Full effects of land use change in the representative concentration pathways

Article

Published Version

Davies-Barnard, T., Valdes, P. J., Singarayer, J. S., Pacifico, F. M. and Jones, C. D. (2014) Full effects of land use change in the representative concentration pathways. Environmental Research Letters, 9 (11). 114014. ISSN 1748-9326 doi: https://doi.org/10.1088/1748-9326/9/11/114014 Available at https://centaur.reading.ac.uk/39669/

To link to this article DOI: http://dx.doi.org/10.1088/1748-9326/9/11/114014

Publisher: Institute of Physics

Full effects of land use change in the representative concentration pathways

2014 Environ. Res. Lett. 9 114014

(http://iopscience.iop.org/1748-9326/9/11/114014)

OPEN ACCESS
IOP Publishing

Environmental Research Letters

Environ. Res. Lett. 9 (2014) 114014 (7pp)

doi:10.1088/1748-9326/9/11/114014

Full effects of land use change in the representative concentration pathways

T Davies-Barnard[1,3], **P J Valdes**[1], **J S Singarayer**[2], **F M Pacifico**[3] and **C D Jones**[4]

[1] Cabot Institute and School of Geographical Sciences, University of Bristol, University Road, Bristol BS8 1SS, UK
[2] Department of Meteorology, Earley Gate, PO Box 243, Reading, UK
[3] College of Engineering, Mathematics and Physical Sciences, University of Exeter, Laver Building, North Park Road, Exeter EX4 4QE, UK
[4] Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3PB, UK

E-mail: t.davies-barnard@exeter.ac.uk

Received 27 June 2014, revised 25 October 2014
Accepted for publication 27 October 2014
Published 18 November 2014

Abstract

Future land use change (LUC) is an important component of the IPCC representative concentration pathways (RCPs), but in these scenarios' radiative forcing targets the climate impact of LUC only includes greenhouse gases. However, climate effects due to physical changes of the land surface can be as large. Here we show the critical importance of including non-carbon impacts of LUC when considering the RCPs. Using an ensemble of climate model simulations with and without LUC, we show that the net climate effect is very different from the carbon-only effect. Despite opposite signs of LUC, all the RCPs assessed here have a small net warming from LUC because of varying biogeophysical effects, and in RCP4.5 the warming is outside of the expected variability. The afforestation in RCP4.5 decreases surface albedo, making the net global temperature anomaly over land around five times larger than RCPs 2.6 and 8.5, for around twice the amount of LUC. Consequent changes to circulation in RCP4.5 in turn reduce Arctic sea ice cover. The small net positive temperature effect from LUC could make RCP4.5's universal carbon tax, which incentivizes retaining and growing forest, counter productive with respect to climate. However, there are spatial differences in the balance of impacts, and potential climate gains would need to be assessed against other environmental aims.

S Online supplementary data available from stacks.iop.org/ERL/9/114014/mmedia

Keywords: earth system model, land use change, representative concentration pathways

1. Introduction

The IPCC (International Panel on Climate Change) fifth assessment report assessed 21st century projections from a new range of socio-economic scenarios for climate modelling—the representative concentration pathways (RCPs). They span a range from low to high radiative forcing, corresponding to aggressive mitigation policies or business as usual (Van Vuuren *et al* 2011). They also include different representations of future land use change (LUC) (Hurtt *et al* 2011). RCP4.5 has a decrease in agricultural land (crop and pasture) by 2100, whereas RCP2.6 and RCP8.5 both have increases (see figure 1(a) and supplementary material figure 1, available at stacks.iop.org/ERL/9/114014/mmedia). This results in a reduction of forest in RCP2.6 and RCP8.5, mainly in the tropics, and an increase in forest in RCP4.5, predominantly in the mid latitudes (Hurtt *et al* 2011). The RCP scenarios include land carbon emissions and uptake (biogeochemical effects) in their radiative forcing targets. However, they do not account for non-greenhouse gas changes to climate, via the surface energy balance (biogeophysical

