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Key Points:
- Land area changed by climate is larger than from land use change in the RCPs
- Climate-induced forest increases offset 90% of deforestation in RCP8.5
- Land cover change is a net carbon sink when land use and climate are included

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Quantifying the relative importance of land cover change from climate and land use in the representative concentration pathways

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Abstract Climate change is projected to cause substantial alterations in vegetation distribution, but these have been given little attention in comparison to land use in the Representative Concentration Pathway (RCP) scenarios. Here we assess the climate-induced land cover changes (CILCC) in the RCPs and compare them to land use land cover change (LULCC). To do this, we use an ensemble of simulations with and without LULCC in Earth System Model HadGEM2-ES (Hadley Centre Global Environmental Model 2) - for RCP2.6, RCP4.5, and RCP8.5. We find that climate change causes an expansion poleward of vegetation that affects more land area than LULCC in all of the RCPs considered here. The terrestrial carbon changes from CILCC are also larger than for LULCC. When considering only forest, the LULCC is larger, but the CILCC is highly variable with the overall radiative forcing of the scenario. The CILCC forest increase compensates 90% of the global anthropogenic deforestation by 2100 in RCP8.5 but just 3% in RCP2.6. Overall, bigger land cover changes tend to originate from LULCC in the shorter term or lower radiative forcing scenarios and from CILCC in the longer term and higher radiative forcing scenarios. The extent to which CILCC could compensate for LULCC raises difficult questions regarding global forest and biodiversity offsetting, especially at different time scales. This research shows the importance of considering the relative size of CILCC to LULCC, especially with regard to the ecological effects of the different RCPs.

1. Introduction

The distribution of vegetation across the globe is due to a combination of climatic and anthropogenic influences, both of which are likely to alter over the next century. Dynamic global vegetation models are used to project the distribution of vegetation as the climate changes, and the results of this are referred to here as climate-induced land cover change (CILCC). The human alterations to the land surface are often known as land use land cover change (LULCC) and encompass variations in agricultural land requirement. Possible scenarios of LULCC are projected in the Representative Concentration Pathways (RCPs) [*Hurtt et al.*, 2011]. The RCPs are a set of future scenarios of climate change used for the Fifth Climate Model Intercomparison Project (CMIP5) and the IPCC (International Panel on Climate Change) Fifth Assessment Report [*Taylor et al.*, 2012]. They vary in their total radiative forcing increase by 2100, which is indicated by the number of the RCP, (i.e., RCP8.5 has a radiative forcing increase of 8.5 $W m^{-2}$ by 2100 compared to preindustrial levels) [*van Vuuren et al.*, 2011]. The LULCC in the RCPs is prescribed by the scenario, and varies over time, although it is imposed differently between models, resulting in substantial variations [*de Noblet-Ducoudré et al.*, 2012]. The pattern of LULCC in the RCPs has been well documented and is not linearly related to the radiative forcing of the scenario [*Hurtt et al.*, 2011; *Jones et al.*, 2011; *van Vuuren et al.*, 2011; *Betts et al.*, 2013; *Brovkin et al.*, 2013]. Notably, RCP4.5 has afforestation in the middle to high latitudes, and RCP2.6 and RCP8.5 both have tropical deforestation [*Hurtt et al.*, 2011]. LULCC in the RCPs has been extensively researched with regard to its magnitude and importance [e.g., *Thomson et al.*, 2010; *Hurtt et al.*, 2011; *Jones et al.*, 2012; *Lawrence et al.*, 2012; *Brovkin et al.*, 2013; *Davies-Barnard et al.*, 2014a; *Wilkenskjeld et al.*, 2014]. However, changes to vegetation cover can occur due to responses to climatic alterations, as well as direct human influence.

CILCC in the RCPs is simulated in some Earth System Models, but is not a core part of the RCP scenarios; i.e., it is a simulated response, not an imposed forcing or boundary condition. Vegetation in the models is primarily limited by temperature, water availability, and carbon dioxide availability to determine the type, distribution, and amount of vegetation across the globe. Very few of the CMIP5 Earth System Models include dynamic vegetation (that is needed to project CILCC), and therefore, little work has been done on CILCC in the RCPs, especially for the time period up to 2100. Briefly discussed in the IPCC Fifth Assessment Report [*Ciais et al.*, 2013], CILCC tends to be considered over longer time scales (for instance 2100–2300) and not in the context of LULCC. Recent research that does examine the 2005–2100 CILCC in the RCPs is hampered by the fact that the land cover changes are generally combined together within the standard RCP output [*Betts et al.*, 2013], making it difficult to ascertain what is LULCC and what is CILCC. Understanding CILCC is crucial to understanding both the magnitude of progressive changes (which we focus on here) but also allow the identification of potential regional ecological thresholds where abrupt and irreversible changes occur, e.g., Amazon dieback [*Good et al.*, 2012].

We aim here to highlight the importance of including CILCC in discussions of land cover change (LCC) in the RCPs. To do this, we disentangle vegetation changes induced by land use change (LULCC) and vegetation changes induced by changes to climate and atmospheric composition (CILCC). We use an ensemble of simulations of a selection of the RCP scenarios with and without LULCC in Earth System Model Hadley Centre Global Environmental Model version 2-Earth System (HadGEM2-ES) (section 2). We show that for crucial aspects of environmental change in this model, such as forest and land carbon change (section 3), CILCC is often comparable and sometimes larger than LULCC. We conclude that CILCC has significant impacts for ecosystem change that are at least as big as those for LULCC (section 4) and the exact magnitude of these changes is a key research question that should be addressed.

