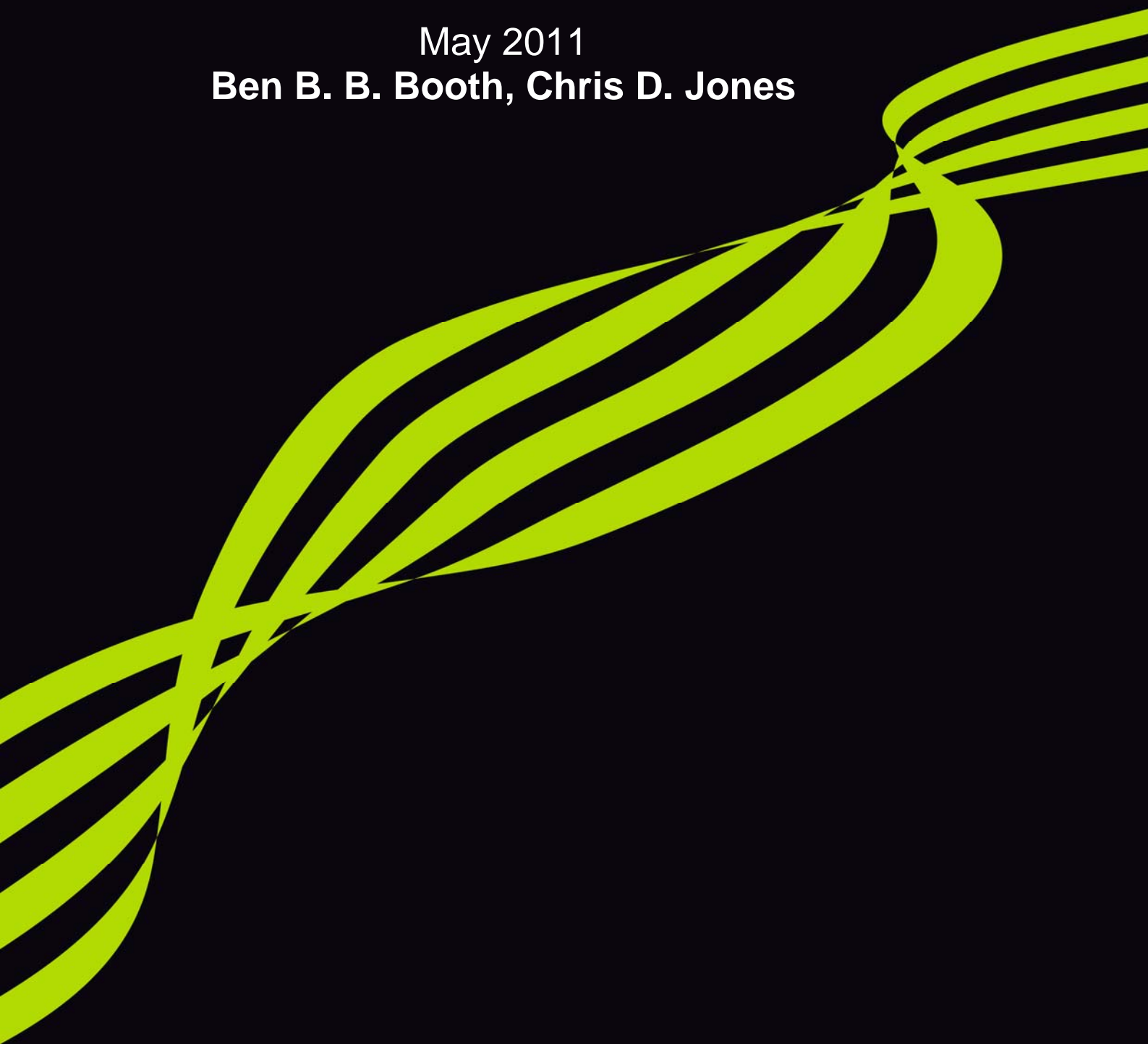


Hadley Centre Technical Note 89

Terrestrial response of QUMPC ensemble

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Introduction

Uncertainties in parameter estimation within current climate models have been shown to give rise to a broad range of future climate model responses. Previous experiments exploring parameter uncertainty in atmospheric and ocean physics have shown that in many cases parametric uncertainty is sufficient to reproduce current multi-model differences. Here we look at the land carbon response to ensemble exploration of 6 land carbon cycle parameters. The implication for this uncertainty for global climate change is explored in Booth et al, 2011. The implication of the parameter uncertainty for the land carbon response is explored and the relative impact on vegetation and soil stores is shown. We show that the land carbon parameter uncertainty leads to a larger range of soil carbon changes than vegetation carbon and explore the drivers of this range. The soil carbon stores are dominated by changes in vegetation input rather than soil carbon loss.

Methods

The experiments were carried out using a 17-member ensemble of a version of the third generation Hadley Centre model, HadCM3C. This model combined the carbon cycle components (land and ocean) from the lower resolution model HadCM3LC (Cox, et al., 2000) submitted to the Coupled Climate Carbon Cycle Model Inter-comparison Project (C⁴MIP, Friedlingstein et al., 2006), with an interactive sulphur cycle component (Jones et al, 2001) within the standard HadCM3 resolution. The model ensemble members were all individually flux corrected for temperature and salinity, which minimised the regional temperature biases produced by this model (relative to HadCM3).

The ensemble consisted of the standard member (where parameter values were left at the standard parameter values) and 16 perturbed members which each sampled a different part of the possible 6 dimensional parameter space using an efficient design (latin hypercube) to give a broad sampling of possible parameter combinations. The ensemble was used to conduct two experimental phases: historical and a future business as usual scenario based on the A1B SRES scenario (Nakicenovic et al, 2000) using non-CO₂ forcings as described by Johns et al, 2003. In both phases the models were driven by carbon emissions, not concentrations, and the resultant concentrations were calculated from the model's carbon cycle. In addition to CO₂ emissions the models were also forced by a range of other greenhouse gases (methane, N₂O, CFCs), historical and future (A1B) tropospheric and stratospheric ozone changes, natural and anthropogenic sulphate aerosol precursor, background effusive and explosive volcanic eruptions and historical changes in incoming solar radiation. For the natural forcings in the future phase, only background effusive volcanoes were included and future incoming solar radiation was assumed to be steady with time, with a 11 year cycle superimposed. The historical and A1B (with the exception of CO₂ emissions being prescribed rather than concentrations) was identical to those used to explore uncertainties in other earth system components (Collins, 2010; 2007, Murphy et al, 2007).

