induced increases in atmospheric CO₂ have likely enhanced the terrestrial C uptake during the 20th century (Sarmiento et al., 2010) more than global warming has enhanced microbial decomposition and corresponding release by heterotrophic respiration (R_h). It is, however, uncertain whether this increase can be sustained into the future (McCarthy et al., 2010; Norby et al., 2010; Zak et al., 2011). Indeed, some ecosystems appear to lack any significant response to increasing atmospheric CO₂ (Adair et al., 2009; Bader et al., 2009; Norby et al., 2010). According to previous modelling studies, any additional terrestrial carbon uptake linked to CO₂ fertilization is also likely to be more than offset in the future by the increase in heterotrophic soil respiration (R_h) following warming (Cox et al., 2000). This extra C released into the atmosphere would further accelerate global warming (Kirschbaum, 2000) and a climate change-driven acceleration of soil organic C decomposition rates would therefore represent a positive feedback on climate (Kirschbaum, 2004). However, there is a lack of agreement between model-based estimates of when and at what rate soil C storage might begin to decline (Friedlingstein et al., 2006). Further, net primary production and microbial decomposition are controlled by the availability

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of nitrogen (N) and phosphorus (P), with N-limitation tending to dominate in temperate and boreal ecosystems, and P-limitation tending to dominate in the tropics (Luo et al., 2004; Vitousek et al., 2010; Wang et al., 2010; Goll et al., 2012). Recently, there has been an extensive effort to implement these processes in global terrestrial ecosystem models (e.g. Thornton et al., 2007; Sokolov et al., 2008; Yang et al., 2009; Wang et al., 2010; Zaehle and Friend, 2010; Esser et al., 2011; Menge et al., 2012). Generally, adding N-limitation reduces the simulated global land C uptake during the 20th century relative to non-nutrient limited simulations. Early results suggest P-limitation makes a negligible difference to the global terrestrial carbon uptake, but can introduce very large regional differences particularly in the tropics (Zhang et al., 2011). However, despite the recognition of the importance of interactions between these biogeochemical cycles, interactions between terrestrial C and N cycles are represented in just three of the ESMs used in the Coupled Model Intercomparison Project, Phase 5 (CMIP5; Taylor et al., 2012) while the terrestrial P cycle is omitted in all CMIP5 simulations (Todd-Brown et al., 2013). This introduces critical uncertainties in projections as nutrient limitation prevents vegetation growth at the rate allowed for by CO₂ fertilization in different ways between models.

An additional uncertainty resides in current parameterizations of microbial decomposition and corresponding heterotrophic respiration (R_h) in Earth System Models. So far, all CMIP5 models represent decomposition as a first-order process (Todd-Brown et al., 2013) in which instantaneous soil moisture and soil temperature are used to adjust a time-invariant decay rate that is applied to the amount of substrate available (i.e. C pool size). Put in a mathematical way, at each time step the actual amount of microbial decomposition D_m in a specific C pool, is calculated as

$$D_m = k \times f_W(\theta_s) \times f_T(T_s) \times C_s \quad (1)$$

with k the reference decay rate that is scaled by f_T , a function of soil temperature T_s , and by f_W , a function of soil moisture θ_s (usually expressed as a fraction of water saturation; Moyano et al., 2012) and C_s the amount of C in the pool. Part of the decomposition

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is emitted as CO_2 and this flux corresponds to R_h while the rest is typically assigned to different soil C pools. The lack of physiological control has been recently identified as being inconsistent with our current understanding of decomposition process (e.g. Allison et al., 2010; Schmidt et al., 2011). Nevertheless, first-order kinetics applied to a succession of C pools with different residence time are able to explain complex processes including the apparent thermal acclimation of decomposers to warming (Luo et al., 2001) with a quick depletion in the most labile pools (Kirschbaum, 2004; Knorr et al., 2005). However, in current models, simple changes in the formulation of f_W , the soil moisture-respiration function (SMRF), and f_T , the soil temperature-respiration function (STRF) can have a major impact on R_h (Falloon et al., 2011; Exbrayat et al., 2013). These impacts on R_h can determine whether soil carbon stores increase or decrease for the same change in net primary productivity (NPP) meaning they control whether the soil will remain a sink, or convert to a source of CO_2 in the future. The various representations of R_h are also responsible, at least in part, for the six-fold range in soil C achieved by CMIP5 simulations at the end of the 20th century in response to a three-fold range in NPP (Todd-Brown et al., 2013).

In this paper, we address two questions arising from the current parameterization of the land carbon cycle. First, how do N and P limitations on plant productivity affect the response of soil C to different combinations of SMRF and STRF over the 20th century? Second, how sensitive is R_h to the formulation of its response to changes in soil moisture and soil temperature? We explore these two sources of uncertainty in combination and quantify their influence on the response of the terrestrial component of a global Earth System Model to the historical increase in atmospheric CO_2 and associated warming. Therefore, we examine at global and regional scales how the simulated historical carbon cycle is affected by the way soil moisture and soil temperature control R_h using three SMRFs, three STRFs and N and P limitation.

2 Methods

2.1 Modelling system

We use the Carnegie–Ames–Stanford Approach with Carbon-Nitrogen-Phosphorus (CASA-CNP) land biogeochemical model (Wang et al., 2010) coupled with the Community Atmosphere-Biosphere Land Exchange (CABLE) land surface model (Wang et al., 2011). CASA-CNP simulates the turnover of terrestrial carbon based on 3 vegetation, 3 litter and 3 soil pools. Soil heterotrophic respiration (R_h) sums the CO_2 fluxes from the decomposition of litter and soil carbon. In each pool, R_h is represented as a first-order process that depends on substrate availability, soil moisture and soil temperature and these two latter terms are calculated in CABLE in response to meteorological forcing. CASA-CNP can be run in a carbon only (C), C with nitrogen limitation (CN), and CN with phosphorus limitations (CNP) mode. Effectively, NPP is limited by the concentration of N (in CN mode) as well as P (in CNP mode) in leaves. The uptake of mineral N and labile P depends on their availability in soils while mineralization rates are tightly linked to C decomposition rates (Wang et al., 2010). We use parameter values for CASA-CNP that were previously reported by Wang et al. (2010). The CABLE + CASA-CNP terrestrial system has been coupled to the CSIRO Mk3L climate system model (Phipps et al., 2011; Zhang et al., 2011). The relatively coarse resolution of the model (5.6° latitude \times 3.2° longitude) makes it a computationally efficient candidate of choice to create multiple simulations for sensitivity analyses while simulated climate is still representative of historical period (Phipps et al., 2011). Since we address the terrestrial carbon balance, our setup uses prescribed sea surface temperatures (SSTs) from the CSIRO Mk3.6 model (Rotstayn et al., 2012) using CMIP5 historical forcing data from 1850 to 2005 (Taylor et al., 2012) that were re-gridded at the resolution of Mk3L.