2. Methods

2.1. Model and Model Simulations

We use the Met Office Hadley Centre's coupled Earth System Model, HadGEM2-ES [*Collins et al.*, 2011; *Martin et al.*, 2011]. This coupled model includes the MOSES2 (Met Office Surface Exchange Scheme version 2) land surface scheme [*Essery et al.*, 2001]; the TRIFFID (Top-down Representation of Interactive Foliage and Flora Including Dynamics) dynamic global vegetation model in dynamic mode [*Cox*, 2001]; the Hadley Centre Global Environmental Model version 1 (HadGEM1) physical model [*Martin et al.*, 2006]; and interactive ocean biogeochemistry, terrestrial biogeochemistry and dust, and interactive atmospheric chemistry and aerosols. The atmosphere component contains 38 1.875° x 1.25° levels and interacts with water, energy, and carbon within the land surface scheme [*Essery et al.*, 2003] and the dynamic vegetation model [*Cox*, 2001].

Within the dynamic vegetation land surface part of the model there are nine land surface types, including five plant functional types: broadleaf tree; needleleaf tree; C_3 and C_4 grasses and shrubs; and inland water, ice, and urban. The model does not distinguish between primary and secondary land types. The agricultural fraction is imposed as an area where broadleaf and needleleaf trees and shrubs cannot be grown. Crops are physiologically identical to grasses in the model. Increases in agricultural fraction within a grid box are preferentially expanded into existing grass areas, only converting trees to agricultural land when the other plant functional types (PFTs) are not available. The vegetation distribution in the model is determined by a hierarchy based on height. This results in there being a succession from grasses to shrubs and then needleleaf and broadleaf trees, as the climate becomes suitable. The dynamic global vegetation model within HadGEM2-ES, TRIFFID, is a well-known and used model, extensively documented in *Cox et al.* [1998] and *Clark et al.* [2011]. It is one of the models used in the multimodel Global Carbon Project annual carbon budgets [*Le Quéré et al.*, 2014a, 2014b]. It has been the land surface model for several generations of the Hadley Centre climate model, and therefore used in the IPCC's assessment reports, including the most recent [*Stocker et al.*, 2013]. The present-day vegetation distribution within HadGEM2-ES is assessed in *Collins et al.* [2011] and shows good agreement with present-day distributions. For the tropical forests in particular, *Good et al.* [2012] shows that the distribution in climate space validates well. The model intercomparison by *Anav et al.* [2013] shows that HadGEM2 has a reasonable representation of the land carbon stores.

The model setup is as for the HadGEM2-ES CMIP5 simulations [*Jones et al.*, 2011] and the LUCID (Land Use and Climate, IDentification of robust impacts) simulations of RCPs [*Brovkin et al.*, 2013], using a fully dynamic

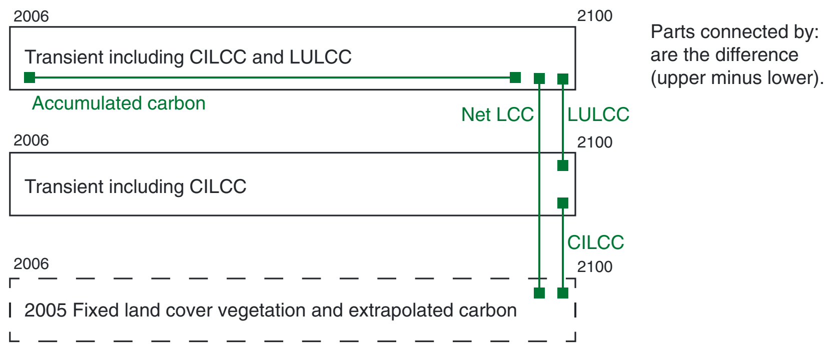

Figure 1. Conceptual diagram of the simulations and how the different diagnostics used in the paper are calculated.

atmosphere and ocean model. We use simulations of three of the RCP scenarios: RCP2.6, RCP4.5, and RCP8.5, from 2006 to 2100. Four ensemble members are initialized from historical simulations that ran from 1850 to 2005 and run for 95 years up to 2100. Two sets of simulations are used for each RCP—the standard RCP that includes LULCC, and a simulation where the agricultural fraction remains at the 2005 levels. For the simulations without LULCC, all nonland use forcings (greenhouse gas concentrations and other aerosol forcings, etc.) are prescribed as for the equivalent RCP [*Meinshausen et al.*, 2011].

2.2. Use of Simulations

The LULCC is taken here to be the change in the agricultural fraction imposed onto the model by the RCP scenario. It is inferred from the difference between the normal "RCP" scenarios (with LULCC) and the "NoLUC" scenarios (without LULCC) for the last year of the simulations (2100). The CILCC is taken here to be the changes in vegetation caused by anthropogenic climate change over the period of 2005–2100. This is inferred from the difference between the mean of the 2005 NoLUC values compared to the 2100 NoLUC values. The net changes are considered to be the standard 2005 NoLUC values compared to the RCP 2100 values. The net changes include both CILCC and LULCC changes. So the LCC calculations can be described thus

$$\text{LULCC} = \text{RCP}^{2100} - \text{NoLUC}^{2100}$$
$$\text{CILCC} = \text{NoLUC}^{2100} - \text{Fix2005}^{2100}$$
$$\text{Net LCC} = \text{RCP}^{2100} - \text{Fix2005}^{2100}$$

where the Fix2005 is a fixed 95 years of the 2005 land cover. Figure 1 shows how we diagnose the vegetation and carbon changes.