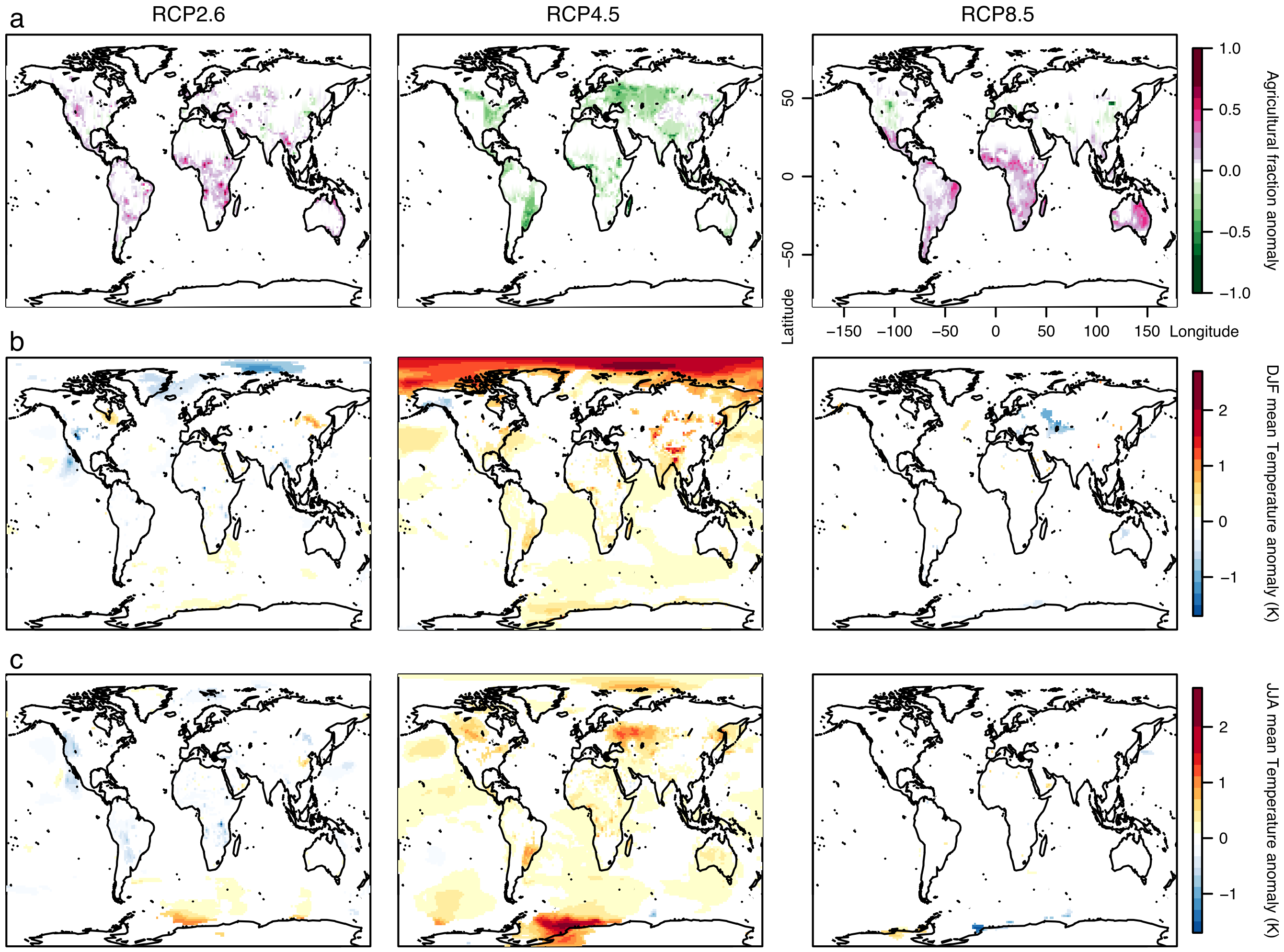

Figure 1. Differences in agricultural land and seasonal temperature in the three RCP scenarios considered here between the RCP and NoLUC simulations. (a) Anomaly in agricultural land (total pasture + cropland) at the end of the century. (b) Northern hemisphere winter (December/January/February) and (c) summertime (June/July/August) temperature (K) anomalies for the mean of 2070–2100 (RCP-NoLUC). Areas in (b) and (c) where $p > 0.05$ from the results of a Wilcoxon rank sum test are not plotted (see supplementary material discussion 1 for more details about the statistical testing and for the plots seasonal and annual plots with all anomalies plotted).

effects, e.g. albedo, evapotranspiration etc). Earth system models (ESMs), however, include both. Therefore ESMs can be used to understand the full climate effects of LUC in the RCPs, rather than only the effects from biogeochemical changes (greenhouse gases).

Biogeophysical and biogeochemical effects can have opposite signals (Pongratz *et al* 2010, Matthews *et al* 2004) and it is spatially variable which is most important (Bonan 2008). Biogeochemical effects are often stronger in the tropics because of high biomass content of tropical forests. Biogeophysical effects tend to be stronger in the temperate and high latitudes because of differences in albedo between surfaces with and without snow (Bonan 2008). Therefore the location of the LUC affects the sensitivity of the RCPs to their respective LUC. To assess the balance of biogeophysical and biogeochemical forcings from LUC in the RCPs, we use ensembles in HadGEM2-ES (Collins *et al* 2011) for three of the RCP simulations (Jones *et al* 2011) with land cover fixed in its 2005 state. This gives 'NoLUC' simulations, which can be compared to the standard 'RCP' simulations that give the biogeophysical effects of LUC in the temperature anomaly. The biogeochemical effect is inferred from the model's land carbon anomaly. The net effect of LUC is inferred from the biogeophysical and biogeochemical effects combined.

