

Assessing the implications of human land-use change for the transient climate response to cumulative carbon emissions

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Assessing the implications of human land-use change for the transient climate response to cumulative carbon emissions

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Abstract

Recent research has shown evidence of a linear climate response to cumulative CO₂ emissions, which implies that the source, timing, and amount of emissions does not significantly influence the climate response per unit emission. Furthermore, these analyses have generally assumed that the climate response to land-use CO₂ emissions is equivalent to that of fossil fuels under the assumption that, once in the atmosphere, the radiative forcing induced by CO₂ is not sensitive to the emissions source. However, land-cover change also affects surface albedo and the strength of terrestrial carbon sinks, both of which have an additional climate effect. In this study, we use a coupled climate-carbon cycle model to assess the climate response to historical and future cumulative land-use CO₂ emissions, in order to compare it to the response to fossil fuel CO₂. We find that when we isolate the CO₂-induced (biogeochemical) temperature changes associated with land-use change, then the climate response to cumulative land-use emissions is equivalent to that of fossil fuel CO₂. We show further that the globally-averaged albedo-induced biophysical cooling from land-use change is non-negligible and may be of comparable magnitude to the biogeochemical warming, with the result that the net climate response to land-use change is substantially different from a linear response to cumulative emissions. However, our new simulations suggest that the biophysical cooling from land-use change follows its own independent (negative) linear response to cumulative net land-use CO₂ emissions, which may provide a useful scaling factor for certain applications when evaluating the full transient climate response to emissions.

1. Introduction

The transient climate response to cumulative carbon emissions (or TCRE), defines the global temperature response to cumulative emissions of CO₂ (Matthews *et al* 2009, Gillett *et al* 2013) and has been identified as a useful and practical tool for evaluating CO₂-induced climate changes (Collins *et al* 2013). While Earth system models may have large uncertainties when representing specific physical processes that have an impact on temperature, most of these models consistently demonstrate a linear temperature response to cumulative emissions. Sensitivity simulations further suggest that a constant TCRE value (constant linear slope) can reasonably represent the climate effect of cumulative emissions over a wide range of emission scenarios for a single model (e.g., Leduc *et al* 2015).

Furthermore, the TCRE remains relatively constant as models evolve over time (Allen *et al* 2009, Matthews *et al* 2009). While the TCRE linearity is robust, most climate models also show that the temperature sensitivity to cumulative emissions decreases under very high emissions scenarios (Allen *et al* 2009), due in part to the radiative band saturation for certain wavelengths for very high atmospheric CO₂ concentrations. Nevertheless, due to its simplicity and relative independence to the emissions scenario, the TCRE relationship has become a measure for defining policy initiatives for CO₂ mitigation (Meinshausen *et al* 2009, Zickfeld *et al* 2009, Raupach *et al* 2011, Matthews *et al* 2012).

An important component of total anthropogenic CO₂ emissions are emissions from land use change (LUC), which represent a substantial fraction of the

total historical emissions. Land use emissions have the complicating effect of changes in the albedo of land surface, as well as other effects of changing vegetation types, which can have additional impacts on the climate response to land-use change (Pongratz *et al* 2010). Most research on TCRE to this point assesses climate response with combined fossil fuel and land use emissions, without addressing the spatial interaction of the biosphere to albedo-induced temperature changes from LUC. However, many studies have shown that the biophysical effects of land-use change are an important contributor to historical climate changes (Brovkin *et al* 2006, Eby *et al* 2013) and are also relevant to capturing the climate response to future changes in land-use (Davies-Barnard *et al* 2014).

It is therefore important to carefully assess the climate response to cumulative LUC CO₂ emissions within the context of land surface changes. The objective of this study is to evaluate the influence of spatially-explicit LUC on the TCRE, including both the historical period and future RCP scenarios. We use a suite of simulations of the University of Victoria Earth System Climate Model (UVic ESCM) to isolate both the biogeochemical (the CO₂ radiative warming from land use CO₂ emissions) and biophysical (land-surface changes from agriculture and pasture affecting surface albedo, roughness, and energy balance) components of temperature change, in order to evaluate the full range of impacts of LUC on the transient temperature evolution.