Even without changes in land cover, terrestrial carbon storage in biomass and soil organic matter is projected to alter due to changes in vegetation productivity, turnover, litter input to soil, and soil conditions (such as temperature and moisture). Therefore, to assess the CILCC separately to the accumulated vegetation carbon (not from LCC), a control without CILCC, LULCC, but with accumulated carbon is required. These were not feasible to run as fully coupled simulations due to the computational expense, so we extrapolated the control baselines of 2005 land cover including the increases to land carbon from increased carbon dioxide and temperature but exclude the changes from LCC. These extrapolated values are used as a "control" scenario (Fix2005) with which to infer the amount of land carbon attributable to CILCC from the anomaly. Therefore, the land carbon changes can be described thus

$$\text{LULCC carbon} = \text{RCP}^{2100} - \text{NoLUC}^{2100}$$
$$\text{CILCC carbon} = \text{NoLUC}^{2100} - \text{Fix2005}^{2100}$$
$$\text{Net LCC carbon} = \text{RCP}^{2100} - \text{Fix2005}^{2100}$$
$$\text{Accumulated carbon} = \text{RCP}^{2100} - \text{RCP}^{2006}$$

To obtain the grid box vegetation carbon, the carbon on each plant functional type (PFT) tile is weighted by the proportion of each PFT in the grid box. Therefore, to approximate the vegetation carbon without any LCC, we weighted the 2100 vegetation carbon on each PFT tile by the 2005 vegetation PFT distribution (rather

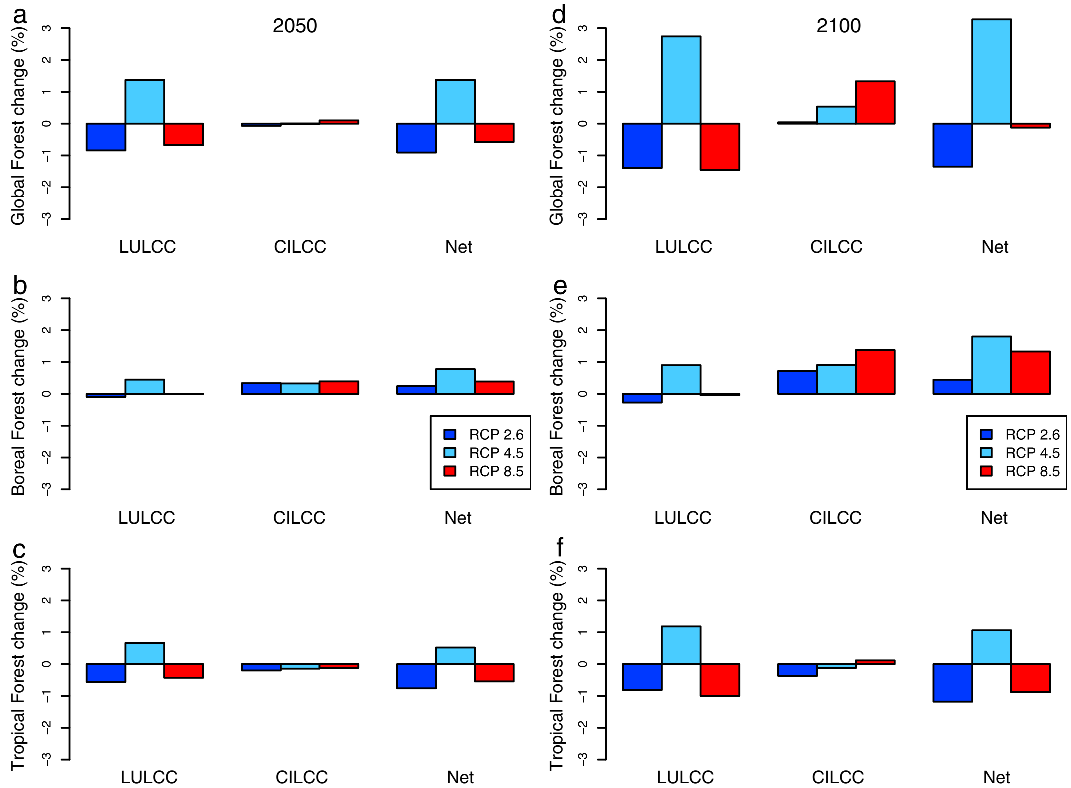

Figure 2. Changes in forest fraction (in percent of total global land area) (a) globally, (b) temperate/boreal forest area (33.75 N–83.75 N; middle- to high-latitude northern hemisphere), and (c) the tropics (16.25 S–21.25 N). (d–f) Same as in Figures 2a–2c. (Figures 2a–2c) Years 2050–2006 and (Figures 2d–2f) 2100–2006.

than the 2100 PFT distribution). This gives what the vegetation carbon would be in no LCC simulations (excluding LULCC and CILCC but including accumulated carbon).

To estimate the soil carbon, we take the 2005 soil carbon and scale it annually with the 2005 litter carbon and soil respiration. The soil carbon is updated each year with the input of carbon from litter carbon, and then the soil respiration (which scales with the amount of soil carbon) is removed. To estimate the soil carbon, we therefore start with the 2005 soil carbon, add the litter carbon weighted by the difference between the 2005 and "*n*" year PFTs, and then take away the respiration weighted by proportional difference between the 2005 soil carbon and the *n* year soil carbon. This is repeated from $n = 2005$ to $n = 2100$. Thus, the calculation used is

$$\begin{aligned} \mathrm{CS\_nlcc}(n+1) &= \mathrm{CS\_nlcc}(n) + [\mathrm{LIT\_nlcc}*(\mathrm{PFT\_original}/\mathrm{PFT\_2005}(n))] \\ &- [\mathrm{RH\_original}(n)*(\mathrm{CS\_nlcc}(n)/\mathrm{CS\_original}(n))] \end{aligned}$$

where "nlcc" is the constructed value, "original" is the original RCP simulation value, CS is the soil carbon, LIT is the litter carbon, PFT is the plant functional types on tiles, and RH is the soil respiration.