2. Methods

We use the Met Office Hadley Centre's coupled earth system model, HadGEM2-ES (Collins *et al* 2011, Martin *et al* 2011) which includes the MOSES2 land-surface scheme (Essery *et al* 2001); the TRIFFID dynamic global-vegetation model in dynamic mode (Cox 2001); the four-pool RothC soil carbon model (Jones *et al* 2005); the HadGEM1 atmospheric model (Martin *et al* 2006); interactive ocean biogeochemistry; terrestrial biogeochemistry; dust and interactive atmospheric chemistry; and aerosols. The atmosphere component contains 38 1.875° × 1.25° levels and interacts with water, energy and carbon within the land surface scheme and the dynamic vegetation model. The simulations use a fully dynamic atmosphere and ocean model.

Five plant functional types (broadleaf tree, needleleaf tree, C_3 and C_4 grasses and shrubs) are simulated in the model, representing broad category generalizations. In particular, the grass plant functional types also encompass crops. The agricultural fraction in HadGEM2-ES is imposed as an area where broadleaf and needleleaf trees and shrubs cannot be grown. Therefore the agricultural fraction can only be bare soil, or C_3 and C_4 grasses. Increases in agricultural fraction within a grid box are preferentially expanded into grasses, only converting trees to agricultural fraction when other plant function types are not available.

The model setup is as for the HadGEM2-ES CMIP5 simulations (Jones *et al* 2011) and the HadGEM2-ES setup for the LUCID simulations (Brovkin *et al* 2013). The simulations are concentration driven, allowing simulations with and without LUCs to be run. This also allows decoupling of the biogeochemistry from the biogeophysics, so both can be considered individually. There are four initial condition ensemble members for each of the three RCPs considered here (RCP2.6, RCP4.5 and RCP8.5), for a combination of the standard RCP (with LUC) or NoLUC (with no LUC). I.e. 3 RCPs × 2 land use scenarios × 4 ensemble members = 24 simulations in total. The ensemble members are initialized from four historical simulations that ran from 1850–2005 (see Jones *et al* 2011). Each simulation is run for 95 years, from 2005 to 2100. Therefore the ensemble has an 'RCP' simulation (with LUC) and a 'NoLUC' simulation without LUC.

The total agricultural fraction (cropland and pasture) remains constant (to the 2005 value) in the NoLUC simulations. For the standard RCP, the LUC is as determined by the Integrated Assessment Model scenario for that RCP. For all the NoLUC simulations, all non land-use forcings (greenhouse gas concentrations and other aerosol forcings, etc) are prescribed as for the equivalent RCP (Meinshausen *et al* 2011). Therefore the NoLUC simulations do not have any greenhouse gas feedbacks from LUC included (i.e. they only include the biogeophysical impacts of the LUC).

From the anomaly between the standard RCP (with LUC) and the NoLUC simulations, two LUC effects on the radiative forcing can be seen: biogeophyiscal and biogeochemical. The biogeochemical forcing from LUC arises from the additional CO_2 put into the atmosphere by the LUC, and the climate model's sensitivity to this additional radiative forcing. The additional carbon is diagnosed from the HadGEM2-ES simulated land carbon stores (soil and vegetation) and this is converted to a resulting additional global climate change using the Transient Response to Cumulative Emissions (TRCE) (Gillett *et al* 2013), which is an approach that has demonstrated proportionality between carbon emissions and temperature rise. This approach has been extensively used in the IPCC fifth assessment report.

The biogeophysical forcing from LUC arises from physical changes to the land surface from LUC. From our model simulations we diagnose the result of this forcing from the anomaly of the climate mean (2070–2100) of the standard RCP ensemble (i.e. including LUC) and the equivalent NoLUC simulation. The net climate forcing of LUC is not simulated explicitly, but produced from combining the global biogeochemical and biogeophysical values, with the assumption that they combine linearly. The anomalies used here are the climate mean (2070–2100) for RCP minus NoLUC. Therefore the anomalies here give the effect (biogeophysical, biogeochemical, or net) of the LUC.

3. Results

The mean annual temperature of the RCP4.5 ensemble (with LUC) has a small difference of 0.19 K (land only) compared to the NoLUC ensemble, that emerges around 2070 (see figure 2(a)). In contrast, the two scenarios of deforestation (RCP2.6 and RCP8.5) have ensemble mean annual global temperatures that are almost identical to their equivalent NoLUC ensembles. The largest physiological difference between the plant functional types in the model is the difference between grasses and trees, and thus the forest fraction changes gives a guide as to what scale of change should be expected. Given that the absolute change in forest fraction is twice the size in RCP4.5 than in RCP8.5 or RCP2.6 (+2.4% and −1.2% of total land area respectively) it might be supposed that the climatic changes would also be twice the size. The change in carbon conforms to this assumption, with around twice as much change in temperature from the biogeochemical changes in RCP4.5 than in RCP2.6 or RCP8.5 (see figure 2(b)). However, the biogeophysical temperature change in RCP4.5 is 9.5 times and 4.7 times the response of the RCP2.6 and RCP8.5. Hence we are seeing around 2.5 times the size of response that would be expected if the response were simply proportional to the change in forest fraction (see figure 2(b)) and supplementary material table 1).