A similar approach was taken to previous explorations of parameter uncertainties in other earth system components (e.g. Murphy et al, 2004, 2007, Collins et al, 2007), by identifying parameters within the land surface which were both important for the land carbon cycle functioning and for which there is a current range of plausible parameter values. In total 6 parameters were identified. The first four impact plant physiology. These were top leaf nitrogen concentration (expressed as a fraction of leaf carbon content); the ratio of leaf internal to external CO₂ concentration across plant stomata (a factor which represents the efficiency of CO₂ fixation across the plant stomata); the covariation of two parameters (Tupp and Tlow) which determine the temperature dependence of the carboxylation of rubisco, a key temperature control of plant photosynthesis within the model formulation and finally the critical volumetric soil moisture concentration below which plants become moisture limited. Two of the parameters impact soil responses. These were the critical volumetric soil moisture, which (as well as well as controls on plant water uptake) determines the soil moisture controls on surface evaporation, and the parameter controlling the temperature dependence of soil respiration (Q10). The final parameter explored within this work was the minimum Leaf Area Index (LAI) for plant expansion, a plant functional type (PFT) competition parameter, which determines the minimum LAI before plants spend NPP on expansion;; Figure 1 shows the impact of these parameter perturbation and the 6 parameters and the parameter ranges (and their basis) are documented in Booth et al, submitted.

Most of the parameters explored within this experiment share commonalities with other contemporary land surface carbon cycle model representations. Focusing first on temperature controls of photosynthesis (Figure 1 lower left), we perturb a parameter which determines the temperature dependence of the carboxylation of Rubisco, which forms part of the Collatz photosynthesis formulation (Collatz et al, 1991 and 1992). Most current models represent photosynthetic temperature controls using formulation either directly from Farquar et al, 1980, or simplifications, such as developed by Collatz used in this study. The parametrisation controlling the temperature dependence of soil respiration is a Q10-like temperature dependence (Figure 1, bottom panel), which is also a common model formulation for C⁴MIP generation of models. Inter-model differences will arise depending on whether the soil respiration is a function of soil or air temperature, however current models will agree on the form of any Q10 sensitivity if not necessarily the interpretation of the magnitude. Another parameter, the Leaf nitrogen leaf concentration (the impact of which can be see in Figure 1, between the difference of VCmax (upper left) and the temperature component of VCmax (lower left)) is also central to modelled maximum photosynthesis current land surface carbon cycle models, either as a parameter (as is modelled here) or as a prognostic of an interactive nitrogen cycle. Two further parameters explored here however, F0 and minLAI, are more specific to the MOSES 2/TRIFFID model formulation used in this study. F0 is a parameter in the Jacobs closure (Jacobs, 1994) of photosynthesis with Vapour Pressure Deficit (VPD) and controls the sensitivity of stomatal opening to VPD changes. There is less agreement between current model formulations about how this closure is done and so the implication of any emergent parameter sensitivity will need more careful interpretation. The final parameter, minLAI (Figure 1, lower right), relates to plant competition rules in the dynamical vegetation representation (the minimum LAI before NPP is donated to plant expansion). Any sensitivity associated with this

parameter is likely to tell us about the importance of how we represent plant competition in our models.

Land carbon response

The ensemble samples a broad range of future land carbon responses. The consequences of these responses on the wider climate change are explored in more detail in Booth et al, submitted. Here we specifically examine the land carbon response specifically. Figure 2 shows the change in historical and future (A1B) land carbon storage for the 17 ensemble members relative to the initial 1860 carbon stores. During the historical period the majority of simulations capture the net uptake of land carbon, except two members that suggest a net historical land carbon loss (shown by dashed lines).

The majority of models simulate an increase in land carbon content during the recent contemporary period and the next 50 years (upper panel, Figure 2). As this scenario for the next century unfolds, the changes in land carbon storages increasingly diverge. Uptake of anthropogenic carbon dioxide is an important sink of contemporary emissions and currently acts as a break on climate change, a characteristic captured by the majority of the ensemble. An important threshold to note is the point where a model transitions from a positive land carbon content change to a negative one (in other words the rate of change in land carbon uptake becomes negative). A model which transitions to a negative change in land carbon represents a switch of the land surface to a net source of atmospheric carbon dioxide, rather than a net sink of anthropogenic emissions which it represents in the present day. A second transition worth noting is the point where the land surface carbon storage crosses zero, in some models. This represents the point beyond which the land surface no longer represents a net sink of all historical emitted anthropogenic carbon. This switch is a feature of the previous HadCM3LC model (Cox et al, 2000) and is also evident in the standard model configuration of HadCM3C (Figure 2, black line). Only three other model configurations show stronger net source behaviour by the end of the century, with the majority (13 out of 16) producing less net tendency to emit carbon than the standard model. A large fraction of models however approach this net sink to source switch for this scenario which highlights the potential for changes in land carbon cycling to enhance the impact of future emissions.

The tendency for many models to switch to being net emitters of CO₂ by 2100 is largely not driven by changes in above ground vegetation carbon storage. The majority of simulations suggest that above ground vegetation (Figure 2, central panel) is likely to store more carbon in the future. Only two simulations suggest that future vegetation carbon stores are likely to fall below present levels. Interestingly the simulation that reproduces the least tendency to take up future vegetation carbon is not one of the two simulations that fail to capture the historic increase in net land carbon. The majority of the ensemble members show a greater capacity to take up future vegetation carbon than the standard model configuration (black dashed line). From the interest of what this tells us about the range of possible future vegetation carbon response, there are two things to note. Firstly the spread across the ensemble is close to 300 Gton carbon by the end of the century. This spread explains the smaller fraction of the total spread in future land carbon (upper panel, Figure 2). The

larger fraction results from future changes in soil carbon stores (see below). The second aspect to note is that for a number of simulations the future change in vegetation carbon stores is not linear with time nor, by inference, temperature. While a number of simulations produce continually increasing vegetation storage through the simulation, others simulate a peak in future vegetation storage followed by a steady decline. This behaviour is evident for the standard model and has been documented before (Cox et al, 2000). A number of simulations show even more pronounced transitions of vegetation carbon uptake to vegetation carbon loss than the standard model (though few show the complete loss of the net sink of anthropogenic emissions that the standard model shows). From the predictability point of view this transition in carbon uptake represents a challenge. It suggests that potentially observable changes in contemporary carbon stocks are likely to be a poor indicator of future vegetation carbon pools.