These off-line calculations of the global soil and vegetation carbon values use the same equations as the land surface model, Joint UK Land Environment Simulator (JULES) [*Clark et al.*, 2011], that is within the coupled model. This approach has the advantage that a global value for the land carbon can be produced very efficiently and has been demonstrated as effective in other instances (for instance *Liddicoat et al.* [2013]).

3. Results

3.1. Forest

The most notable CILCC is a global increase in forest (needleleaf and broadleaf trees) that has an approximately proportional relationship with the total radiative forcing of the scenario (see Figure 2d). This is in contrast to the LULCC, which is scenario dependent and does not have the relationship with net climate forcing that might be expected. RCP2.6 and RCP8.5 both have substantial deforestation, whereas RCP4.5 has afforestation (Figure 2d). Although RCP2.6 and RCP8.5 have very similar levels of anthropogenic deforestation, their net forest change is very different. In RCP2.6, the CILCC offsets only 3% of anthropogenic deforestation, whereas it offsets 91% in RCP8.5. The larger increase in CILCC forest in RCP8.5 is due to higher temperature and atmospheric carbon dioxide concentration, which allows more poleward expansion of forest than in RCP2.6 (see Figures 2e, 4a, and 4b).

The LULCC and CILCC forest fraction changes have noticeably different latitudinal patterns, with the tropics contributing more to LULCC and the boreal forests contributing more to CILCC. The net changes in the boreal forest latitudinal band (Figure 2e) are dominated by the CILCC increases in forest, with only relatively small LULCC. The tropics show the opposite pattern, with little CILCC and the net forest change dominated by the LULCC (see Figure 2f). Because of this, there are only a small number of isolated grid cells where both LULCC and CILCC are both strong. Globally, most of the LULCC in RCP2.6 and RCP8.5 is in the tropics, and most of the CILCC is boreal. RCP4.5 is slightly different, as there is extensive middle- to high-latitude afforestation due to the scenario's universal carbon tax making afforestation a viable mitigation option [*Thomson et al.*, 2010, 2011]. However, all three RCP scenarios considered here have positive net forest contributions from boreal forests, mainly from CILCC, and net tropical contributions that result mainly from LULCC.

The balance of CILCC and LULCC is different at the centennial and midcentury time scales. The LULCC occurs relatively earlier, since LULCC agricultural expansion is instantaneous as it imposed in each year within the model. The CILCC vegetation expansion happens more gradually and therefore slightly later, as the expansion of vegetation northward is commensurate with the increase in temperature and carbon dioxide. It also takes around 80 years in this model for abandoned agricultural land to fully reforest in the model. By 2050, globally, there is very little CILCC (see Figures 2a–2c), and consequently, there is much more influence of LULCC on the net boreal forest LCC than at 2100. Thus, the global forest amount at 2050 is more strongly influenced by the tropics and LULCC. Because of the lack of CILCC at 2050, the net LCC of RCP2.6 and RCP8.5 are much more similar than at 2100. The impact of time scale on the balance of whether LULCC or CILCC is most dominant continues further into the future. The relatively slow rate of forest growth means that for a transient climate forcing, as is projected in the RCPs, there will be committed vegetation changes for some time after the forcing stops [*Jones et al.*, 2009]. Therefore, on the multicentennial scale, CILCC is likely to be more important than LULCC.

In the tropics, there is only very slight dieback of broadleaf trees (Figures 2d and 4a) in favor of C_4 grasses. Amazon dieback was a well-known feature in previous versions of the Hadley Centre model (notably HadCM3) and was primarily caused by changes to precipitation over the Amazon under climate change [*Cox et al.*, 2003, 2004; *Betts et al.*, 2004; *Huntingford et al.*, 2008; *Malhi et al.*, 2009]. Amazon dieback is absent in this version of the model (HadGEM2-ES), with only up to 10% dieback over the southern edges of the Amazon (Figure 4a) [*Good et al.*, 2012]. However, since the dieback is approximately the same magnitude in all three RCPs considered here, this suggests that a relatively small change in climate may still trigger a tipping point in the Amazon in this model, which increases in carbon dioxide only very slightly compensate for (Figure 2f). In the tropics overall, this Amazon dieback is mitigated by increase in broadleaf trees over the Congo basin, where shrubs give way to broadleaf trees as the climate warms (see Figures 4a and 4c). This gives the result that in RCP2.6 the tropics has a slight decrease in forest from CILCC, but RCP4.5 has a slight increase, again aiding the mitigation of LULCC in higher radiative forcing scenarios like RCP8.5, but not RCP2.6.

3.2. All Vegetation

Considering the LCC across all vegetation types, CILCC is larger than LULCC at 2100 in all the scenarios considered here (Figures 3–5). As a percent of global land area, CILCC is only slightly more than LULCC in RCP2.6 and RCP4.5 (CILCC: 3.2% and 5.5% and LULCC: 2.9% and 5.1%, respectively). However, for the high scenario, RCP8.5, the CILCC and LULCC are 8.6% and 3.9%, respectively, making CILCC a factor of 2 bigger. The LCC values quoted above are the conservatively calculated net figures; in that, no annual or decadal variations are included, and the values are the simple total difference in the amount of a PFT globally between 2005 and 2100 (rather than including changes of the same land type moving to different areas)

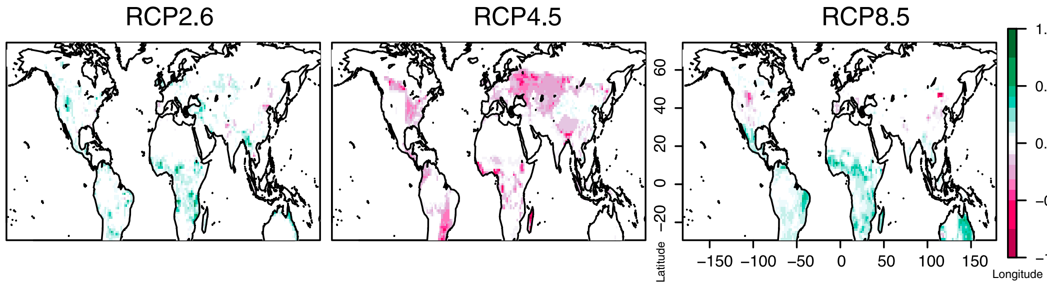

Figure 3. The LULCC 2005 to 2100, encompassing the agricultural fraction changes (crop and pastureland).