The seasonal biogeophysical changes in temperature over land in RCP4.5 (figures 1(b) and (c)) are correlated with areas of albedo change and subsequent changes to the surface turbulent fluxes (latent and sensible heat). This is consistent with other LUC experiments that find a decrease in albedo under afforestation because the differences in the albedo of crops, shrubs and trees are large in the summer because of higher leaf areas in the growing season (Brovkin *et al* 2013, Govindasamy *et al* 2001, Davies-Barnard *et al* 2014, De Noblet-Ducoudré *et al* 2012). The seasonal temperature response over land is smaller in the tropics, but still a warming. This is consistent with other land use simulations with HadGEM2-ES (e.g. Davies-Barnard *et al* 2014) but not with conventional understanding of the effects of tropical deforestation (Bonan 2008, Claussen *et al* 2001, Hallgren *et al* 2013). However, in this model, the evapotranspirative cooling from afforestation is not sufficient to cancel out the warming effect of decreased surface albedo changes locally in the tropics. Therefore the global warming is larger than might otherwise be expected, as there is no tropical cooling from afforestation to offset the warming from afforestation in the mid to high latitudes.

As well as warming over land, there are significant temperature changes over the ocean, (mainly warming)

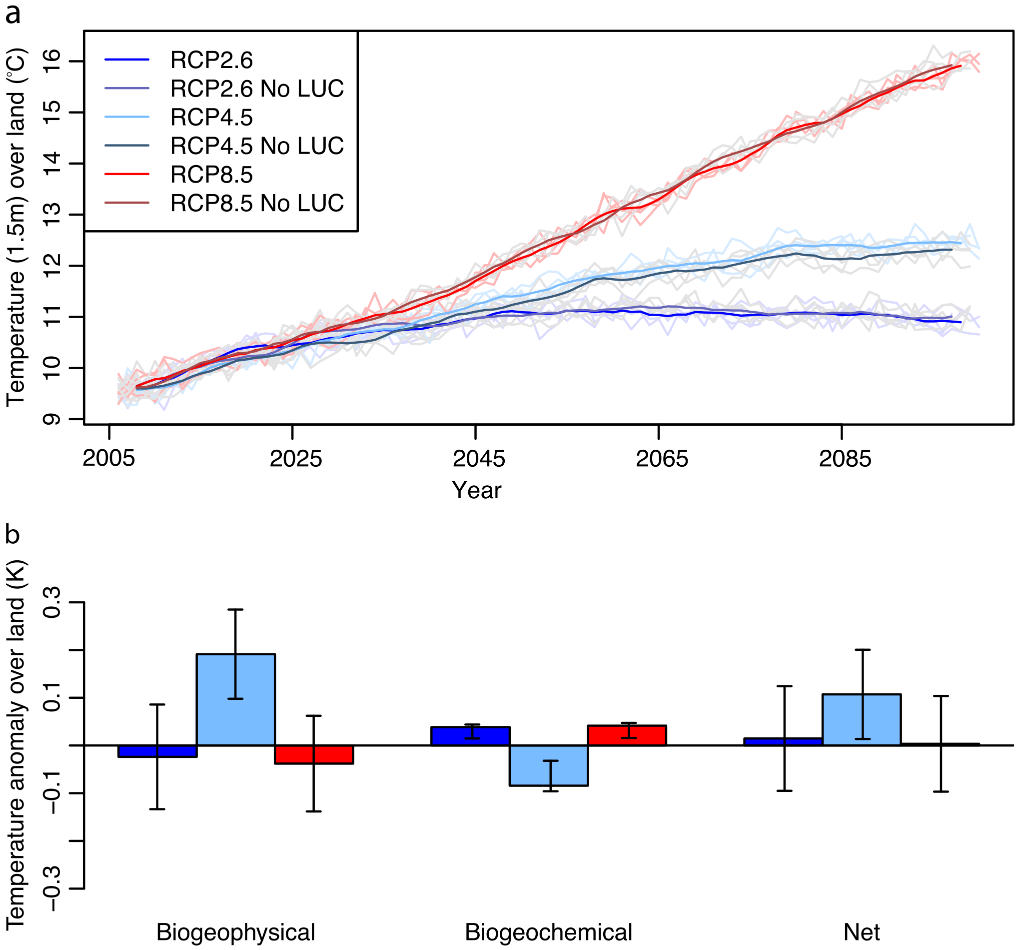

Figure 2. Ensemble global mean annual temperature timeseries of the RCP and NoLUC simulations (biogeophysical changes) (a), and the mean annual global anomalies of biogeophyisical, biogeochemical and net differences between RCP and NoLUC over the time period 2070–2100. (a) Mean annual global temperature (at 1.5 m) over time (land only), for the ensembles and ensemble mean of RCP2.6, RCP4.5 and RCP8.5, with and without LUC. (b) Temperature (at 1.5 m) anomaly (RCP-NoLUC) over land from the last 30 years of the simulations (2070–2100) for the biogeophysical (as above), biogeochemical (from TRCE) and net temperature changes (biogeophysical + biogeochemical). The error bars for the biogeophysical represent the standard deviation of the whole RCP run ensemble for 2005–2100, standardized to the rolling ensemble mean. The error bars for the biogeochemical represent the whole range of resultant temperatures for TRCE values all the CMIP5 models (these are off center because HadGEM2-ES is near the top of the CMIP5 range). The net has the same error bars as the biogeophysical. The values shown here vary slightly from other quoted values due to different averaging periods. The colours used here are as used by the IPCC AR5 report, to enable a frame of reference.