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2.2 Model versions

To examine the uncertainty linked to the choice of biophysical response functions, three SMRFs and three STRFs were implemented in the CASA-CNP model (Fig. 1). These three SMRFs and STRFs represent the key features of a larger suite of functions used in a previous offline site-scale studies with the CABLE + CASA-CNP modelling system (Exbrayat et al., 2013) and their exact formulation can be found in Tables 1 and 2 for the SMRF and STRF respectively. As shown in Fig. 1, the general consensus is that soil respiration is enhanced by intermediate moisture associated with warm temperatures. For example, while the bell-shaped CASA-CNP SMRF simulates a smooth response of soil respiration to drying conditions, SOILN (Jansson and Berg, 1985) and TRIFFID (Cox, 2001) predicts a constantly null or low moisture adjustment below wilting point respectively. Further, SOILN considers a whole range of optimal moisture conditions while the two other SMRFs both have a single, though different, optimal moisture. In saturated conditions, TRIFFID allows a higher respiration rate than the other SMRFs. Comparing the STRFs, CASA-CNP allows higher respiration rate for temperatures below +10 °C, while K1995 (Kirschbaum, 1995) is higher than the others between +10 °C and +40 °C. Finally PnET (Aber et al., 1997) displays the highest temperature-based adjustment of R_h for soil temperatures above +40 °C. Interestingly, while CASA-CNP and PnET continue to increase, K1995 starts decreasing above +37 °C.

2.3 Experiments

Simulations were performed using the modelling system described in Sect. 2.1 with each combination of SMRF, STRF and nutrient limitation mode (C-only, CN and CNP): a total of 27 model versions. Following Zhang et al. (2011), we first initialised the 27 model versions offline using constant pre-industrial CO₂ (284.7 ppmv) and 5 yr of previously equilibrated climatology and gross primary production sourced from a Mk3L-CABLE-CASACNP simulation. Once equilibrated off-line, total C storage for each of the 27 equilibration runs were used to reinitialise the coupled climate model and a fur-

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ther spin-up was undertaken until soil carbon storage achieved steady-state. Finally, historical transient runs including increasing atmospheric CO₂, based on CMIP5 specifications, and driven by corresponding CSIRO Mk3.6 SSTs were performed for each of the 27 model versions for 1850–2005. By prescribing atmospheric CO₂ we recognise that we limit the land–atmosphere coupling to energy and water exchanges between the land and the atmosphere. This is not a full coupling (e.g. Friedlingstein et al., 2006) where atmospheric carbon is also affected by terrestrial primary production and respiration fluxes. However, our experiments permit an assessment of how the choice of STRF, SMRF and nutrients affect terrestrial systems and R_h more simply than if we allowed for these feedbacks, or if we allowed ocean–atmosphere exchanges or land use change to affect atmospheric CO₂. We note, of course, that these fluxes are included implicitly in the prescribed atmospheric CO₂ data. Finally, by using the same radiative forcing in all simulations, we isolate the effect of the different R_h parameterizations on the terrestrial carbon cycle more simply than if variations in atmospheric CO₂ occurred in our simulations. For simplicity, we could have driven CASA-CNP with prescribed historical weather observations but using a climate model provides the opportunity to perform 21st century projections in the near future.

3 Results

3.1 Global land carbon balance

The global net ecosystem accumulation (NEA) of terrestrial carbon since 1850 is shown in Fig. 2 (a positive accumulation corresponds to a net terrestrial sink). Each panel in Fig. 2 shows results for all 9 combinations of SMRF and STRF for a given C-only (Fig. 2), CN (Fig. 2b) or CNP (Fig. 2c) mode using thin black lines. The shaded area represents the total simulated range for a given nutrient limitation mode. All simulations show a net accumulation of carbon over the 20th century at the global scale as NPP increases on average due to a combination of CO₂ fertilization and warmer tempera-

tures driven by the observed CO₂ increases. However, there are very major changes between the results from the C, CN and CNP modes and between the various SMRF and STRFs.

For the C-only mode, the uncertainty in the simulated NEA introduced by different SMRF and STRF is very large, ranging from 207 to 438 GtC (Fig. 2a). To illustrate the magnitude of the terrestrial sink, this represents ~ 43 % to ~ 92 % of the ~ 475 PgC of accumulated emissions from fossil-fuel and land-use change represented in each panel of Fig. 2 from data by the Carbon Dioxide Information Analysis Center (CDIAC; Houghton, 2008; Boden et al., 2010). Adding N-limitation reduces the terrestrial sink to between 61 and 175 PgC for the 20th century, or 13 % and 37 % of anthropogenic fossil-fuel emissions. This is more in accordance with results from the Global Carbon Project reported by Le Quéré et al. (2009). The uncertainty in the CN-mode, resulting from the choice of STRF and SMRF, also decreases by about a factor of two relative to the C-only mode. The results from the CNP-mode demonstrate a further reduction in both the magnitude and variability in NEA to 41–134 PgC or ~ 9 % to ~ 28 % of anthropogenic emissions. Note that while the uncertainty ranges of CN and CNP modes overlap, the lowest member of the C-mode family (Fig. 2a) accumulates ~ 40 PgC more than the highest member of the CN and CNP simulations (Fig. 2b, c).

We compare these simulations with previous estimates of global terrestrial NEA. Figure 3 compares our simulation results with estimates using the time periods available from Canadell et al. (2007) and Sitch et al. (2008). In terms of the mean terrestrial sink, every simulation in the C-only mode, for all combinations of STRF and SMRF, overestimates NEA as compared to previous studies. In addition, over the period 1959–2005 and 1970–1999 the C-only mode simulates excessive variability in the terrestrial sink (Fig. 3a, b). Generally, results for the mean terrestrial uptake from the CN and CNP models are more consistent with the estimates by Canadell et al. (2007) and Sitch et al. (2008). Results over the second half of the 20th century (Fig. 3a) suggest the CN mode is most similar to previous estimates with almost all combinations of STRF and SMRF within the ~ 0.75 PgCa⁻¹ uncertainty range provided by Sitch et al. (2008)

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and matching the estimate of Canadell et al. (2007). Over the same period all CNP simulations are below the range suggested by Sitch et al. (2008). A similar result for CN is shown for all other time periods (Fig. 3b–e) where CN mode is in agreement with the estimate of Canadell et al. (2007) and the range given by Sitch et al. (2008) where available. CNP mode is always lower on average but is consistent with the range given by Sitch et al. (2008) for 1980–1989 and overlaps the estimate by Canadell et al. (2007) for the periods 1980–1989 and 2000–2005. CNP mode is below available estimates in 1970–1999 (Fig. 3b) and 1990–1999 (Fig. 3d). However the estimated land carbon sink by Canadell et al. (2007) and Sitch et al. (2008) also depends on the estimated CO₂ emission from land use change. If a lower CO₂ emission from land use change is used, as suggested by Arora and Boer (2010), the estimated land carbon sink would be much lower.

The lower panels of Fig. 3 show the variability of the land sink as illustrated by the standard deviation of annual NEA. Over the two longest periods (Fig. 3a, b) the C-only mode simulates excessive variability compared to Canadell et al. (2007). Both the CN and CNP modes are closer to Canadell et al. (2007) though slightly high in 1959–2005. Over the shorter periods, CN and CNP modes always overlap the estimate by Canadell et al. (2007) while the C-only mode is too variable during 1990–1999. In effect, CN and CNP modes largely capture the mean and the variability in the land sink on all timescales, but the C-only mode simulates too high a mean, and too variable a sink. We next investigate the regional implications of the choice of SMRF and STRF to explain the two-fold range in NEA simulated between simulations with the same nutrient-limitation.