[*Pongratz et al.*, 2014; *Wilkenskjeld et al.*, 2014]. Methods of LCC calculation that included the gross changes would probably give higher CILCC values because the shifts in the PFTs would be accounted for, whereas the current method mainly accounts for the expansions. The majority of the CILCC expansion is broadleaf trees at the high latitudes (Figure 4a), but there are shifts in vegetation all the way down the order of vegetation succession (Figures 4 and 5). As the temperature and carbon dioxide increase, more dominant or more appropriately adapted PFTs are able to move into the regions previously unable to support them. The C_3 grasses colonize furthest north, replacing the areas of bare soil and C_4 grasses (Figure 5). However, since the dynamic vegetation in the model works on a height hierarchy, shrubs and then trees have competitive advantage over grasses as the climate becomes appropriate for them, causing shrubs and then trees to move into areas previously occupied by C_3 grasses (Figures 4 and 5). Broadleaf trees are the most dominant PFT in the model and therefore have an expansion with little dieback, and the other PFTs have shifts. Thus, the net change can be small even when the gross change is much more widespread, because the net change does not account for the shifts. Therefore, the result that CILCC is larger than LULCC is likely to be robust for all the RCP scenarios considered here, as by excluding shifts in distribution it is quite conservative.

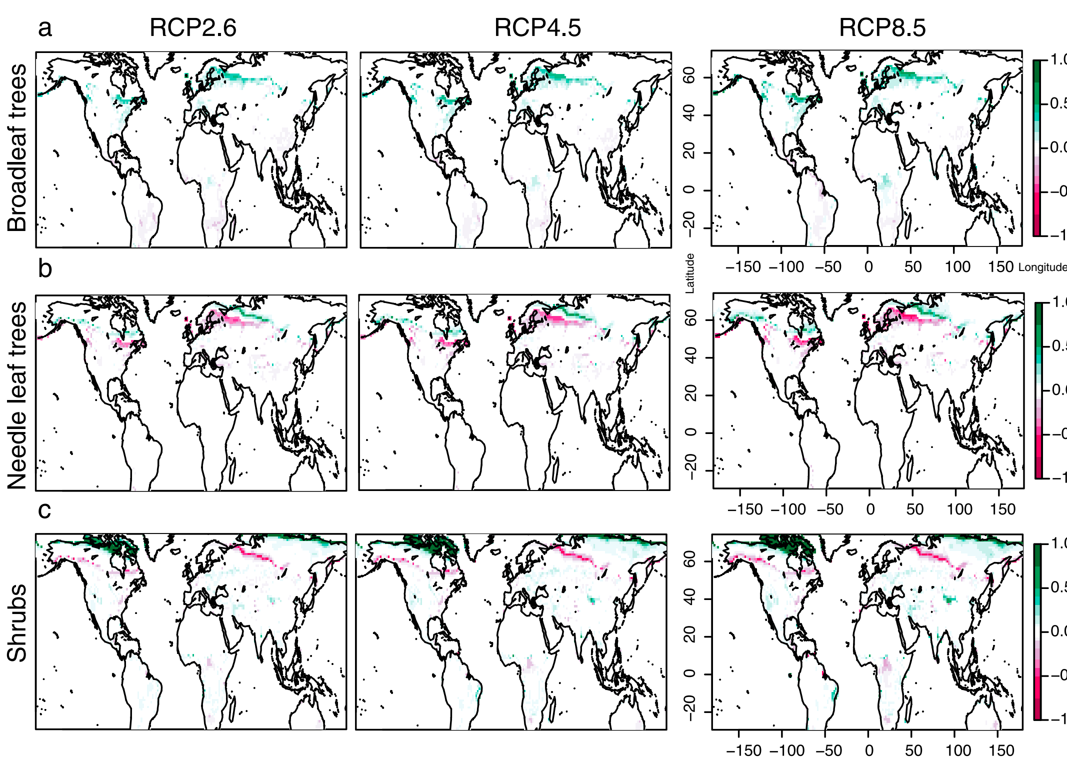

Figure 4. Changes in woody vegetation surface types, 2100–2005 from CILCC. (a) Broadleaf trees, (b) needleleaf trees, and (c) shrubs.