The spread in future soil carbon changes is broader than the spread in vegetation carbon, spanning a model with a loss of over 700 Gton Carbon to a couple of models which produce an increase closer to 300 Gton Carbon by the end of the century. The spread of change in soil carbon stocks dominates the overall change in land carbon stores.

The changes in vegetation carbon, soil carbon and total land carbon in 2100 are summarised in Table 1, which in contrast to Figure 2, is expressed relative to present day levels. The two simulations which do not show an overall carbon uptake in the 20th century both show a net carbon loss from the soil in this period. Setting these two models aside, the remaining ensemble show 20th century net carbon uptake and then diverge markedly in the future. Similarly to the situation with the vegetation carbon, contemporary changes in soil carbon stocks provide poor indication of future changes.

So it looks like the broad range in terrestrial carbon changes is dominated by changes in the soil rather than the vegetation stores. This does not necessarily imply that it is soil processes however which determine this ensemble spread. Within this ensemble we sample uncertainties in parameters which both influence plant primary productivity, and hence litter input into soils, and the temperature dependence of soil respiration (represented through the Q10 function). The spread in changes in soil carbon may be driven either by the differences in soil respiration sensitivity or by changes in litter input to soils, driven by differences in vegetation responses between ensemble members. We characterise the impact of uncertainty in the temperature dependence of soil respiration on carbon store changes from the modelled soil residence timescales. In Figure 3 the relative importance of change in litter input and soil residence timescale can be compared to understand the drivers of the range of soil carbon changes in Table 1. There is clearly a broad spread of change in the litter input across models, which range from increases of 70% to decreases of 30% (Figure 3, upper panel). Most models show an increase in litter input, consistent with the general picture of increases in future vegetation carbon (shown in Figure 3). For most models there appears to be a fairly linear relationship between near future changes and the changes by the end of the century. Similarly to the responses of vegetation stores shown previously (Figure 2), a subset of the ensemble show non-linear behaviour, where the sign of change itself changes with higher temperatures.

The soil residence timescale (Figure 3, lower panel) represents the average time that carbon remains in the soil pool and can be calculated by the soil carbon store divided by the soil respiration. Soil model respiration is parameterised as a function of temperature using the common Q10 relationship where there respiration increases by a factor X for every 10 degrees of temperature change. The factor X in this case is known as the soil respiration Q10 value and the ensemble explores a range between 1.5 and 3.5 degrees (Booth et al, submitted). Falloon et al (2011) show that sensitivity to changes in soil moisture can also be an important control on soil respiration, but temperature sensitivity of respiration is the dominant uncertainty. Unsurprisingly then, all the models show a decrease in soil residence timescales with warmer conditions and the rate that soil residence timescales declines with temperature is correlated with the model Q10 values (correlation of 0.60). The future trends also appear linear with temperature across ensemble members and clearly individual models have temperature responses distinct from other models. By the end of the century, the ensemble shows reduction in soil residence timescale between 20-50%.

The larger differences in percentage change in litter flux between models clearly points to litter changes as the dominant driver of inter-model differences in soil carbon change and therefore uncertainty in vegetation processes in agreement with Matthews et al (2005). It also suggests that the non-linear responses to temperature change in both vegetation and soil carbon stores, arise from vegetation rather than soil processes. This has implications for future predictability. Here we look at the relationship between the magnitude of future land carbon response and contemporary stores of carbon. The ensemble explores a broad range of present day vegetation and soil carbon stores, as shown in Figure 4. The simulated present day vegetation carbon ranges from 200-940 Gton Carbon, with soil stores ranging between 440-1850 Gton Carbon. The terrestrial ensemble explores a similar range of vegetation carbon as the C⁴MIP however while spanning much of the C⁴MIP soil carbon range it also explores smaller soil carbon stores than C⁴MIP ensemble.

Observationally based uncertainty for both land carbon stores is large. The uncertainty range on the vegetation carbon store is shown in Figure 4 based on the Olson et al. 1985, dataset. The land carbon ensemble fully spans this uncertainty range. The Olson dataset suggested a “medium” vegetation estimate, which was later revised. This latest “medium” estimate is indicated in the figure. Soil carbon stores are more difficult to estimate, requiring intensive site measurements. The soil carbon estimates currently available are based on a limited number of observational sites for different soil types which are then extrapolated to produce global inventories based on global maps of soil type classification. The limited number of site measurements and the large degree of heterogeneity across single soil types makes uncertainty estimates especially problematic. This is a challenge which is compounded by the variable quality of available data in different geographical regions. HadCM3C and other C4MIP-class models also do not simulate the large amounts of carbon stored in organic peat deposits. For these reasons observational uncertainties in the soil carbon inventories are not presented, but are likely at the very minimum to be as least as large as uncertainties in the better observed vegetation stores.

Also shown in Figure 4 is the relationship between contemporary stores and the magnitude of future land carbon change (graded according to net land carbon loss/gain by colour). There is no obvious relationship between present day carbon stores and future response. The large range of soil store changes previously found to account for the majority of the uncertainty in land surface carbon contribution within C⁴MIP projections, suggesting perhaps that inter-model differences in soil respiration processes may explain the inter-model differences. This was an idea which was subsequently explored in Jones et al, 2003, using perturbations to Q10 functions within a single model, which found a strong relationship between the Q10 parameterisation and soil carbon response. The soil respiration parameterisation (Q10) controls the sensitivity of soil carbon loss to temperature changes and so this ensemble represented an opportunity to explore this. As we have previously shown in Figure 3, the soil carbon changes have a larger contribution from litter input. A further reason why soil carbon processes may play less of a part that might be expected (beyond the more limited range of soil residence timescale changes relative to litter inputs, covered in Figure 3) is related to the size of present day stores. The runs which simulate low (high) soil carbon storage for the present-day are generally those with high (low) Q10 parameter values. As a consequence high Q10 simulations, which would be expected to exhibit larger increases in soil respiration fluxes in the future, are limited by the size of the initial soil carbon stores.