3.2 Regional variations

To understand the roughly two-fold difference in global NEA simulated by all model versions in each nutrient mode (Fig. 2), we investigate spatial differences in NEA. Figure 4 shows the change in average land carbon (vegetation + litter + soil), or NEA, for each SMRF and STRF for the CN simulations from 1850–1859 to 1996–2005. We

use these simulations as reference since they were the most similar to independent estimates of global NEA for 1959–2005 (Sect. 3.1). Each panel in Fig. 4 represents a combination of a SMRF (rows) with a STRF (columns). Although regional differences appear depending on the choice of a SMRF when keeping the same STRF, most of the uncertainty in NEA is related to the choice of a STRF. For example, most of the continents show an increase in land carbon between 1850 and 2005 using the CASA STRF (leftmost column), a result weakly sensitive to the choice of SMRF. However, if the K1995 or PnET STRF is used (rightmost column), a large region of negative NEA (i.e. a net source of CO₂) is simulated in the northern latitudes of eastern Eurasia. This negative NEA occurs irrespective of the choice of SMRF. The K1995 and PnET STRFs also simulate a decrease in NEA over high latitudes of North America, but only if the CASA and SOILN SMRFs are used. Elsewhere, excluding desert regions, all combinations of SMRF and STRFs simulate an increase in NEA over the period. However, the magnitude of NEA varies such that much larger regions experience larger increases in NEA using the PnET STRF (increases exceeding 4 kg C m⁻²) than if CASA or K1995 is used (e.g. central Europe).

Spatial differences in NEA can be linked to how soil conditions affect the response of R_h depending on the choice of SMRF and STRF. Figure 5 shows the change in soil carbon between the 10 first and 10 last years of the simulations. Negative NEA (net carbon sources) in the northern parts of Eurasia in the K1995 and PnET STRF simulations are linked with soil carbon (Fig. 5). Similarly to Fig. 4, Fig. 5 shows that the soil carbon change is much more sensitive to the choice of a STRF as compared to the choice of a SMRF. For example, Fig. 5 highlights large (> 3 kg C m⁻²) losses in soil carbon in the northern parts of Eurasia if either the K1995 or PnET STRFs are used but little change if CASA STRF is used. This correlates with negative NEA observed in corresponding simulations (Fig. 4) which we attribute to soil warming that triggers higher R_h . As a result, any increases in NPP in these regions linked to elevated CO₂ are more than offset by soil respiration when the K1995 and PnET STRFs are used but are robust to warming if the CASA STRF is used. Elsewhere, there are quite large differences in

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the results for soil carbon as the STRF and SMRFs are varied. Results with the PnET STRF tend to lead to a larger increase in soil carbon that explains most of the corresponding highly positive NEA. SMRFs also lead to large differences, especially over central Europe. Figure 5 shows a gradual increase in soil carbon accumulation from the CASA SMRF, through the SOILN SMRF to the TRIFFID SMRF. This additional sink is most apparent when the PnET STRF is used as TRIFFID accumulates soil carbon in places where the CASA and SOILN SMRFs lose carbon (e.g. Americas).

The spatial impact of N limitation on the C-only simulations can be examined by comparing the difference in total NEA between C-only and CN simulations (Fig. 6). NEA in the C-only simulations is generally very much higher than in the CN-limited simulations. This is most obvious in the mid- and high-latitudes of the Northern Hemisphere where the difference between C-only and CN simulations in NEA exceeds 5 kg C m^{-2} (Fig. 6) which is large enough to change the sign of NEA and change these regions from net sources in CN simulations to net sinks in C-only simulations (stipples on Fig. 6), especially with the K1995 STRF. Removing N-limitation also increases NEA by $\sim 1\text{--}2 \text{ kg C m}^{-2}$ over many continental surfaces (Fig. 6). Nevertheless, the extreme north-east of Eurasia remains a source of CO_2 in all simulations with K1995 and PnET (Figs. 4 and 6) in the C-only mode despite plant productivity (i.e. carbon uptake) not limited by nutrients and a globally higher NEA (Fig. 2). There are still areas within a region with low NEA but generally N-limitation strongly suppresses this variability, thereby reducing the range of NEA simulated by the various combinations to that shown in Fig. 4.

Figure 7 shows the impact of the choice of STRF and SMRF of soil carbon for the C-only simulations as compared to CN simulations. This shows a result similar to the NEA results shown in Fig. 6. Again, most dramatic changes are in the mid and high latitudes of the Northern Hemisphere, where soil carbon increase is up to 4 kg C m^{-2} higher in the C-only simulations (Fig. 7) with the PnET STRF. Some areas of northern Eurasia remain a source for atmospheric CO_2 , though smaller than in the CN-limited simulations. Away from the mid and high latitudes of the Northern Hemisphere, Fig. 7 suggests the differences in soil carbon between the C-only and CN simulations are commonly small

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However, comparing our range of results due to different SMRFs and STRFs across the three nutrient modes with estimates of NEA from Canadell et al. (2007) and Sitch et al. (2008) suggests that the C-only mode simulates an excessively high terrestrial uptake. In general, the CN mode appears most consistent with other estimates. Earlier studies, each using a single SMRF or STRF, predicted a reduction in the CO₂ fertilization effect by up to 72 % when considering N-limitation (Thornton et al., 2007; Sokolov et al., 2008; Jain et al., 2009; Zaehle et al., 2010; Bonan and Levis, 2010; Zhang et al., 2011) and our average reduction of 64 % in global NEA (Fig. 2) due to N-limitations is consistent with these previous estimates. Our results suggest that reductions in CO₂ fertilization simulated by CASA-CNP in response to N and P limitations (Zhang et al., 2011) are robust to the choice of STRF or SMRF. Since the results from CN and CNP modes overlap for all time periods (Fig. 3) we cannot confidently differentiate between these configurations.

It would be straightforward to calibrate the model in C-only mode to reduce the over-estimation of NEA although it would be computationally infeasible to calibrate all variations. However, if the C-only mode was calibrated to match observations, the CN and CNP modes would then grossly underestimate observations. Further, parameter values optimised to reproduce observed data would likely compensate for the lack of representation of key biogeochemical processes (N and P), introducing a high risk of obtaining acceptable simulations for the wrong reasons. It has been demonstrated that over-fitted parameters that provided acceptable calibration results were not able to capture the response of a system to changes if some processes were missing in the model structure (e.g. Exbrayat et al., 2013b). Since the availability of N and P has a key influence on NEA (Vitousek and Howarth, 1991; Luo et al., 2004; Vitousek et al., 2010; Goll et al., 2012), results from CN and CNP are likely more robust than C-only. Rather than calibrating a C-only version, adding N and P to more correctly reflect the behaviour of the biogeochemical system is preferable.