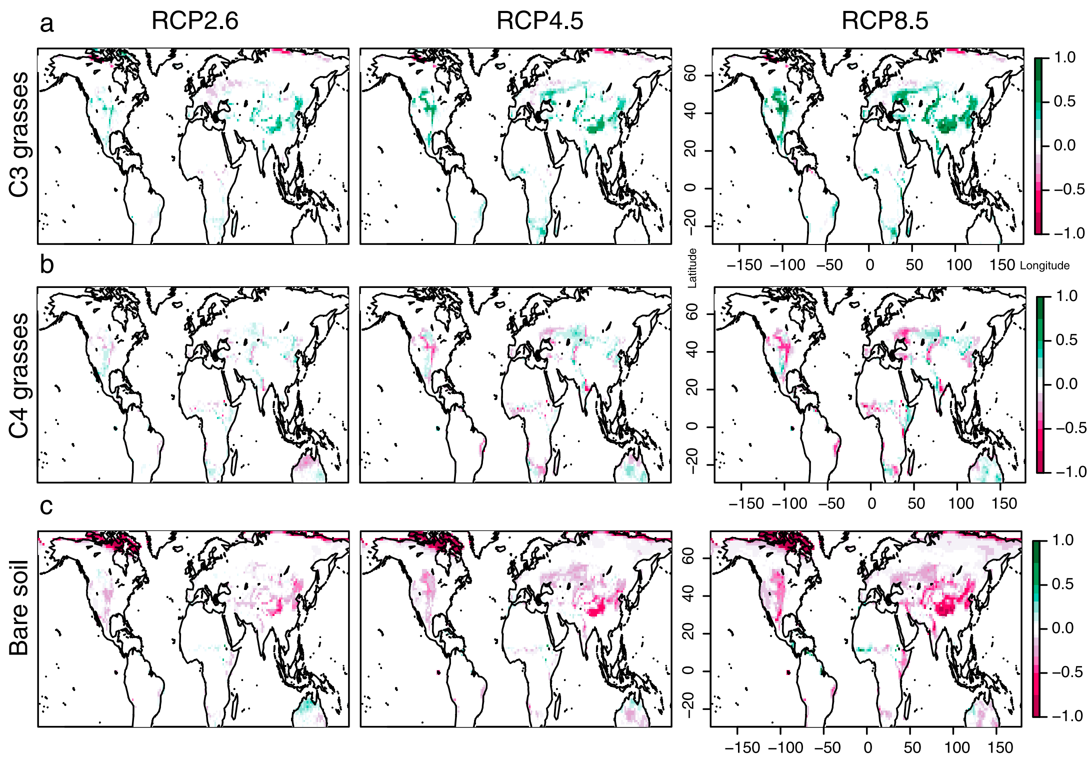

Figure 5. Changes in selected nonwoody vegetation/surface types from CILCC, 2100–2005. (a) C_3 grasses, (b) C_4 grasses, and (c) bare soil.

3.3. Carbon Cycle

CILCC is the largest contributor to carbon changes from net LCC and determines the signal (Figure 6a). The land carbon changes from CILCC are larger than those from LULCC in all the scenarios considered here. The net land carbon change is a sink in all three scenarios, strongly influenced by the CILCC. Soil carbon is the biggest contribution from CILCC and is several times the size of the LULCC soil carbon change (Figure 6b). The difference in the change in soil carbon due to CILCC and LULCC is because of changes in net primary production (NPP) that increase the inputs to the soil carbon [*Jones and Falloon*, 2009]. This is in line with the overall change in soil and vegetation carbon for all land cover (not just changed) from 2006 to 2100, which increases by 180–425 GtC carbon globally over the 95 year simulation (see Figures 6d–6f). The expansion of vegetation into areas previously allocated as bare soil due to CILCC means that more litter is available to increase the soil carbon. For deforestation LULCC, the soil carbon increases a little under deforestation because some of the belowground biomass carbon goes into the soil. But the LULCC soil carbon in afforestation scenario RCP4.5 has soil carbon emissions because the trees replacing the grass have marginally lower NPP, and therefore, there is a loss of soil carbon. Note that the gross primary production is higher for trees overall, but trees also have higher maintenance requirements, and thus can have lower NPP. Vegetation carbon (Figure 6c) shows the opposite trend to soil carbon, with the LULCC carbon changes larger than the CILCC. The vegetation carbon changes for both CILCC and LULCC are similar to the equivalent changes in forest fraction, as in this model trees are the main stores of vegetation carbon (compare Figure 6c with Figure 2d). However, this model does not represent any harvesting processes, which if included, would probably drive the soil carbon input down rather than up, for conversation to crops (by reducing the litter inputs when the harvest is removed elsewhere). Despite these uncertainties, these simulations suggest that net LCC is a carbon sink in all the RCPs considered here and the contribution of CILCC is larger than LULCC.

The LCC also affects the climate through changes to the atmospheric greenhouse gas concentration. The net LCC carbon change gives a cooling (Figure 6a) amounting to −0.02 K in RCP2.6, −0.21 K in RCP4.5, and −0.18 K in RCP8.5 (calculated using the HadGEM2-ES transient climate response to emissions [*Gillett et al.*, 2013]). It is notable that including CILCC changes the sign of the climate effects of net LCC in two of the