Relationships between vegetation response and future change

So far we have looked at responses of land carbon stores to changing climate and found no straight forward relationship between present day stores or trends and future responses due to non-linear relationships between land carbon response and future temperature change. Part of this non-linearity may arise from rapid forest loss, which was an iconic result in the original configuration of the dynamical vegetation model used in this study (Cox et al, 2000). Here we look at land cover changes in both Tropical and Boreal regions.

The land surface model used in our ensemble explicitly resolves the geographical competition between different plant functional types. The resultant vegetation maps are not prescribed but are simulated as the result of the competition processes. We can show (Figure 5) that the ensemble simulates a range of historical vegetation distributions and that there is little relationship between these distributions and the magnitude of the future carbon cycle response. A single observational estimate of the vegetation distribution is shown, based on dominant vegetation classes in the IGBP database (Rayner et al, 2005). Caution needs to be taken in placing too much weight on this observational point – as uncertainties are introduced into this estimate due to averaging over large latitudinal bands the data on the dominant gridbox vegetation type, rather than the actual distribution of vegetation. This point in Figure 5 does however suggest the general region which is consistent with the real world. The latitudinal averages of the ensemble tree fractions span a wide range. Taking the model at the lower end of this range (model P) there is clearly insufficient forest cover in either the Tropical or the Boreal regions to be consistent with the real world. Potentially this is an important deficiency as this would unrealistically limit the carbon release from any potential future forest loss. At the other end of the scale a

number of models simulate larger forest fractions (both Boreal and Tropical) than the region consistent with the real world. Again this is potentially significant as these models would contain a greater land carbon stores which could be released as a result of any real world future climate driven forest loss. While models at the lower end (model P for example) could potentially be down weighted as less credible, the same can not be done for models on the upper end of forest coverage (models C and D for example). This is because disturbance processes which act to limit forest extent in the real world, are partially represented (land use is represented by a time invariant fraction) or not represented (fire) within this modelling framework. Without these processes it is difficult to evaluate the plausibility of the vegetation dynamics which leads to models with large forest fractions. In any case, there is no strong relationship between present day forest cover and the magnitude of the carbon cycle response, as indicated by the distribution of both low and high carbon cycle responses across the distribution of forest coverage (colour, Figure 5).

Also shown on Figure 5 are the latitudinal averages of Tropical and Boreal forest cover at the end of the 21st century. All models consistently show an expansion of the Boreal forest extent as a result of climate change. This is due to warmer Boreal conditions leading to less restricted photosynthesis in this region. The tropical forest picture is more complicated, with individual ensemble members exhibiting either Tropical forest loss or gain. This does not appear to be linked to the forest distribution in the present day, but rather to the magnitude of the future carbon cycle feedbacks. The models with the stronger (weaker) future warming are more likely to produce more pronounced tropical forest loss (gain). While this tropical forest loss (gain) will have a positive (negative) feedback on the magnitude of the carbon cycle response it is not the primary driver of the magnitude. This is evident when comparing pairs of models with similar carbon cycle responses (H and G for example) which show markedly different magnitudes of tropical forest change. This suggests that other carbon cycle processes are governing the overall magnitude of the response, with forest changes contributing as a secondary feedback. Similarly, dynamical changes in vegetation coverage do not appear to be sufficient to explain the non-linear land carbon responses illustrated in the previous section.

Although changes in carbon due to changes in vegetation coverage may not be the dominant changes, the timescales of shifts in biomes are such that they cannot be fully realised within the course of the 21st century. It is likely that ecosystems will continue to respond to climate change for decades or even centuries after the climate has stopped changing (Jones et al 2009). The implications of this for carbon storage are complex (Smith and Shugart, 1993). Jones et al (2010) show that carbon losses in the short term due to loss of tropical ecosystems may be more than compensated for in the longer term by slower increases in high latitude forests.

Robust Land Carbon Responses.

Despite the large range of future global carbon cycle responses documented above, significant intra-ensemble agreement does exist in the sign of the future changes in vegetation and soil carbon stores (Figure 6) in a number of regions. Future changes in

vegetation carbon stores are dominated by regions of large scale increase. This happens predominantly in the high northern latitudes (driven by a northward expansion of the Taiga or Boreal forest) and in higher altitude, lower latitude regions (such as the Himalaya, East African mountains, Serra do Mar and Andean ranges) where cooler temperatures minimise the direct impact of temperature on photosynthesis. Smaller regions of vegetation carbon loss are also evident, in Central America, northern Brazil, the Kalahari and Crimea regions.

The general pattern of soil carbon change is predominantly that of carbon loss (primarily in central North America, Central America and northern South America, continental Europe and Southern Africa) as warmer temperatures lead to increased soil decomposition. Only small regions of soil carbon gain are evident in the extreme north, and isolated high altitude regions (where increases of vegetation carbon inputs outweigh temperature driven loss from soils).

Conclusions

Within this Technical Note, we have documented the changes in the land carbon stores produced by ensemble exploration of land carbon parameter uncertainty. We have shown that this uncertainty leads to a very broad range of future land carbon changes across the ensemble, which are dominated by changes in the soil carbon storage. However it is differences between vegetation responses between models which drives much of the soil storage differences and therefore determines the majority of the land carbon response.

We've looked at relationships between near term and long term trends and between present day carbon stores and the magnitude of future land carbon change and shown in both cases that near term/contemporary carbon state is not strongly related to future change. This represents a challenge for our ability to predict future changes and arises from non-linearities, in some models, of the vegetation carbon response to temperature change.