N and P limitations reduce the absolute uncertainty in net carbon uptake and slow down the terrestrial C cycle. However, the uncertainty introduced by SMRFs and

STRFs remains significant under all nutrient limitation modes. This uncertainty leads some model versions with equivalent N and P limitations to simulate twice as much uptake as other versions. This is true of C-only, CN and CNP modes (Figs. 2 and 3). To illustrate this, we analyse the annual net ecosystem exchange (NEE) normalised by the annual net primary productivity (NPP). We chose NPP because while it is affected by NP limitations, it is not directly affected by the choice of SMRF or STRF (Fig. 10). Figure 3 indicates that, by reducing all C fluxes and turnover processes, NP limitations stabilise the system. As a result, CN and CNP modes (Fig. 10b, c) do not exhibit the post-1960 step change in NEE that corresponds to a greater carbon sink in the C-only model (Fig. 10a) associated with increasing atmospheric CO₂ concentration. Figure 10b, c, however, shows that the ensembles of NP limited simulations often contain both net sources and net sinks during a same year. This generates the large uncertainty bounds shown in Fig. 2 even though the ensemble spread appears small relative to the effect of introducing NP limitations. The differences in STRF and SMRF also lead the highest cumulative NEA to be double the lowest NEA in C-only, CN and CNP modes. To compare the spread generated by the different SMRFs and STRFs relative to variability in NEE/NPP we calculate a measure analogous to a signal-to-noise ratio for each C-only, CN and CNP mode. We define the “signal” as the temporal variability in NEE/NPP, calculated as the standard deviation of the annual mean NEE/NPP (in black in Fig. 10). The “noise” is calculated as the intra-annual variability between combinations of SMRF and STRF. This is calculated as the standard deviation of the distance to the annual mean NEE/NPP for all models in the ranges, for all years (ranges in grey in Fig. 10). This signal-to-noise ratio decreases from 3.8 to 1.7 and 1.4 in C-only, CN and CNP modes respectively. This indicates that the uncertainty due to the SMRFs and STRFs relative to the variability in NEE increases when NP limitations are added, making the correct definition of these response functions increasingly important as the representation of the terrestrial carbon uptake improves.

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4.2 Regional implications

In Sect. 4.1, we showed that differences in SMRFs and STRFs increase in importance to the total global uncertainty when NP limitations were included. Nevertheless, all simulations describe the global land surface as a net sink for the historical period.

5 However, at regional scales, the implications of changing STRFs and SMRFs can be very large regardless of whether nutrient limitations are included (Figs. 4, 5, 8 and 9) or not (Figs. 6, 7). The NEA simulated by CABLE-CASA-CNP with different combination of SMRF and STRF from 1850 to 2005 can change from a carbon sink to a carbon source at regional scales. Since we prescribed atmospheric CO_2 , NPP is very similar

10 for all our C-only model simulations. NPP is also very similar within all the N-limited simulations, and the same is true of the NP limited simulations. We therefore cannot assign the differences in NEA and changes in soil carbon to these small variations in C uptake. According to Eq. (1), in Earth System Models, the amount of decomposition, and therefore R_h , is controlled by a time-invariant reference k parameter, the SMRF \times STRF product ($f_W(\theta_s) \times f_T(T_s)$ in Eq. 1) and the amount C_s of carbon available in soil for decomposition. Changes in soil moisture and temperature simulated over the historical period imply a change in the SMRF \times STRF product that represents the soil physical state control on R_h . As shown by their respective shapes (Fig. 1), the different functions do not have the same sensitivity to a change in the soil temperature or moisture.

20 Figure 11 shows the change in the average value of the SMRF \times STRF product between the 10 first and 10 last years of the CN simulations. There are large variations between the different model versions depending on both SMRF and STRF. First, R_h does not increase everywhere and there are significant decreases in dry regions (e.g. Arabic peninsula, Western Sahara and Western Australia) with the SOILN SMRF used with the K1995 or PnET STRFs. This is because SOILN is the most constraining function in these dry conditions (Fig. 1). All model versions using the K1995 STRF have the highest relative increase in R_h in northern Eurasia while the other STRFs do not imply an increase of more than 20% in R_h except when used with SOILN. This does not

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correlate with the change in soil C (Fig. 5). Further, the influence of R_h on NEA (Fig. 4) as the model versions losing the most soil C (blue colours on Fig. 5) are not the one where the SMRF \times STRF product increases the most (Fig. 11), except perhaps when using the SOILN SMRF with the K1995 STRF. In other words, changes in STRF and SMRF do not explain the simulated changes in carbon storage.

Equation (1) highlights that in the first-order parameterization of microbial decomposition, substrate availability C_s is also a regulating factor. The initial amount of soil C to which the relative change in the SMRF \times STRF product is applied also affects the response of R_h and thereby NEA. In our simulations, all model versions were brought to equilibrium until C pools achieved a steady-state in which $R_h = \text{NPP}$. This is a standard procedure (e.g. Wang et al., 2010; Xia et al., 2012) which would most likely have been used in all CMIP5 simulations that incorporated carbon. However, if the product of a specific combination of a SMRF and a STRF has a lower value, it will require higher substrate to achieve the same steady-state in which R_h compensates NPP (given that NPP is similar between our simulations). Figure 12 shows the average soil C density at equilibration for all CN simulations. Large differences are observed in the total pool size as a function of the SMRF and STRF (similar patterns exist in C-only and CNP simulations). For example, the K1995 and PnET STRFs equilibrate at much higher carbon density than CASA functions in the mid- to high-latitudes in the Northern Hemisphere. This is due to the relative position of these functions for cold temperatures (Fig. 1): the CASA STRF is systematically above the two other STRFs for soil temperatures below 10 °C. It therefore requires less substrate to simulate R_h at a level that compensates for the same NPP. Conversely, the PnET STRF causes the model to equilibrate at a higher soil C density in warmer regions as it is well below the two other functions for soil temperature corresponding to Africa and South America. Differences implied by SMRFs are more localised and do not depend on a latitudinal temperature gradient; there are of course dry and wet regions at any latitude. SOILN is the most limiting SMRF in dry conditions and therefore south-west Australia, southern Africa and the western edge

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of South America always equilibrate at a higher level with this SMRF than with the two others as the limit requires more substrate to achieve the same R_h to compensate NPP.

Figure 13 presents the change in soil C as a function of initial conditions (i.e. in 1850 after spin-up) in all simulations. Grid boxes with low initial values can gain or lose C for all combinations of a SMRF with a STRF. The C-only simulations accumulate soil C irrespective of the initial conditions because the lack of nutrient limitation allows for a higher NPP which offsets R_h . In contrast, in the nutrient limited CN and CNP modes, lower NPP leads to a loss in soil carbon through the historical period where substrate availability is initially high. This is particularly true for the K1995 and PnET simulations. Even where the relative change in the SMRF \times STRF product was not particularly strong (e.g. TRIFFID SMRF with PnET STRF in Fig. 11), the change in the SMRF \times STRF product is applied to higher substrate availability. This enhances R_h more than increases in soil C implied by higher NPP. Thus, while soil carbon accumulates in the C-only simulations everywhere, this sink changes to a net source of carbon in the N and NP limited simulations over the historical period (Figs. 7 and 9) in regions that equilibrate at high levels of soil carbon.