especially in the Arctic winter (December/January/February, DJF) in RCP4.5 (figure 1(c)) from sea ice changes (figure 3). Including temperature changes over the oceans, the global biogeophysical annual mean temperature response (+0.14 K) in RCP4.5 is a little lower than the land-only mean though proportionally larger than RCP2.6 and RCP8.5 (−0.01 K and −0.015 K) (see supplementary material table 1). The Arctic warming is strongly linked to changes in sea ice coverage in RCP4.5 (figure 3(b)), and appears across all the ensemble members. The changes are driven by northward feedbacks from European and North American LUC, which have been found previously to affect the sea ice extent and temperature (Bonan *et al* 1992, Rogers *et al* 2013). The decrease in mid - high latitude land albedo in JJA results in decreases to the mean sea level pressure in that region, driving changes to circulation northward and resulting in strong warm air advection over the Arctic and resulting reductions of summer sea ice (see figure 3 and supplementary material figure 4). In DJF, the pressure anomaly reverses and the circulation changes bring warmer wetter air from the north Atlantic. This results in further sea ice loss, which further intensifies the warming, mainly through the loss of the insulating effect of sea ice in reducing heat loss from the ocean surface. This feedback between temperate forest, sea ice and albedo gives a polar amplification of the effect of the LUC, especially for RCP4.5 (see figure 3 and supplementary material figure 5).

In the Southern hemisphere there are consistent changes in sea ice extent and temperature between RCP2.6, RCP4.5 and RCP8.5, that suggest that LUC is also resulting in changes to circulation in the southern hemisphere. RCP2.6 has little LUC in the southern hemisphere, but RCP4.5 has afforestation over Uruguay and southern Brazil and RCP8.5 has increased agricultural land over Australia, southern Africa and Argentina (see figure 1(a)). Though a causal link is