We have also looked at the range of contemporary vegetation coverage explored by the ensemble and how these respond in the future. There is a general picture of Boreal forest expansion across the ensemble. The response of the Tropical forest is mixed, with models suggesting both future expansion and loss. There is a relationship between models with large future carbon responses and forest loss however large differences in fractional Tropical change between models with similar future land carbon responses suggest that future forest loss/expansion is unlikely to be the dominant driver of future change.

Finally we looked for patterns of robust vegetation and soil change and identified regions across the ensemble where there is general agreement on the sign of the change. Vegetation carbon content in the future is expected to increase at high latitude and high altitude regions, while wide spread tropical soil carbon loss is found across most ensemble members.

The range of land carbon responses illustrates implications of parametric uncertainties within one current land carbon cycle model formulation. These ensemble differences do not arise from different structural model assumptions. All the ensemble members share the same conceptual framework for how the land carbon cycle is represented. In light of this, it may make sense to consider whether existing differences between different modelling structures (e.g. Friedlingstein et al, 2006) arise from differences between equally plausible parameter estimation in formulations common across models rather than structural differences between current models.

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Figure 1: Upper left: The range of VCmax values for Broadleaf Trees resulting from perturbations to Leaf Nitrogen Concentrations and Temperature controls on the Carboxylation of Rubisco. Lower Left: Illustrates how perturbations to the temperature controls on the Carboxylation of Rubisco change the total temperature dependence of photosynthesis. Upper Right: Illustrates the relationship between Broadleaf LAI and the fraction of NPP devoted to plant expansion. Lower Right Illustrates the impact of perturbations of to the Critical Soil Moisture concentrations on availability of water for plant uptake and evaporation to the atmosphere. Bottom panel: The impact of perturbations to the Q10 temperature dependence of soil respiration. The perturbations to the Q10 relationship are renormalised using the Specific Soil Respiration Rate coefficient so that the contemporary respiration for current global mean conditions is unaffected by the change.

Figure 2: The change in the total land carbon (upper panel), vegetation carbon (middle) and soil carbon (lower) stores from 1880-1900 levels are shown for each of the ensemble members. In each of the panels, the standard HadCM3C configuration is highlighted (dashed black) the two ensemble members which do not show a net historical carbon uptake are indicated by the dashed blue-white lines.

Figure 3. The change in Litter input (upper panel) and soil residence timescale (lower panel) with global surface temperature change for each of the terrestrial carbon cycle ensemble members. Colour scale used to distinguish between different ensemble members only.

Figure 4. The ensemble global carbon stores for Vegetation (y-axis) and Soils (x-axis) are plotted for each member of the perturbed ensemble (letters) and the standard (square). The land stores for the C⁴MIP ensemble is also shown (numbers) along with a key. In addition each perturbed ensemble member is ranked according to the magnitude of the carbon cycle feedback, indicated by the colour (from large (red) through to small feedback (dark blue)). Observational estimates of the vegetation carbon store (Olson dataset⁵⁷) are illustrated by the grey shading (min to max). In addition the latest estimate of the “medium” vegetation carbon amount are also shown (dashed line on vertical axis) ⁵⁷. No equivalent uncertainty range for the soil carbon stores are currently available. A single soil carbon estimate is given (dashed line on horizontal axis) but the uncertainty range is likely to be large.

Figure 5. The fractional distribution of tropical (20N-20S) and boreal (40-75N) forest cover is shown for the standard (triangle) and perturbed ensemble members (letters). The historical (1980) model distributions are indicated by the large letters (or triangle) while the future 2095 forest distributions are indicated by the small characters. The past and future forest fractions illustrate changes in dynamical forest cover as a response to (or contributing to) climatic changes. In addition each perturbed ensemble member is ranked according to the magnitude of the carbon cycle feedback, indicated by the colour (from large (red) through to small feedback (dark blue)). One estimate of tropical tree cover is also included (cross) based on translation of the IGBP-DIScover land cover classification⁶² into the TRIFFID plant functional types (Cox 2001).

Figure 6. The ensemble mean change in vegetation carbon (upper panel) and soil carbon (lower panel) in the 2090s relative to present day, in Gton carbon/m². The mean ensemble response is only shown where the ensemble mean exceeds one standard deviation of the intra-ensemble spread. In other words only the response of the carbon stores are shown when there is broad ensemble agreement on the sign of the change. There is a clear signal of an increase in vegetation carbon across the

ensemble, particularly in the high latitude boreal region. Regions of low latitude vegetation growth coincide with high altitude terrain. Areas of vegetation carbon loss are evident in Central America, Northern Brazil, the Kalahari and Crimea regions. The soil carbon change is dominated by widespread carbon loss (primarily in central North America, Central America and northern South America, continental Europe and Southern Africa). Small regions of soil carbon gain are evident in the extreme north, and isolated high altitude regions.

Change in Terrestrial Carbon Pools (2090s – present day)	Global Vegetation Carbon (Gton Carbon)	Global Soil Carbon (Gton Carbon)	Global total Land Carbon (Gton Carbon)
Standard	-7.6	-203.2	-210.9
a	54.9	-138.9	-84.0
b	59.9	-139.1	-79.2
c	182.7	210.7	393.4
d	154.0	183.3	337.3
e	25.4	-185.7	-160.3
f	45.5	-120.3	-74.8
g	-79.1	-417.9	-497.0
h	14.5	-647.0	-632.5
i	-33.5	-297.7	-331.1
j	89.3	32.9	122.2
k	65.7	-188.0	-122.3
l	151.1	-115.2	35.7
m	123.2	-36.7	86.4
n	-82.7	-323.8	-406.5
o	89.1	-124.9	-35.8
p	46.7	-88.8	-42.1
Standard deviation	76.6	204.7	268.2

Table 1. This table shows the change in Vegetation (2nd column), Soil (3rd column) and total land (4th column) carbon between present day and the 2090s. The change in stores are given in Gton Carbon. In addition to changes in individual changes across the ensemble, the standard deviation of the intra-ensemble spread is shown at the bottom.