Total soil C ranges from 765 PgC to 3495 PgC in our CN simulations. This approximates the six-fold range found in CMIP5 models (Todd-Brown et al., 2013). We adopted a colour scale similar to Fig. 3 of Todd-Brown et al. (2013) to presents soil C in different CMIP5 ESMs. The regional differences implied by the different SMRFs and STRFs map particularly well onto the diversity shown by the CMIP5 models. We do not explore this in detail here but we suspect that these similarities between our simulations and CMIP5 results strongly indicate that the formulation of the time and space invariant SMRF and STRF is a key source of uncertainty that requires more attention in the current first-order description of microbial decomposition. We see here an analogy with the model-specific nature of soil moisture described by Koster et al. (2009). That is: the amount of soil C as simulated in ESMs is not something that can be directly compared with a quantity that might be measured in the field. Rather, soil C in each model is the value required by the model to reach steady-state, and through which variations trigger

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an acceptable response of land–atmosphere exchanges to historical changes. Since observations are not available to constrain the model in the future, a large uncertainty arises that can be exemplified by the lack of consensus between model projections in a previous inter-comparison project despite a rather good agreement for historical simulations (Friedlingstein et al., 2006). This adds to recently stated concerns that the current parameterization of decomposition is not consistent with our understanding of the process (Allison et al., 2010; Schmidt et al., 2011; Todd-Brown et al., 2012) because of the lack of representation of key physiological processes including enzyme control on decomposition. We see here a critical need to refine this part of ESMs as it controls the sign of change in soil C and NEA, hence the carbon-climate feedback from the land on the atmosphere.

5 Conclusions

We have used 27 combinations of STRFs, SMRFs and nutrient limitations in an Earth System Model to explore how the land carbon balance responds to changing atmospheric CO₂ over the period 1850–2005. Implementing N and P limitations on plant productivity in the CASA-CNP ecosystem model allows the simulation of the historical response of the terrestrial C cycle that compares well with independent estimates irrespective of the STRF or SMRF used and reduces the absolute uncertainty that arises from their formulation. The definition of the precise shape of the STRF and SMRF becomes however increasingly important in the nutrient-limited modes relative to the variability in NEA. Further, the choice of STRF and SMRF also controls the amount of soil C required to achieve an equilibrated state in response to the same NPP: a result that we did not foresee! This, in turn, controls the sensitivity of R_h , to temperature and moisture and the sensitivity of the whole land C balance to warming. Due to the size of soil carbon pools even small changes in biophysical control can lead to large fluxes of C losses when applied to big pools. We show that this sensitivity to STRF and SMRF generates a range of equilibrated soil carbon stores very similar to the six-fold range

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of global soil C achieved by CMIP5 models. That is, this huge range in soil carbon in CMIP5 is likely the result of equilibration methods and since the magnitude of the pool affects how much a pool can change under forcing, the wide range of responses in CMIP5 in terms of soil carbon may well be an artefact of the modelling methods used.

Based on our experiments, we recommend representing at least CN interactions in Earth System Models in order to capture the correct magnitude of historical land-atmosphere carbon fluxes. The other clear implication of our results is that a more concerted effort in how microbial decomposition processes are represented in Earth System Models is required. We need to address how equilibrium should be defined or constrained to match some estimates, how nutrients should be represented and how we develop these efforts with limited global databases of soil carbon.

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Table 1. Formulation of the SMRFs implemented in the CASA-CNP model (θ_s : soil moisture, θ_{wilt} : moisture at wilting point, θ_{fc} : moisture at field capacity, θ_{opt} : optimum moisture, θ_{lopt} : lower optimal moisture, all expressed relative to moisture at saturation).

Function	Equation
CASA-CNP	$f_W(\theta_s) = \left(\frac{\theta_s - 1.70}{0.55 - 1.70}\right)^{6.6481} \times \left(\frac{\theta_s + 0.007}{0.55 + 0.007}\right)^{3.22}$
SOILN	$\theta_{opt} = 0.92$ $\theta_{lopt} = \theta_{wilt} + 0.1$ if $\theta_s > \theta_{opt}$ $f_W(\theta_s) = 0.2 + 0.8 \cdot \frac{(1 - \theta_s)}{(1 - \theta_{opt})}$ if $\theta_{lopt} \leq \theta_s \leq \theta_{opt}$ $f_W(\theta_s) = 1$ if $\theta_{wilt} \leq \theta_s \leq \theta_{lopt}$ $f_W(\theta_s) = \frac{\theta_s - \theta_{wilt}}{\theta_{lopt} - \theta_{wilt}}$ if $\theta_s < \theta_{wilt}$ $f_W(\theta_s) = 0$
TRIFFID	$\theta_{opt} = 0.5 \cdot (1 + \theta_{wilt})$ if $\theta_s > \theta_{opt}$ $f_W(\theta_s) = 1 - 0.8 \cdot (\theta_s - \theta_{opt})$ if $\theta_{wilt} \leq \theta_s \leq \theta_{opt}$ $f_W(\theta_s) = 0.2 + 0.8 \cdot \frac{(\theta_s - \theta_{wilt})}{(\theta_{opt} - \theta_{wilt})}$ if $\theta_s < \theta_{wilt}$ $f_W(\theta_s) = 0.2$

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Table 2. Formulation of the STRFs implemented in the CASA-CNP model (T_s : soil temperature in °C).

Function	Equation
CASA-CNP	$f_T(T_s) = 1.72^{(0.1 \cdot (T_s - 35))}$
K1995*	$f_T(T_s) = \exp\left(-3.764 + 0.204 \cdot T_s \cdot \left(1 - \frac{0.5 \cdot T_s}{36.9}\right)\right) \times 0.66^{-1}$
PnET*	$f_T(T_s) = 0.68 \cdot \exp(0.1 \cdot (T_s - 7.1)) \times 12.64^{-1}$

* Last terms in the equations are used to scale the original functions to the CASA-CNP model as explained by Exbrayat et al. (2013a)

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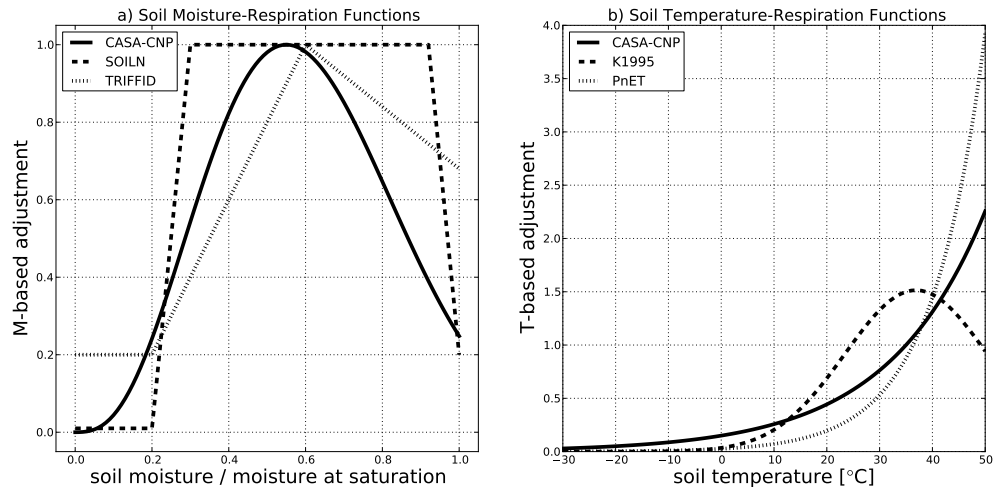


Fig. 1. STRFs and SMRFs implemented in the CASA-CNP model code.