2. Methods

2.1. Model description

The simulations in this paper were performed using the UVic ESCM v. 2.9 (Weaver *et al* 2001, Eby *et al* 2009). The UVic model is classified as an Earth system model of intermediate complexity (Claussen *et al* 2002), providing a simplified mathematical representation of the climate system that is useful for studying paleoclimates and assessing potential future climate changes, such as under 21st-century representative concentration pathway (RCP) scenarios for the latest Intergovernmental Panel on Climate Change (IPCC) report (Eby *et al* 2013). The UVic ESCM operates all model components on a resolution of 1.8° latitude by 3.6° longitude. These include a one-layer (2D) energy-moisture balance model (Weaver *et al* 2001) to calculate atmospheric surface air temperature and humidity, with prescribed winds controlling atmospheric advection and wind stress on the ocean surface. The model ocean is a 3D general circulation model with 19 vertical layers, incorporating inorganic carbon (Ewen *et al* 2004), organic carbon and nutrient cycling (Schmittner *et al* 2008) and ocean sediments (Eby *et al* 2009), coupled to a dynamic-thermodynamic sea ice module (Weaver *et al* 2001).

The terrestrial biosphere component of the UVic ESCM is dynamically represented by the top-down representation of interactive foliage and flora including dynamics (TRIFFID) model, coupled to the one-layer MOSES soil model where vegetation litter is stored and respired (Meissner *et al* 2003). TRIFFID represents five different plant functional types (PFTs): broadleaf trees, needleleaf trees, C3 grasses, C4 grasses, and shrubs. Each PFT uniquely affects the roughness and albedo of the land surface as well as carbon uptake from the atmosphere and transfer to the soil layer. Terrestrial sequestration in the UVic model (Matthews 2007, Pinsonneault *et al* 2011) is enhanced by higher atmospheric CO₂ concentrations. However, the coupling of the nitrogen and carbon cycles is not represented. Agricultural LUC is implemented in the model (as discussed in section 2.2 below) by removing tree and shrub PFTs in the land use fraction of each grid cell and allowing C3 and C4 grasses to grow in their place. In regions designated as pasture areas, 50% of the existing tree or shrubs cover is removed for replacement by grasses. In grid cells where C3 and C4 grasses already predominate, LUC leads to no change in PFT biomass or fractional coverage. In the version of the model used in this paper, 30% of the removed vegetation carbon due to LUC is transferred directly to the soil carbon pool in the form of litter-fall. The remaining 70% is then distributed between direct emissions to the atmosphere (30%), and intermediate storage in two additional wood carbon pools with varying residence times: a fast-respiring wood pool (20% of harvested carbon; 2 year residence time), and a slow-respiring wood pool (50% of harvested carbon; 20 year residence time), based on the book-keeping approach described in (Strassmann *et al* 2008).

2.2. Experimental setup

The model experiments in this paper explore the respective contributions of spatially-explicit LUC and fossil fuel emissions to the total TCRE. The LUC data for the period from 1750 to 2005 used here is based on the HYDE 3.1 data set (Klein Goldewijk *et al* 2011) interpolated to the UVic model resolution, with any resulting land use fractions over the model's ocean grid cells removed rather than redistributed to nearby land grid cells. For the period from 2005 to 2100, LUC data for the RCP scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) are taken from pastoral and agricultural land use fractions used in the EMIC model intercomparison report for the IPCC (Eby *et al* 2013). Annual fossil fuel emission data from the historical period (1750–2005) were obtained from the Carbon Dioxide Information Analysis Centre (Boden *et al* 2013), and harmonized fossil fuel CO₂ emissions for different RCP scenarios for the 2005–2100 period were prescribed from (Meinshausen *et al* 2011).

The model was spun up to equilibrium conditions with year 1750 CO₂ concentration (279 ppmv) and

Table 1. A summary of the transient (time-evolving) simulations presented or used for calculations in this study. ‘Spatial land use’ refers to the application of spatial HYDE 3.1 data in the model, whereas ‘prescribed emissions’ denotes CO₂ emissions released directly to the atmosphere from an emissions data file (in which yearly prescribed emissions are released directly to the model atmosphere). Prescribed CO₂ refers to simulations with a prescribed, time-evolving atmospheric carbon content, in which atmospheric CO₂ is forced to follow a specified CO₂ concentration trend (to which the model’s other carbon reservoirs respond).