Figure 1

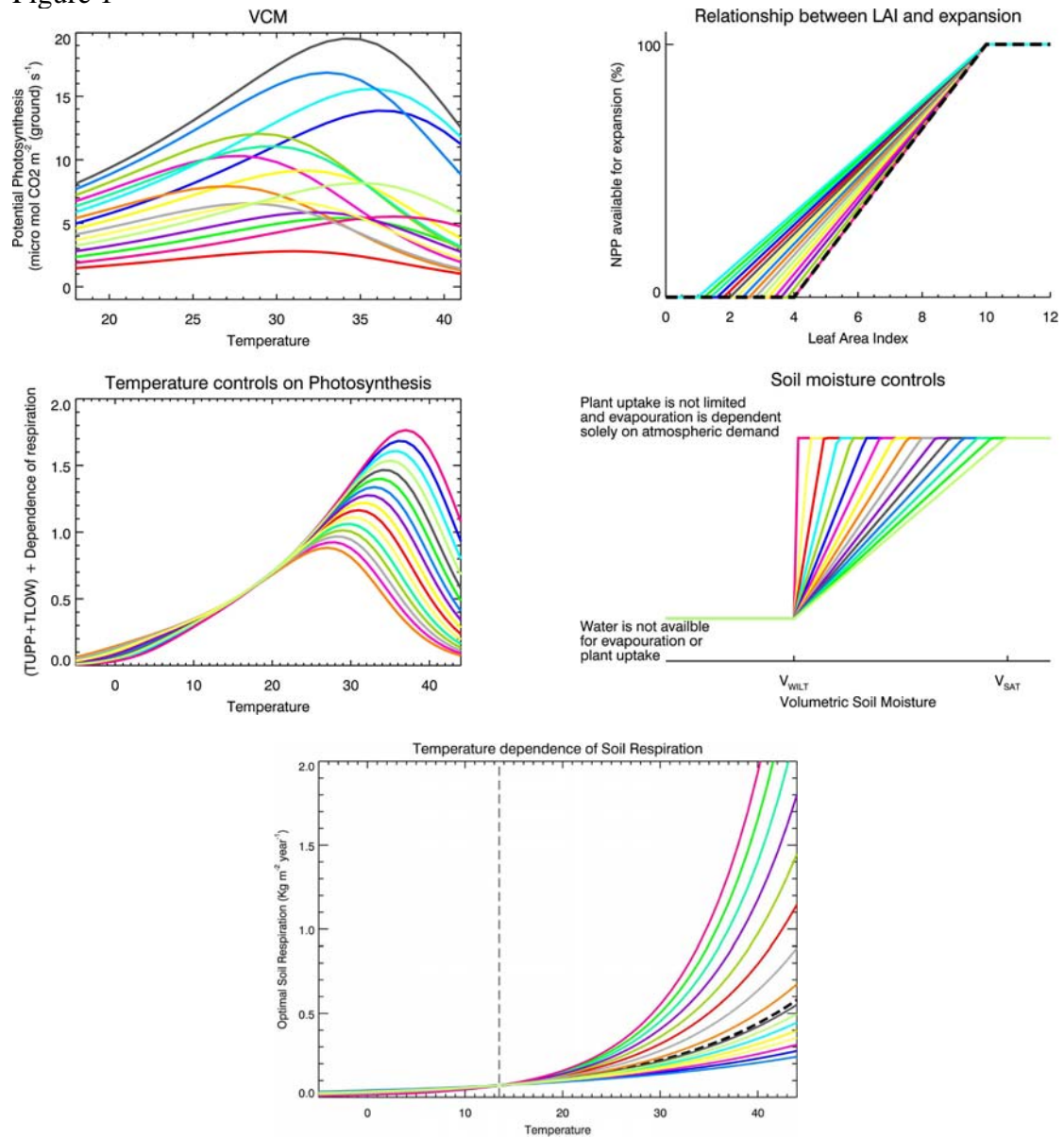


Figure 2

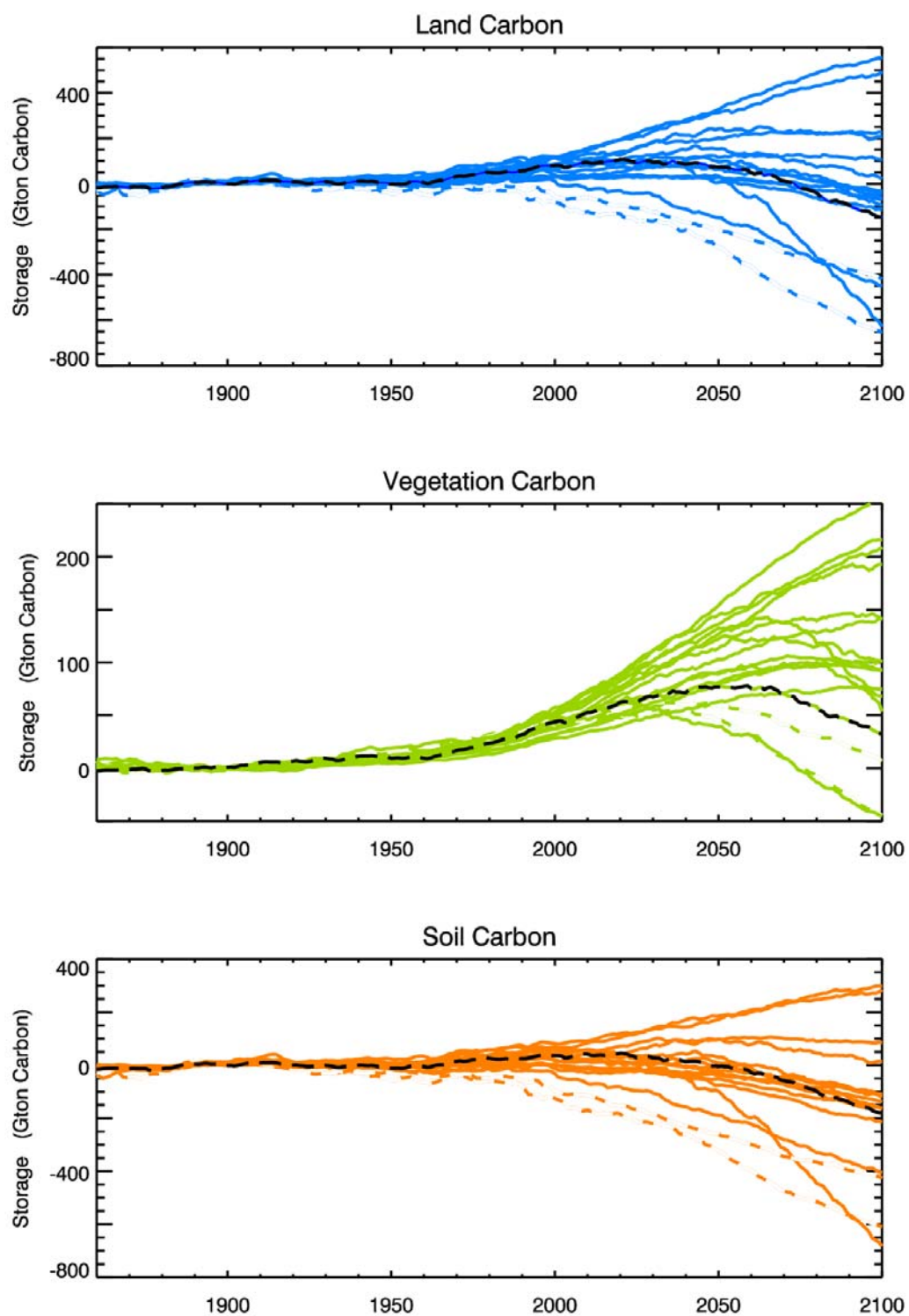


Figure 3

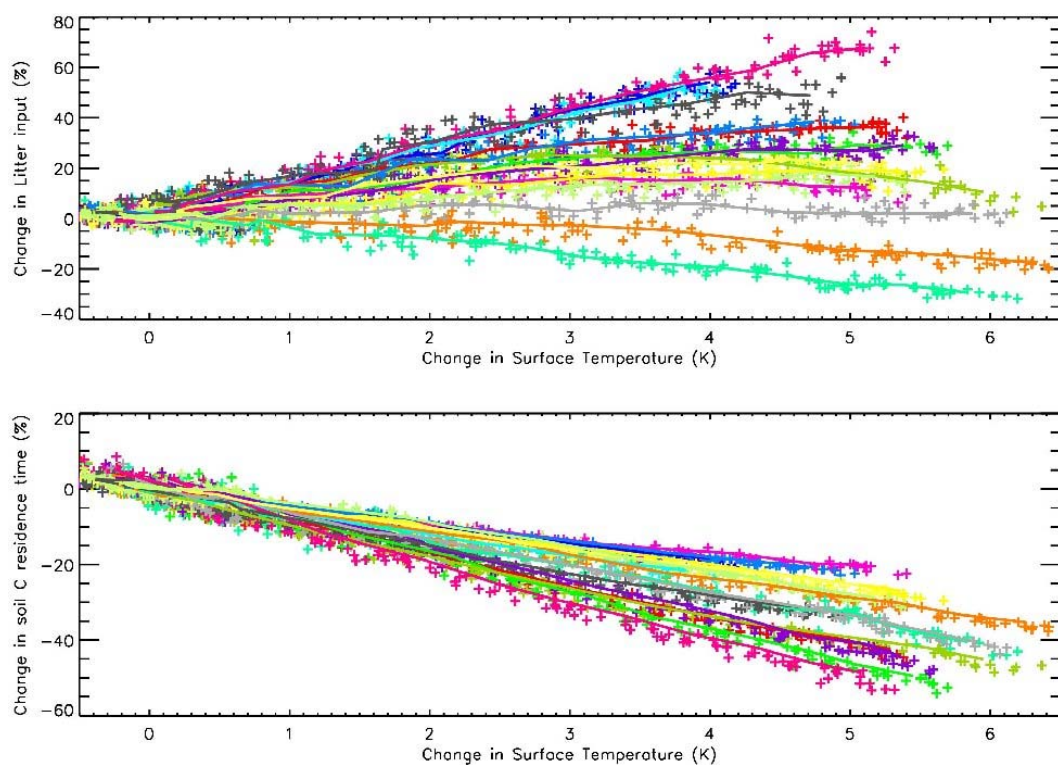