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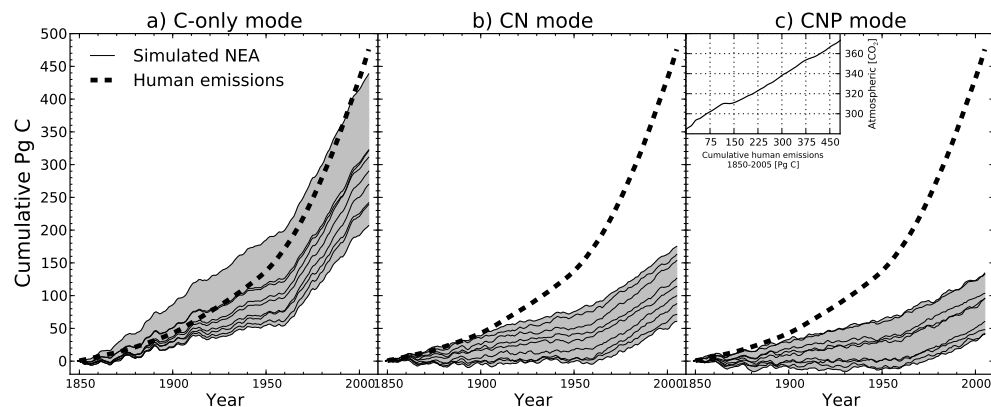


Fig. 2. Global cumulative human carbon emissions and modelled net ecosystem productivity throughout the historical period using CASA-CNP in C, CN and CNP modes. The shaded area represents the model uncertainty. The insert in the right panel shows the relationship between cumulative human emissions and atmospheric CO₂ (in ppmv) over the same period as the model is driven by this latter parameter.

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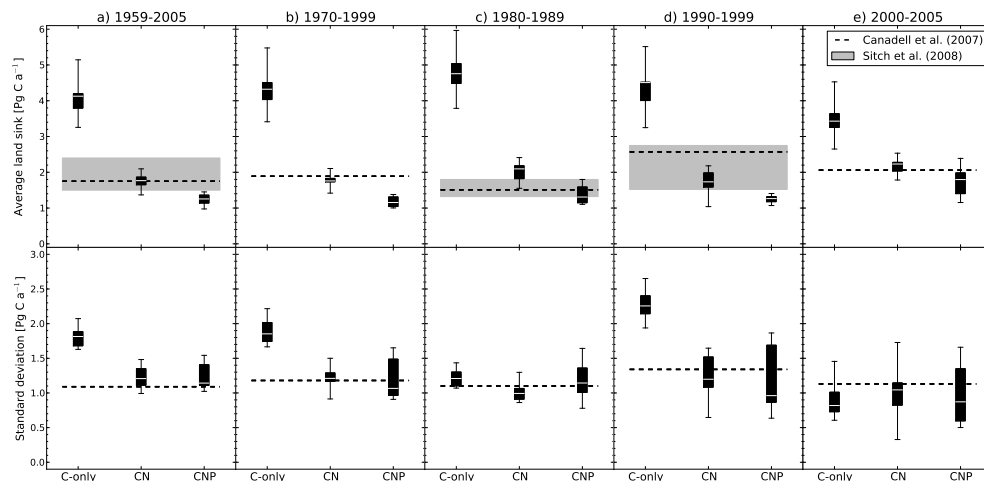


Fig. 3. Comparison of simulated NEA with previous studies. Boxplots indicate the uncertainty in the NEA simulated by all combination of a SMRF and a STRF in a specific nutrient limitation mode as indicated. Markers represent quartiles. Note data from Sitch et al. (2008) covers the period 1958–2002.

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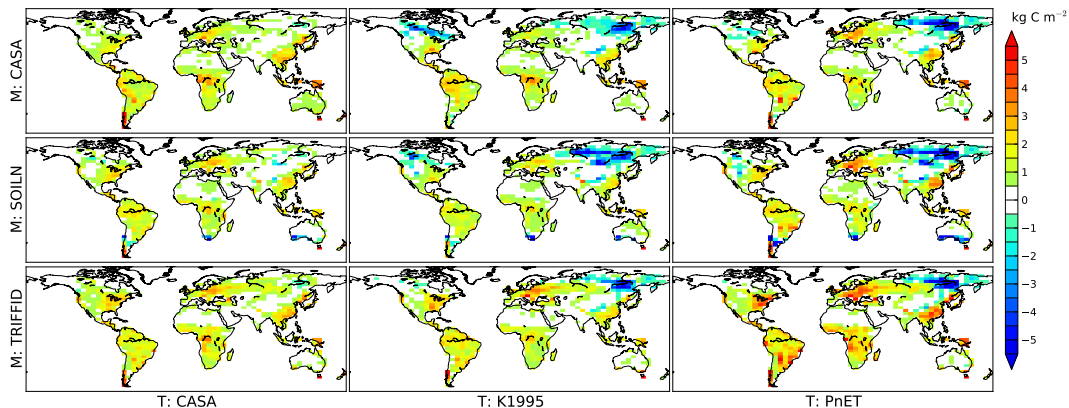


Fig. 4. Change in land carbon during historical simulations as represented by the difference in the average land carbon between 1996–2005 and 1850–1859 in CN simulations. Each sub-panel corresponds to a single combination of response functions, M refers to a SMRF, T to a STRF.

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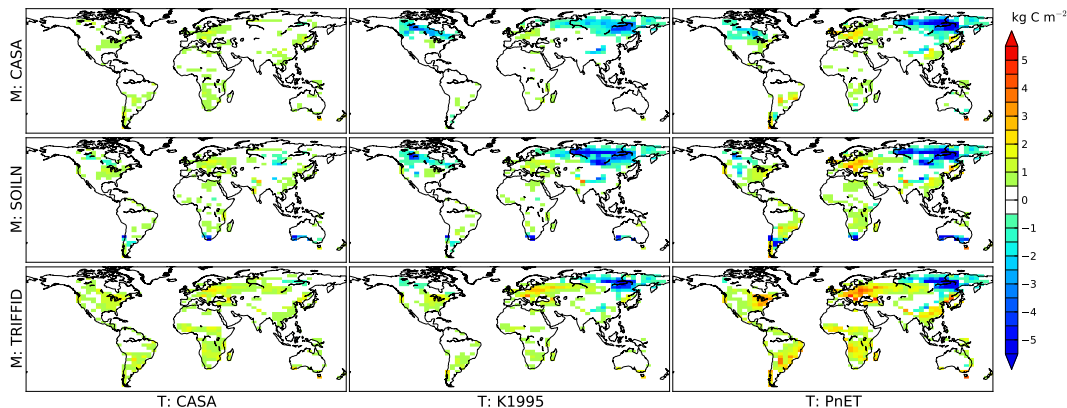


Fig. 5. Change in soil carbon during historical simulations as represented by the difference in the average soil carbon between 1996–2005 and 1850–1859 in CN simulations. Each sub-panel corresponds to a single combination of response functions, M refers to a SMRF, T to a STRF.