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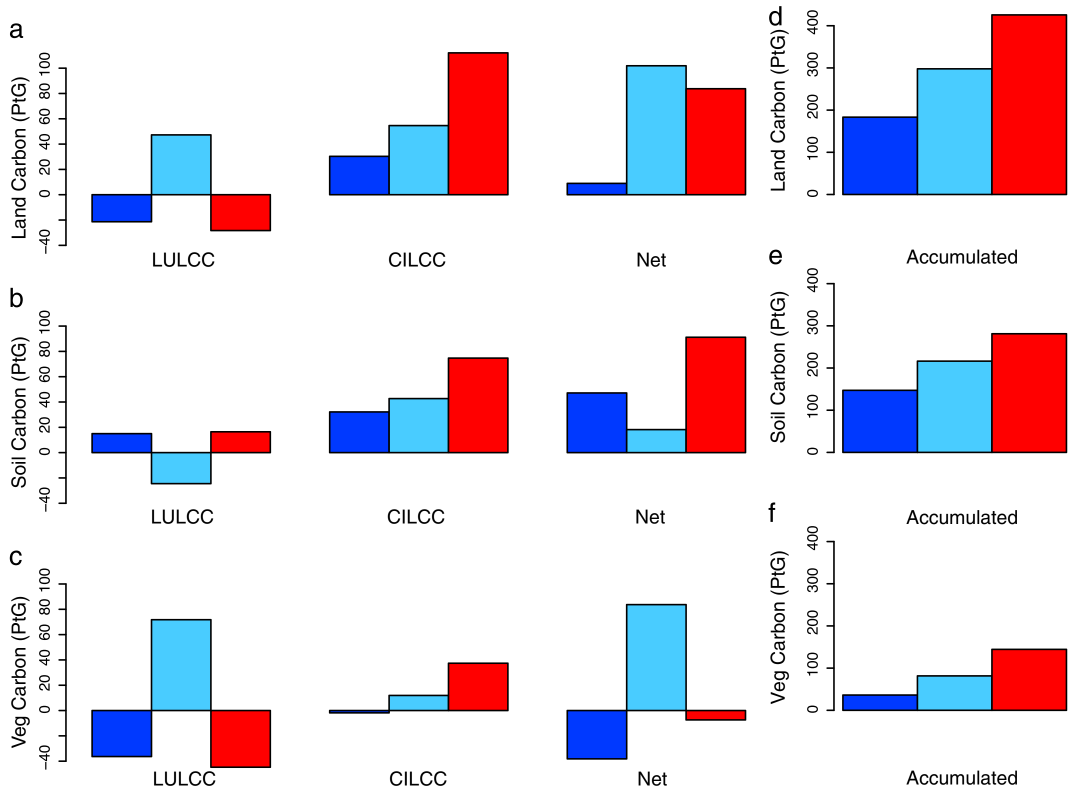

Figure 6. Anomaly of total global land carbon storage changes from different sources, 2100–2005. (a–c) LULCC, CILCC, and Net (LULCC + CILCC). (d–f) Accumulated carbon storage change (from all land surface not just LCC). Separated into (Figures 6a and 6d) vegetation and soil carbon, (Figures 6b and 6e) soil carbon, and (Figures 6c and 6f) vegetation carbon. Note that the scale for Figures 6d–6f is 4 times larger than for Figures 6a–6c.

RCPs. The LULCC carbon-only climate impacts are +0.04 K, −0.08 K, and +0.04 K (for RCP2.6, RCP4.5, and RCP8.5, respectively) [*Davies-Barnard et al.*, 2014b]. The contribution of CILCC to the carbon sink is larger than LULCC in all of the RCPs considered here, with RCP8.5 approximately 4 times larger. Further, the CILCC is also critical in maintaining the airborne fraction of emissions. The LULCC and increasing fossil fuel emissions historically have reduced the proportion of land uptake of anthropogenic carbon emissions [*Canadell et al.*, 2007]. The CILCC, particularly the increase in forest fraction shown in Figure 2, means that the reduced carbon sink from LULCC is partially offset by the increase in the CILCC carbon sink [*Jones et al.*, 2012]. Therefore, CILCC plays a significant role in the climatic impacts from net LCC.

4. Discussion and Conclusions

Comparing the CILCC and LULCC, we find that the CILCC has a significant impact, and in some cases a larger impact than LULCC. In all the RCPs we see a poleward expansion and succession of vegetation, as found by field and model studies of the response of vegetation to climate changes [*Emanuel et al.*, 1985; *Prentice et al.*, 1991; *Woodward et al.*, 1998; *Walther et al.*, 2002; *Soja et al.*, 2007; *Colwell et al.*, 2008; *Betts et al.*, 2013]. The increased temperature opens up new regions that were previously too cold to support vegetation, especially in the high-latitude northern hemisphere [*MacDonald et al.*, 2008]. This contrasts with LULCC in the RCPs, which is mainly in the tropics. In RCP4.5 the CILCC and LULCC globally work in parallel, giving a larger net LCC, whereas in RCP2.6 and RCP8.5 the CILCC and LULCC offset each other.

The large CILCC in RCP8.5 means that it has a form of "forest offsetting" over time between the deforestation in the tropics and the northward expansion of boreal forest. In RCP8.5, 91% of the anthropogenic deforestation is offset by CILCC. This could be perceived as a potential way to offset the biodiversity loss, in a similar way to biodiversity offsetting [*Maron et al.*, 2012; *Reid*, 2013]—compensating for the loss of tropical forest with boreal forest. However, offsetting of the total forest loss globally is an incomplete story.

Tropical forests especially tend to be areas of high biodiversity [*Myers et al.*, 2000], and established primary forests are more diverse than secondary forest [*Gibson et al.*, 2011]. This could be the cause of substantial losses of global biodiversity if tropical forests were offset by boreal forest. The northward shift of forest could also cause loss of some extreme cold adapted habits. Ecosystems allocated in the model as “bare soil” (because none of the model’s plant functional types are able to sustain growth there) or C_3 grasses could be lost entirely. It is difficult for land surface models to effectively simulate these marginal environments, but they are nonetheless important and unique ecosystems.

In the short term, the net LCC would almost certainly cause losses of biodiversity. Although over the full time period to 2100, the forest changes in RCP8.5 almost cancel out; in the period up to 2050, they do not. This question of the time lag is particular problem for biodiversity offsetting, as certain decreases are balanced against uncertain increases [*Moilanen et al.*, 2009; *Bekessy et al.*, 2010]. Probable extinctions in the tropics from LULCC would be unlikely to be meaningfully compensated for by CILCC expansion of boreal forest. Furthermore, it is possible that much of the forest gains would be not be realized, due to “boreal dieback” from effects such as increasing destruction of forests by pests [*Kurz et al.*, 2008]. A forest offsetting policy that relied on CILCC would essentially be “betting” on vegetation changes that may be slow or unable to be realized while sacrificing established ecosystems.