Figure 4

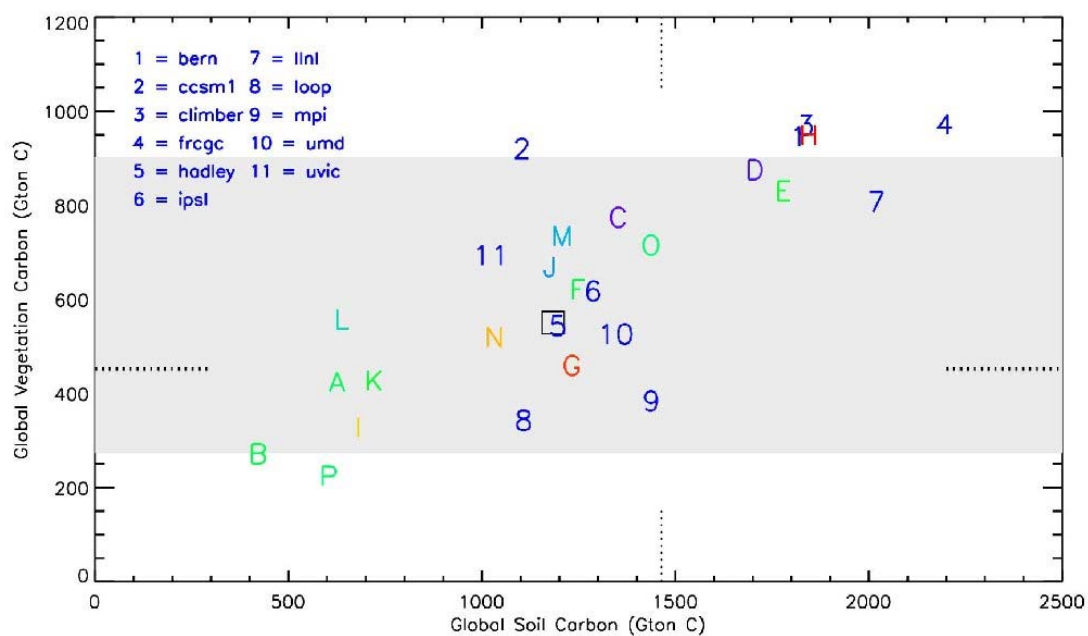


Figure 5

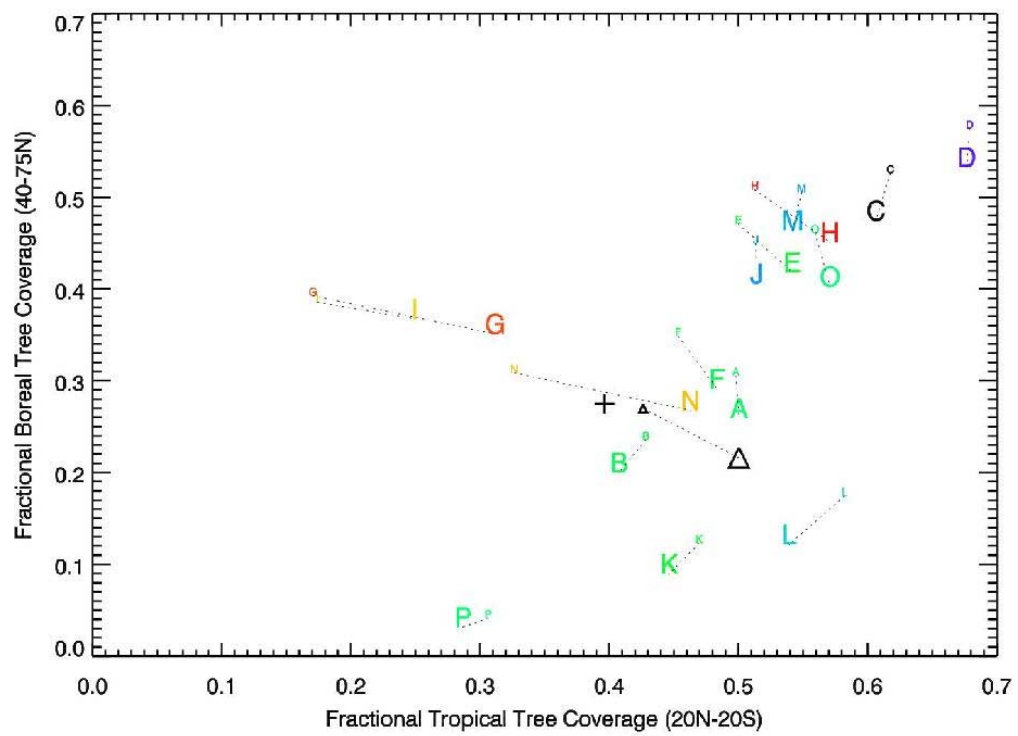


Figure 6a