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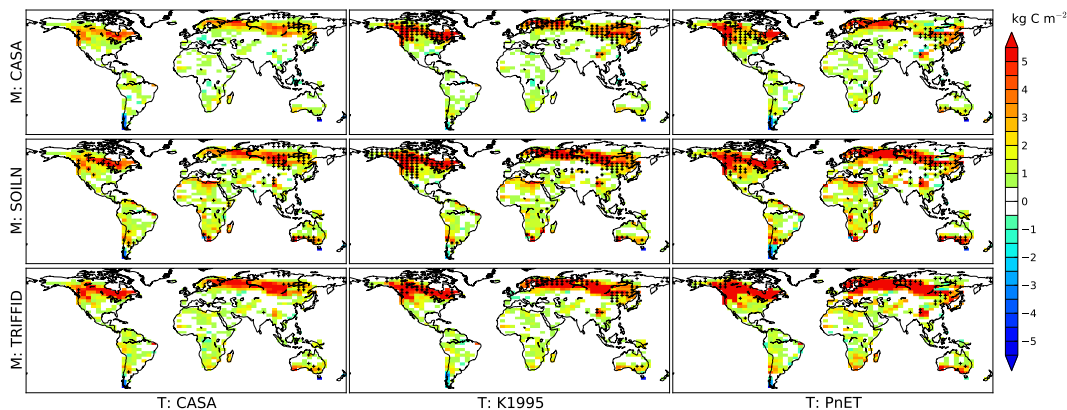


Fig. 6. Difference in NEA between C-only and CN historical simulations for the same combination of SMRF and STRF. Stipples represent areas where the sign of NEA is different between C-only and CN simulations.

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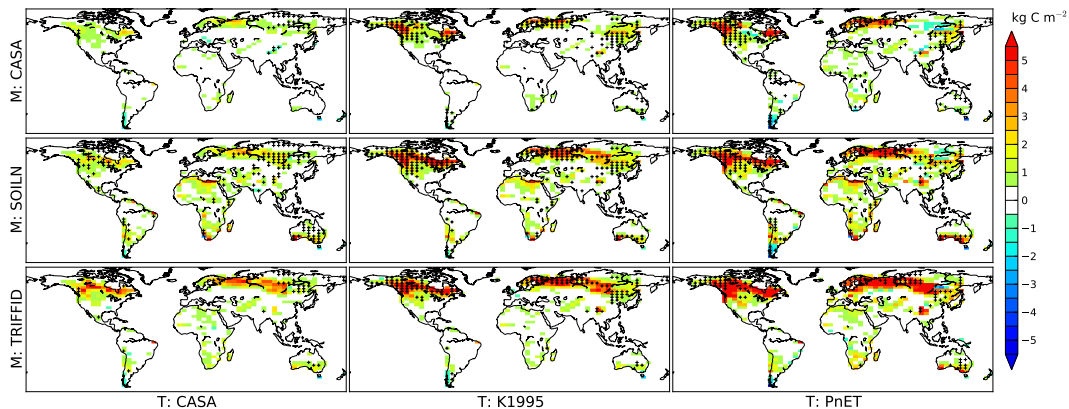


Fig. 7. Difference in soil carbon change between C-only and CN historical simulations for the same combination of SMRF and STRF. Stipples represent areas where the sign of soil C change is different between C-only and CN simulations.

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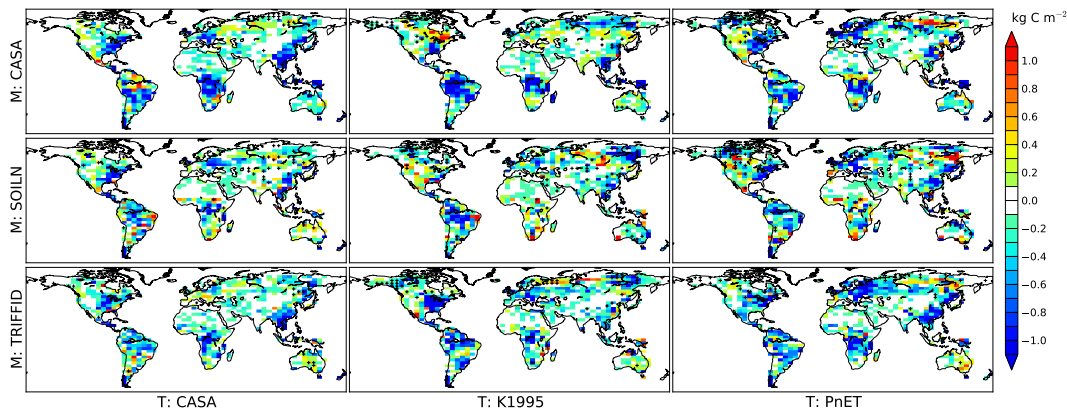


Fig. 8. Difference in NEA between CNP and CN historical simulations for the same combination of SMRF and STRF. Stipples represent areas where the sign of NEA is different between CNP and CN simulations. Please note the change in the scale of the colour bar as compared to previous maps.

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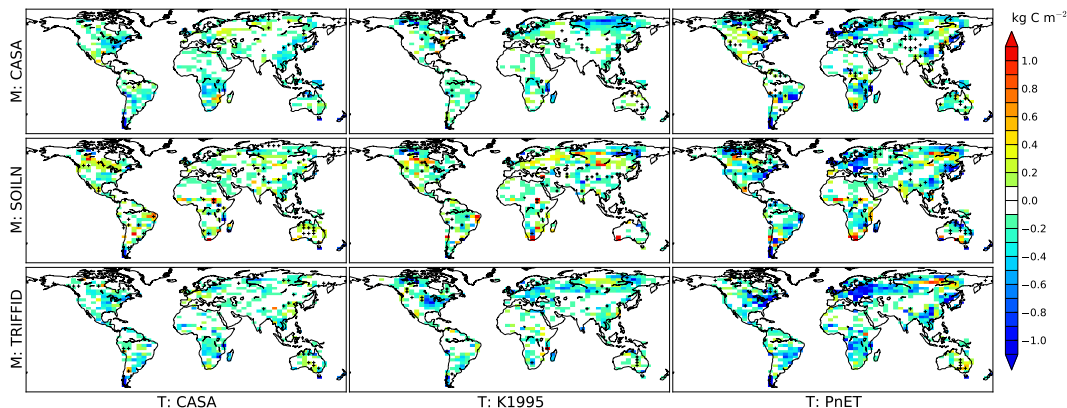


Fig. 9. Difference in soil carbon change between CNP and CN historical simulations for the same combination of SMRF and STRF. Stipples represent areas where the sign of soil C change is different between CNP and CN simulations. Please note the change in the scale of the colour bar as compared to previous maps.