	Spatial land use	Prescribed emissions	Prescribed CO ₂
CTRL	Fixed 1750 A.D. config.	None	None
FF	Fixed 1750 A.D. config.	Fossil fuels	None
LUC	Time-dependent	None	None
LUC + FF	Time-dependent	Fossil fuels	None
EMIT	Fixed 1750 A.D. config.	Total LUC + FF emissions	None
PC(LUC)	Fixed 1750 A.D. config.	None	CO ₂ from LUC
PC(LUC + FF)	Fixed 1750 A.D. config.	None	CO ₂ from LUC + FF

Table 2. Calculations for global net cumulative emissions, geochemical temperature change (ΔT_{GC}), and biophysical temperature change (ΔT_{BP}). In the formulae provided in this table, T denotes annual-average surface air temperature and TC annual-average global terrestrial carbon content, with subscripts indicating the source simulation by its identifying abbreviation from table 1.

Cumulative emissions and net temperature response (ΔT) to emissions			
	Cumulative emissions	Geochemical effect (ΔT_{GC})	Biophysical effect (ΔT_{BP})
LUC-only	$TC_{PC(LUC)} - TC_{LUC}$	$T_{PC(LUC)} - T_{CTRL}$	$T_{LUC} - T_{PC(LUC)}$
FF-only	FF (prescribed)	$T_{FF} - T_{CTRL}$	None
LUC emissions in LUC + FF	$TC_{PC(LUC+FF)} - TC_{LUC+FF}$	$T_{PC(LUC+FF)} - T_{FF}$	$T_{LUC+FF} - T_{PC(LUC+FF)}$
Total emissions in LUC + FF	$TC_{PC(LUC+FF)} - TC_{LUC+FF} + FF$	$T_{PC(LUC+FF)} - T_{CTRL}$	$T_{LUC+FF} - T_{PC(LUC+FF)}$
EMIT	$TC_{PC(LUC+FF)} - TC_{LUC+FF} + FF$	$T_{PC(LUC+FF)} - T_{CTRL}$	None

spatial land cover for the year 1750 based on spatial land use data from HYDE 3.1, which we then used as the initial condition for time-evolving simulations from 1750 to 2100. These transient experiments, summarized in table 1, use either prescribed fossil fuel emissions and/or spatial LUC data as forcing mechanisms. In addition to a control simulation (CTRL) with no external forcing (no fossil fuel emissions and no change in the land use data from the 1750 distribution), transient simulations were run with only LUC forcing (LUC, or LUC-only), with only fossil fuel forcing (FF), and with the LUC and FF forcing applied together (LUC + FF).

We also performed additional simulations with prescribed atmospheric carbon content (PC) to calculate the climate response to the biogeochemical-only and biophysical-only effects of terrestrial emissions. The first of these (PC(LUC) in table 1) is a simulation in which atmospheric CO₂ concentrations simulated by the LUC experiment were prescribed to a second simulation, but this time holding land-use distributions constant at the year 1750 configuration. The second (PC(LUC + FF) in table 1) is a comparable simulation but with prescribed CO₂ concentrations taken from the LUC + FF simulation. Finally we prescribed the net CO₂ emissions from LUC + FF diagnosed to a final simulation (EMIT in table 1) to represent the effect of externally-prescribed land-use CO₂ emissions without the corresponding changing spatial land-cover change. Each of these simulations was performed for the historical period, as well as for each future RCP emission scenario.