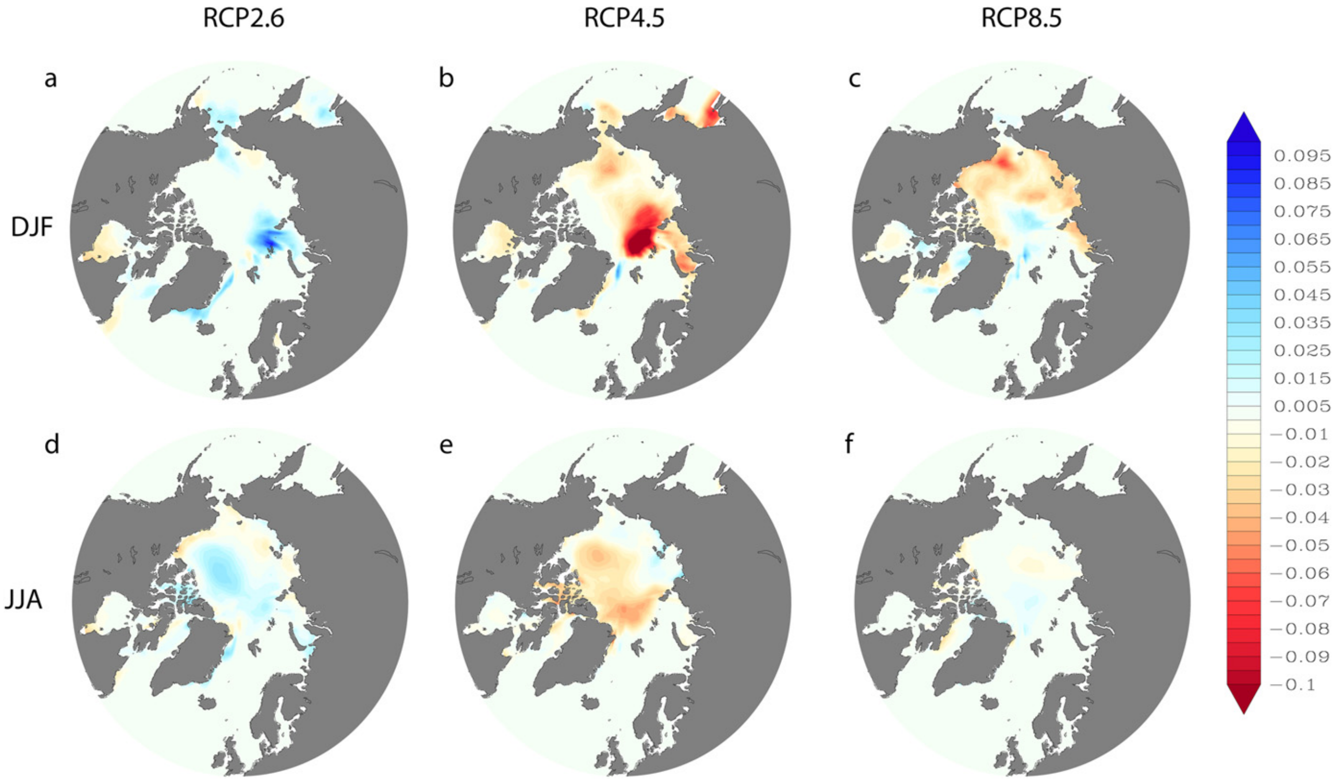

Figure 3. The seasonal anomalies of fraction of sea ice in sea for Northern hemisphere winter (a)–(c) (December/January/February) and summertime (d)–(f) (June/July/August) for the mean of 2070–2100 (RCP-NoLUC).

difficult to establish, there are some similarities to the Northern hemisphere. Circulation changes around Antarctica are seen in RCP4.5 and RCP8.5, but not RCP2.6. The spatial patterns in mean sea level pressure changes are almost exactly opposite between RCP4.5 and RCP8.5 and correlate well with changes in sea ice and 1.5 m temperature (see figures 1(b) and (c), and supplementary material figure 4). Combined with the lack of forcing and response in the southern hemisphere in RCP2.6, this suggests a possible link between the circulation and temperature changes and the southern hemisphere LUC that is different in each of the simulations and not directly proportional with the original forcing.

The carbon emissions from LUC are proportional to the changes in forest fraction in all the simulations considered here (supplementary material table 1). This is because the biogeochemical effects of LUC are not included in the NoLUC simulations, and thus the change in land carbon is primarily from the change in woody vegetation deforest/afforested. The carbon emissions of 18 PgC and 20 PgC from LUC in RCP2.6 and RCP8.5 are equivalent to +0.04 K of warming globally (figure 2(b)), using the HadGEM2-ES transient climate response to emissions (TRCE) of 2.1 K EgC^{-1} (Gillett *et al* 2013) (for the entire CMIP5 TRCE range, +0.01 K to +0.05 K). Cooling from the land carbon uptake of 40 PgC in RCP4.5 is about twice the size of the warming in RCP2.6 and RCP8.5, at −0.08 K, globally, (for the entire CMIP5 TRCE range, −0.03 K to −0.1 K). The change in land carbon storage between the RCP and NoLUC simulations is dependent on the total amount of change in woody plants, especially trees, rather than LUC. The implementation of LUC in the model gives a small change in plant functional type from LUC initially because the model uses up all natural grass in a grid box before converting forest to agricultural land. Since grasses and crops are physiologically identical in the model, there is no effect from LUC in a grid box until all natural grasses within a grid box have been converted to agricultural land. The implementation of LUC in ESMs is one of the biggest uncertainties in the magnitude of LUC forcing (De Noblet-Ducoudré *et al* 2012, Brovkin *et al* 2013, Pitman *et al* 2009), and other models which equally, or preferentially convert forest to cropland, may see higher biogeophysical and biogeochemical impacts, and may simulate the balance between them differently. It should also be noted that the land carbon changes from LUC are different between models by as much as an order of magnitude, and that HadGEM2-ES has some of the smallest land carbon changes due to LUC (Brovkin *et al* 2013).

The net result of the combined biogeophysical and biogeochemical LUC effect is warming in all the RCPs considered here (figure 2(b)) despite differing signs of change in agricultural area (figure 1(a)). The net LUC global impact is very small in RCP2.6 and RCP8.5 (+0.01 K and +0.003 K respectively) and inside of the variability. For these two scenarios, the LUC effect is dominated by the biogeochemical effect of the tropical carbon emissions from deforestation for agricultural land. In RCP4.5 the net global impact is about three to five times larger (+0.11 K) than would be expected if the temperature sensitivity to LUC were the same as RCP2.6