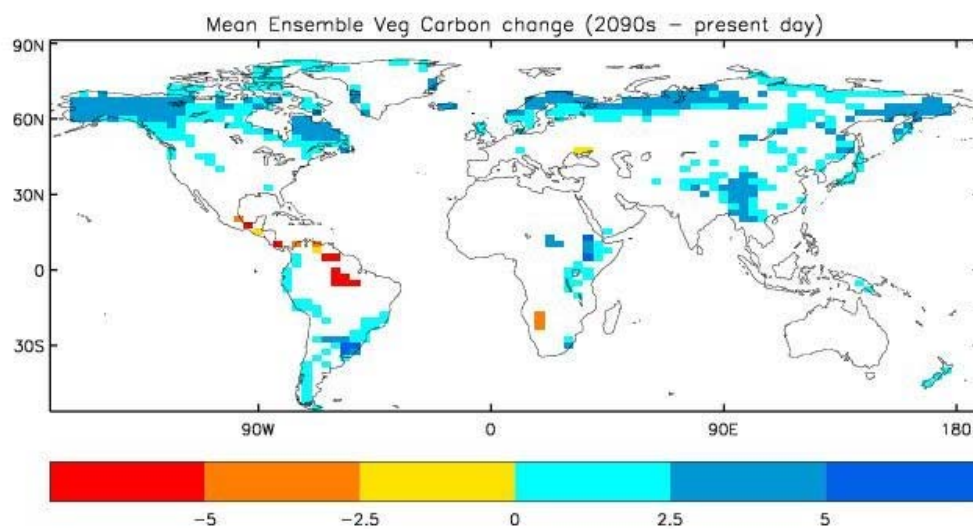
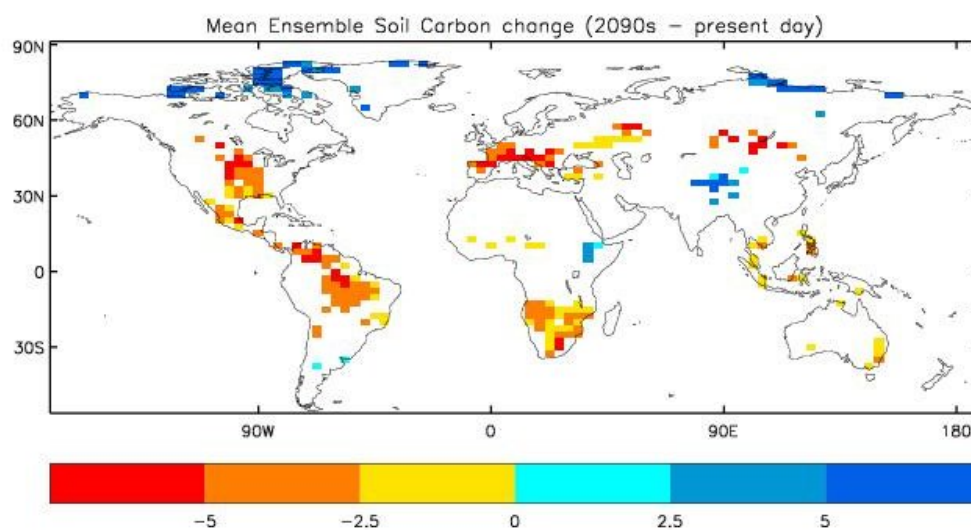


Figure 6b



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