Table 2 summarized the method we used to diagnose the net terrestrial CO₂ emissions from LUC, as well as the individual (bio)geochemical and biophysical effects of LUC. In order to capture both the direct LUC CO₂ emissions and their influence on global vegetation cover, we calculated as the difference in total terrestrial carbon between the PC simulations and the respective simulation with spatially-varying LUC. The results from the PC(LUC) (PC(LUC + FF)) simulation diagnoses the global potential natural vegetation distribution (which, in turn, influences planetary albedo, surface temperature, vegetation coverage, and the strength of the terrestrial carbon sink) in response to the atmosphere CO₂ concentrations obtained in the LUC (LUC + FF) simulation, respectively. As PC(LUC) and LUC (or PC(LUC + FF) and LUC + FF) have the same atmospheric CO₂ concentrations, the difference in the terrestrial carbon storage between these pairs of simulations captures the net effect of spatially-explicit land use on terrestrial carbon storage. These ‘net terrestrial emissions’ therefore include both the direct CO₂ emissions to the atmosphere from land-use change (agriculture and pasture), the atmospheric CO₂ sequestered by the natural potential vegetation (in the PC simulations) in LUC-affected regions, as well as the change in terrestrial carbon storage elsewhere due to terrestrial sequestration and expansions/shifts in vegetation cover attributable to temperature differences between LUC and PC(LUC) (or LUC + FF and PC(LUC + FF)). In general, afforestation reduces the net terrestrial (LUC) emissions reported here, whereas

deforestation (for crops, pasture, and natural die-off) increases these emission totals for a given simulation year. These net emissions resulting (directly and indirectly) from the inclusion of spatial, time-evolving LUC in the model (as calculated in table 2) are described as ‘net terrestrial emissions’ in the results section and ‘LUC emissions’ in figure captions of this paper for the sake of simplicity.

The biogeochemical (BGC) effect (i.e., the CO₂ radiative warming) of these net terrestrial emissions can be calculated as the simulated temperature difference between the two PC simulations (PC(LUC) and PC(LUC + FF)) and the corresponding simulation without any land-use change (CTRL and FF respectively). The total geochemical (GC) effect presented in the results includes the biogeochemical effect (i.e., the CO₂ radiative warming due to net terrestrial emissions alone) in addition to the radiative warming from fossil fuels. Finally the biophysical (BP) effect of land-use changes can be calculated as the difference between the temperature change simulated by the LUC and LUC + FF simulations and the respective PC simulations.