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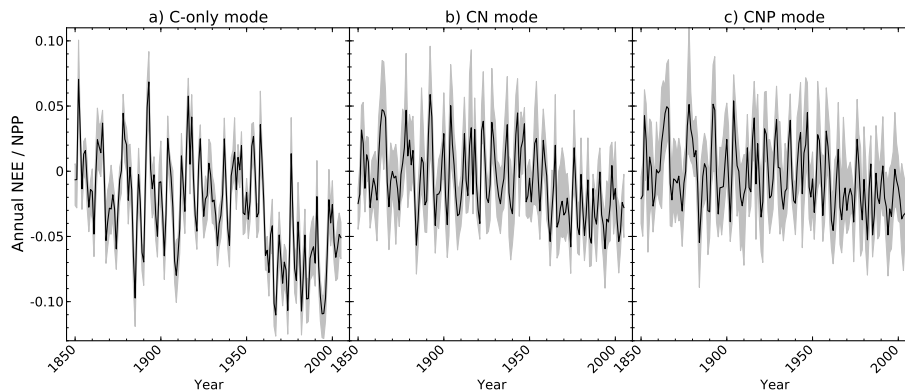


Fig. 10. Time series of net ecosystem exchange (NEE) normalised by net primary productivity (NPP) for all combinations of a SMRF and a STRF in a specific nutrient limitation mode as indicated. Negative values indicate a net sink. The black line represents the annual mean while the shading corresponds to the spread within each mode.

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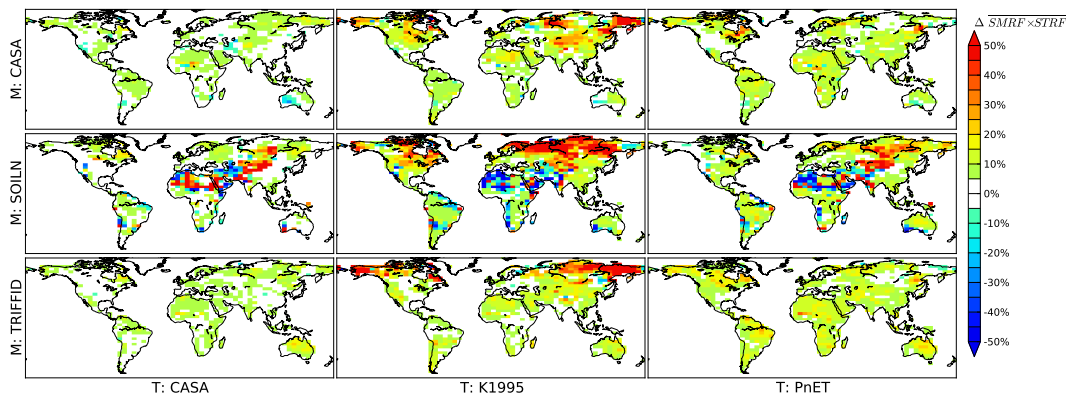


Fig. 11. Change in the average $\text{SMRF} \times \text{STRF}$ product between 1850–1859 and 1995–2006 relative to its initial value in CN simulations (in %). Positive values mean that the product is greater at the end of the historical simulations than at the beginning.

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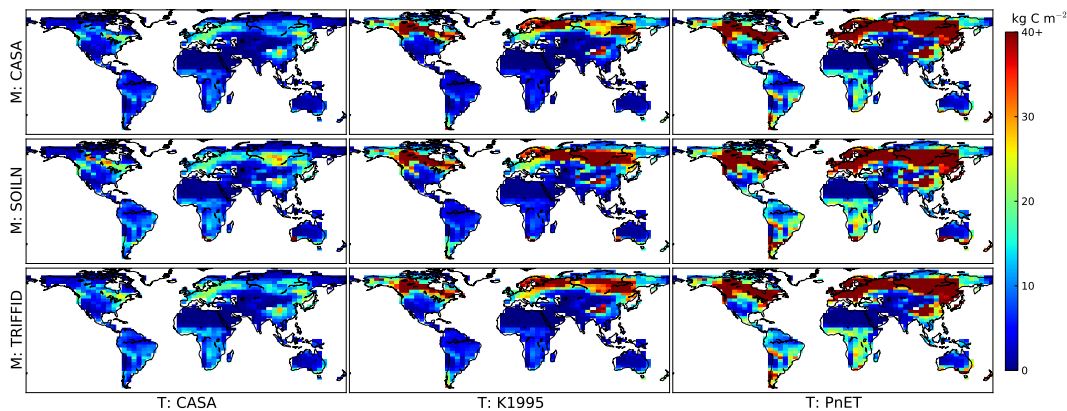


Fig. 12. Soil C density at equilibration in CN simulations.

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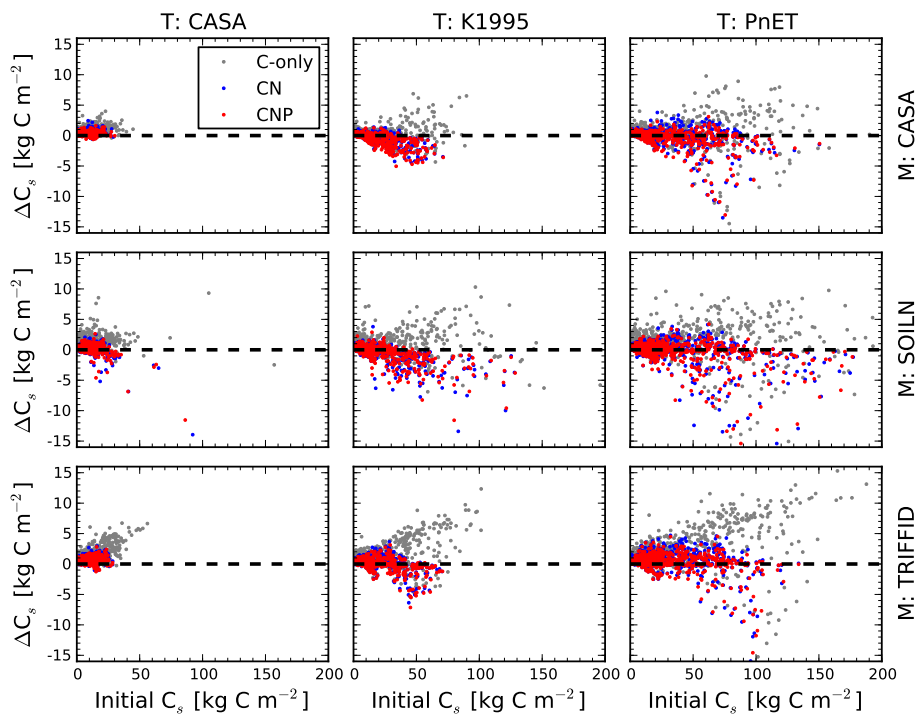


Fig. 13. Change in soil carbon C_s as a function of initial value for all grid boxes for all simulations in C-only, CN and CNP modes as indicated.

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