and RCP8.5, and is outside of the expected variability. However, all the changes in temperature are small compared to the overall climate change by 2100. The increased temperature sensitivity seen in RCP4.5 originates from the strong biogeophysical effects which mean that the biogeophysical warming is larger than the cooling from the carbon sequestered by the afforestation. The LUC in this ESM is actually quite conservative because of a low number of plant functional types in the model (meaning less changes than models where plant functional types are further distinguished), and a relatively slow regrowth time for trees. This is particularly true for RCP4.5, as shown by the much smaller tree cover change in the ESM simulation of trees than in the Integrated Assessment Model simulation. The Integrated Assessment Model that created the original RCP4.5 scenario for the CMIP5 simulations also calculates the change in tree cover, (not used in the ESM in these simulations) as well as the change in agricultural fraction (used by the ESM in these simulations) and assumes faster tree growth than the dynamic vegetation component of HadGEM2-ES. The tree cover change for RCP4.5 in HadGEM2-ES is less than half of the amount by the Integrated Assessment Model simulation (which has a 24% increase in tree cover) (Di Vittorio *et al* 2014). If the model used the land cover change directly from the integrated assessment model, this differential in LUC between the RCP scenarios could potentially be even larger. Overall, this suggests that the net effect of LUC in the RCPs is likely to be dependent on the balance of biogeophysical and biogeochemical impacts at particular latitudes, rather than LUC scenario itself.

4. Discussion and conclusions

The small net warming from LUC in RCP4.5 found here potentially makes it a perverse incentive with regards to climate. The afforestation in RCP4.5 is the result of a universal carbon tax, which counts land carbon emissions towards a country's carbon emission budgets and results in afforestation. In the absence of a universal carbon tax, there is considerably more deforestation, especially in the tropics, (which has its own climatic implications, see for instance, Jones *et al* 2012, Davies-Barnard *et al* 2014). The intention of this policy is to cost-effectively mitigate warming by sequestering carbon via afforestation (Strengers *et al* 2008) and prevent the loss of forest carbon, especially tropical forest (Thomson *et al* 2010, 2011). Instead, the LUC in RCP4.5 may have the opposite effect, enhancing the warming because of the large biogeophysical effect from mid latitude afforestation. Hence the incentive (gaining carbon credits) for afforestation may be perverse (it has the opposite effect to that intended, because instead of mitigating climate change the afforestation contributes to global temperature increase). However, the avoided tropical deforestation in RCP4.5 would have major benefits in terms of preserving primary tropical forest and biodiversity (Gibson *et al* 2011, Thomson *et al* 2010, Powell and Lenton 2013). A spatially differentiated tax might be more appropriate, which did not incentivize mid–high latitude afforestation, thereby avoiding the strongest warming effects. The land carbon tax could also be reposed as an environmental tax, avoiding the sole focus on climate change. A small, uncertain, projected increase in temperature from afforestation should be balanced against the more definite benefits a universal carbon tax could offer by retaining and extending forests, such as maintaining ecosystem services (Chiabai *et al* 2011, Gilroy *et al* 2014).

Our work highlights that LUC in the RCPs is not only variable between the different projections, but that the temperature effect from LUC also varies significantly. This has considerable implications for Integrated Assessment Models that create the RCP scenarios (Van Vuuren *et al* 2011). They urgently need to include some representation of the biogeophysical effects. Whereas carbon emissions are well mixed in the atmosphere, giving them a global impact, biogeophysical effects are much more locally focused. Therefore the more important effects from LUC are likely to be regional scale, especially in mid–high latitude areas of afforestation. However, as shown here, the biogeophysical effects of LUC can still affect the global climate in the RCPs. This is particularly the case for higher latitude land cover changes for which sea ice feedbacks may lead to disproportionately more temperature change per unit area of LUC. The implication of these strong biogeophysical LUC effects is that neither the total net emissions nor the scale of the LUC are good indicators of the resultant temperature change from LUC in the RCPs. The latitude of the LUC may be a better determinant of the LUC effect on temperature, with higher latitude changes resulting in larger local and global changes. Use of Integrated Assessment Models in collaboration with spatially resolved, process-based ESMs is required to more reliably assess the complex implications of future land use policies.

Acknowledgements

We acknowledge funding from the Joint DECC/DEFRA Met Office Hadley Centre Climate Program (GA01101); the Natural Environment Research Council Dtg (NE/J500033/1); and the European Commission's 7th Framework Program Grant Agreement 282672 (EMBRACE). Thank you to the anonymous reviewers, who improved the paper with their comments.

References

Bonan G B 2008 Forests and climate change: forcings, feedbacks, and the climate benefits of forests *Science* **320** 1444–9

Bonan G B, Pollard D and Thompson S L 1992 Effects of boreal forest vegetation on global climate *Nature* **359** 716–8

Brovkin V *et al* 2013 Effect of anthropogenic land-use and land-cover changes on climate and land carbon storage in CMIP5 projections for the twenty-first century *J. Clim.* **26** 6859–81

Chiabai A, Travisi C M, Markandya A, Ding H and Nunes P A L D 2011 Economic assessment of forest ecosystem services losses: cost of policy inaction *Environ. Resour. Econ.* **50** 405–45

Claussen M, Brovkin V and Ganopolski A 2001 Biogeophysical versus biogeochemical feedbacks of large-scale land cover change *Geophys. Res. Lett.* **28** 1011–4

Collins W J *et al* 2011 Development and evaluation of an Earth-system model—HadGEM2 *Geosci. Model Dev.* **4** 1051–75