From the point of view of ecosystem disruption, the greater amount of CILCC than LULCC would suggest that CILCC would cause more disruption in all three of the RCP scenarios considered here. However, habitat destruction, particularly conversion of land to agricultural use, is thought to be the most important driver of biodiversity loss, with climate change less important [*Hassan et al.*, 2005]. Since the CILCC is only slightly higher than the amount of LULCC in RCP2.6 and RCP4.5, it is possible that LULCC may have a bigger impact on biodiversity in these scenarios. For RCP8.5, CILCC would likely still be a larger impact on biodiversity, since the total area affected by CILCC is more than double than from LULCC. As well as the extent of the impact, the duration also should be taken into account. After stabilization of the forcing, the effects of LULCC drop off, whereas the CILCC continues as the vegetation reaches equilibrium. The CILCC is likely to continue well beyond 2100 for decades or even centuries after the forcing has stabilized [*Jones et al.*, 2010; *Liddicoat et al.*, 2013]. Comparing the disruptive impact, CILCC could be a more serious challenge than LULCC, particularly in RCP8.5, because of the longevity and quantity of impact, even if the severity is lower.

The important role of CILCC in terrestrial carbon changes highlights how critical it is to reduce the uncertainty in carbon cycle projections. CILCC accounts for 14–22% of total terrestrial carbon changes (depending on the RCP scenario), whereas LULCC only accounts of 6–12% (Figure 6). Soil carbon is the biggest contributor to the land carbon change from CILCC in the model used here, around 2–3 times larger than vegetation carbon change. However, soil carbon change is highly variable between models, in both net sign and magnitude [*Nishina et al.*, 2014]. Some models project a global decrease in land carbon under climate change, and JULES (the off-line land surface model of HadGEM2-ES) is on the high side of the projections of soil carbon changes [*Nishina et al.*, 2014]. This is likely to be related to the model’s sensitivity to carbon dioxide fertilization, as this (rather than temperature) is the main driver of change in soil carbon in models [*Nishina et al.*, 2014]. Further, the vegetation carbon increase from LULCC afforestation (in RCP4.5) and CILCC may be overestimated because of lack of nitrogen limitation in the model [*Gruber and Galloway*, 2008; *Jain et al.*, 2013]. Conversely, the LULCC deforestation carbon change is small in HadGEM2-ES compared to other models [*Brovkin et al.*, 2013]. However, the soil carbon storage size and future sink size are highly uncertain, and its representation here is one of many possible outcomes.

The carbon effect of net LCC is also influenced by two processes not directly included in the model used in these simulations: secondary LULCC and negative emissions using bioenergy with carbon capture and storage (BECCS). The carbon changes from secondary land use changes (for instance natural to managed forest, which is not accounted for in this model) can be substantial and may account for more carbon emissions than primary land use changes [*Shevliakova et al.*, 2009; *Hurtt et al.*, 2011; *Lawrence et al.*, 2012]. Similarly, BECCS for the RCP2.6 scenario could give negative emissions of between 43.8 and 160.6 GtC [*Kato and Yamagata*, 2014]. According to those projections, the potential of BECCS is likely to be bigger than the net land carbon change in any of the three RCPs considered here (8, 101, or 83 GtC for the three RCPs, respectively; see Figure 5a). Therefore, the lack of representation of secondary LULCC and BECCS is a considerable limitation to this study. It is also notable that the total land carbon change (including non-LCC effects) is at least 4 times the size of the change in land carbon from LCC in this model (see Figures 5d–5f). Thus, the contribution of LCC to overall global carbon emissions is relatively small. However, even though the carbon effects of LCC are not substantial, other environmental impacts of LCC may be worth considering in decision making, as discussed above.

The relative lack of analysis of CILCC in the RCPs can be attributed to a combination of possible causes, including a perceived lack of need and high uncertainty. Few of the CMIP5 models include dynamic vegetation (that projects CILCC), and only around half of the CMIP5 models have vegetation carbon cycle components (19 of 38 models (es-doc v0.9.0.1 CMIP5 model component properties, 2014, http://prod.static.esdoc.webfactional.com/js_client/demo/prod/comparator.html)). Although there is a slight computational cost of including dynamic vegetation to calculate CILCC in Earth System Models, the first implementations of the terrestrial carbon cycle were around 14 years ago [*Cox et al.*, 2000], so this is evidently not a case of inability. LULCC can be imposed onto a model using values from the Integrated Assessment Model that created the scenario, without the need for dynamic vegetation or an integrated terrestrial carbon cycle. This method excludes CILCC and suggests a viewpoint that CILCC is not important or required. This perception is exacerbated by high uncertainty in climate-induced changes to terrestrial carbon storage. Land carbon differences within the parameter range of an individual model can be as big as the differences between the RCPs themselves [*Booth et al.*, 2012] and are highly variable between models [*Nishina et al.*, 2014]. This uncertainty presents a considerable challenge. But by neglecting to examine CILCC, we may be overestimating the importance of LULCC and misestimating land carbon change by as much as 22%.

Comparing the changes from CILCC and LULCC over 2006–2100, we have shown that not only is the CILCC the majority of net LCC, it is also the larger part of land carbon changes from net LCC. Moreover, even where CILCC is not as large as LULCC, as in the case of forest change, it gives rise to issues of offsetting. To what extent forest lost in the tropics could be substituted by boreal forest is both a qualitative and a quantitative issue. Our results suggest that CILCC in RCP8.5 may be able to quantitatively offset the deforestation, whereas it cannot in RCP2.6. Whether such forest offsetting would provide equivalent ecosystem and climate services is much more uncertain and would be a useful extension to this work. Moreover, our work shows that CILCC is an important aspect of the land surface in the RCPs. If the potential size of the climate change impact caused or mitigated by an aspect of the Earth system is a guide for the amount of research that should be done on a topic, then CILCC perhaps warrants more research.

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