Cox P M 2001 Description of the TRIFFID dynamic global vegetation model *Hadley Cent. Tech. Note* **24** 1–16

Davies-Barnard T, Valdes P J, Singarayer J S and Jones C D 2014 Climatic impacts of land-use change due to crop yield increases and a universal carbon tax from a scenario model *J. Clim.* **27** 1413–24

De Noblet-Ducoudré N *et al* 2012 Determining robust impacts of land-use-induced land cover changes on surface climate over north america and eurasia: results from the first set of LUCID experiments *J. Clim.* **25** 3261–81

Di Vittorio A V *et al* 2014 From land use to land cover: restoring the afforestation signal in a coupled integrated assessment—earth system model and the implications for CMIP5 RCP simulations *Biogeosci. Discuss.* **11** 7151–88

Essery R, Best M and Cox P 2001 MOSES 2.2 technical documentation (Hadley Centre Technical Note) Online: (http://biodav.atmos.colostate.edu/kraus/Papers/Biosphere%20Models/HCTN_30.pdf)

Gibson L *et al* 2011 Primary forests are irreplaceable for sustaining tropical biodiversity *Nature* **478** 378–81

Gillett N P, Arora V K, Matthews D and Allen M R 2013 Constraining the ratio of global warming to cumulative CO_2 emissions using CMIP5 simulations *J. Clim.* **26** 6844–58

Gilroy J J, Woodcock P, Edwards F A, Wheeler C, Baptiste B L G, Medina Uribe C A, Haugaasen T and Edwards D P 2014 Cheap carbon and biodiversity co-benefits from forest regeneration in a hotspot of endemism *Nat. Clim. Change* **4** 503–7

Govindasamy B, Duffy P B and Caldeira K 2001 Land use changes and northern hemisphere cooling *Geophys. Res. Lett.* **28** 291–4

Hallgren W, Schlosser C A, Monier E, Kicklighter D, Sokolov A and Melillo J 2013 Climate impacts of a large-scale biofuels expansion *Geophys. Res. Lett.* **40** 1624–30

Hurtt G *et al* 2011 Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands *Clim. Change* **109** 117–61

Jones A D *et al* 2012 Greenhouse gas policy influences climate via direct effects of land-use change *J. Clim.* **26** 3657–70

Jones C D *et al* 2011 The HadGEM2-ES implementation of CMIP5 centennial simulations *Geosci. Model Dev.* **4** 543–70

Jones C, McConnell C, Coleman K, Cox P, Falloon P, Jenkinson D and Powlson D 2005 Global climate change and soil carbon stocks; predictions from two contrasting models for the turnover of organic carbon in soil *Glob. Change Biol.* **11** 154–66

Martin G M *et al* 2011 The HadGEM2 family of met office unified model climate configurations *Geosci. Model Dev.* **4** 723–57

Martin G M, Ringer M A, Pope V D, Jones A, Dearden C and Hinton T J 2006 The physical properties of the atmosphere in the new hadley centre global environmental model (HadGEM1): I. Model description and global climatology *J. Clim.* **19** 1274–301

Matthews H D, Weaver A J, Meissner K J, Gillett N P and Eby M 2004 Natural and anthropogenic climate change: incorporating historical land cover change, vegetation dynamics and the global carbon cycle *Clim. Dyn.* **22** 461–79

Meinshausen M *et al* 2011 The RCP greenhouse gas concentrations and their extensions from 1765 to 2300 *Clim. Change* **109** 213–41

Pitman A J *et al* 2009 Uncertainties in climate responses to past land cover change: first results from the LUCID intercomparison study *Geophys. Res. Lett.* **36** L14814

Pongratz J, Reick C H, Raddatz T and Claussen M 2010 Biogeophysical versus biogeochemical climate response to historical anthropogenic land cover change *Geophys. Res. Lett.* **37** L08702

Powell T W R and Lenton T M 2013 Scenarios for future biodiversity loss due to multiple drivers reveal conflict between mitigating climate change and preserving biodiversity *Environ. Res. Lett.* **8** 025024

Rogers B M, Randerson J T and Bonan G B 2013 High-latitude cooling associated with landscape changes from North American boreal forest fires *Biogeosciences* **10** 699–718

Strengers B J, Minnen J G V and Eickhout B 2008 The role of carbon plantations in mitigating climate change: potentials and costs *Clim. Change* **88** 343–66

Thomson A M *et al* 2011 RCP4.5: A pathway for stabilization of radiative forcing by 2100 *Clim. Change* **109** 77–94

Thomson A M, Calvin K V, Chini L P, Hurtt G, Edmonds J A, Bond-Lamberty B, Frolking S, Wise M A and Janetos A C 2010 Climate mitigation and the future of tropical landscapes *Proc. Natl. Acad. Sci.* **107** 19633–8

Van Vuuren D *et al* 2011 The representative concentration pathways: an overview *Clim. Change* **109** 5–31