3. Results and discussion

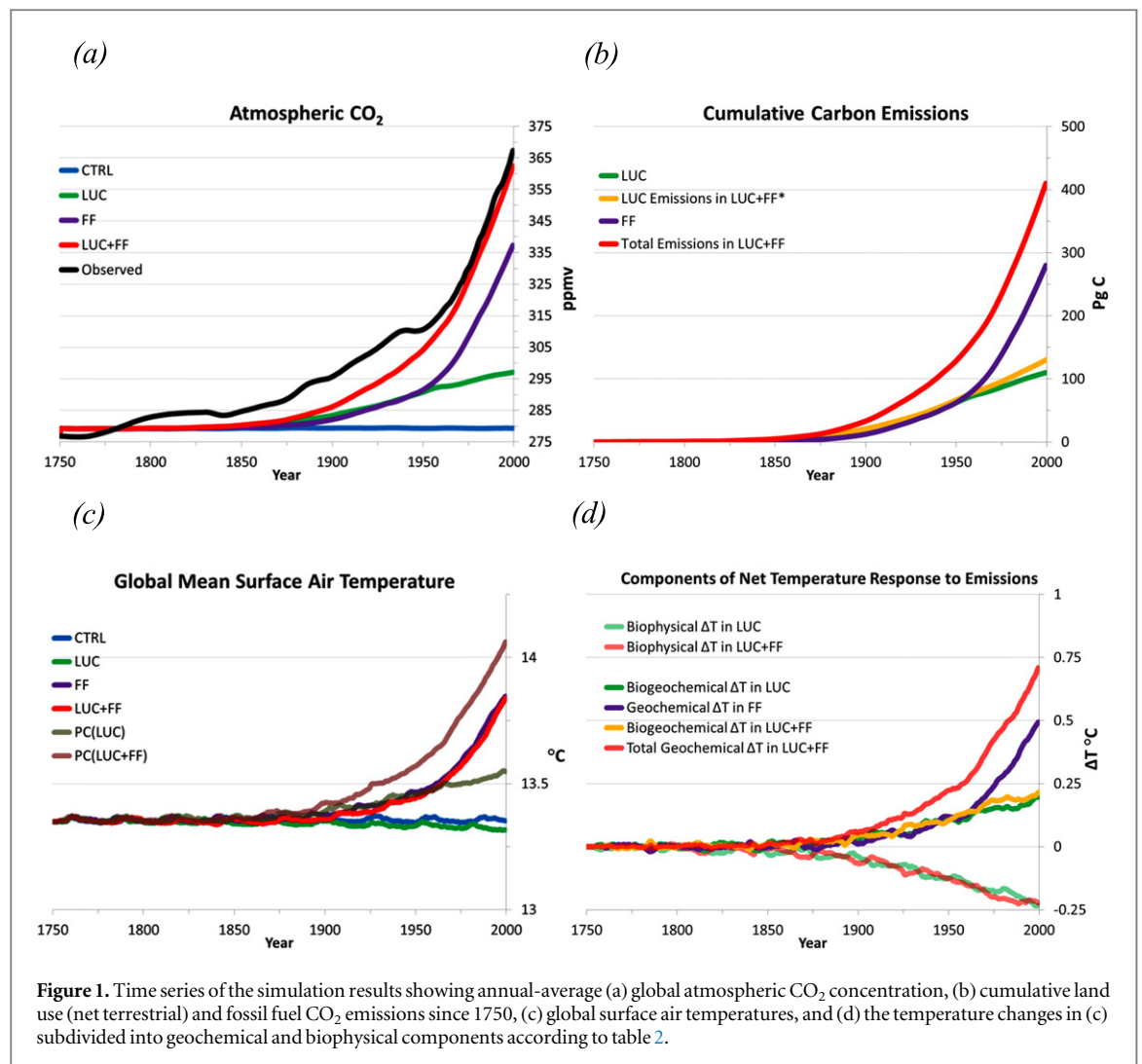
3.1. The historical period: 1750–2000

The results for the 1750–2000 period are presented separately from the RCP scenarios, as this ‘historical’ period represents a shift in the dominant emissions source from LUC to fossil fuels (whereas the RCP emissions are largely dominated by fossil fuels). Figure 1(a) shows the evolution of atmospheric CO₂ during this period, and figure 1(b) provides the cumulative emissions (net terrestrial emissions + fossil fuel emissions) for each simulation. Land use alone (LUC) generated cumulative CO₂ emissions of 110 Pg C, which resulted in an 18 ppm increase in atmospheric CO₂ by the year 2000. Cumulative fossil fuel emissions were 280 Pg C, which by themselves produced a 58 ppm increase, and both land use and fossil fuels together (LUC + FF) produced emissions of 410 Pg C, which led to an 84 ppm increase. An interesting feature of these results is that the sum of emissions from the LUC and FF simulations was smaller than the net emissions in LUC + FF, which results from slightly higher (20 Pg C) cumulative land-use emissions in the LUC + FF simulation as compared to LUC alone (compare the yellow and green lines in figure 1(b)). This reflects an enhancement of simulated LUC emissions associated with higher CO₂ in the LUC + FF simulation; the stronger CO₂ fertilization of the terrestrial biosphere in LUC + FF (as compared to LUC) resulted in the presence of more overall vegetation carbon in the model, which then led to higher net terrestrial emissions when this carbon was removed due to changing land-use distributions.

The LUC + FF simulation reproduces the observed atmospheric CO₂ trend after 1950 reasonably well, though, as with many other models, noticeably underestimates the observed CO₂ increase (by 5–10 ppm) during the late 19th and early 20th centuries. This may be associated with the result that annual net terrestrial emissions values (not shown) obtained in the UVic ESCM from the spatially-explicit LUC are significantly less than annual harmonized LUC emissions estimates (e.g., Meinshausen *et al* 2011) for this period. Low early LUC emissions may be related to the equal treatment of croplands and natural grasses in the model—agriculture and pasture fractions in areas already dominated by bare ground or grasses lead to no change in PFT distribution or biomass in the model (such as for the North American prairies). In addition, the lower-than-observed atmospheric CO₂ values may also be related to a variety of interrelated natural and anthropogenic factors, including (for example) the strength of the model’s ocean carbon sink, the simulated pre-industrial vegetation distribution, an underestimation of per capita land-use for the earlier period in the HYDE 3.1. dataset (Kaplan *et al* 2011), and the omission of a faster soil carbon cycling to the atmosphere in agricultural regions due to tillage (e.g., Stocker *et al* 2011).

The temperature response to the modeled CO₂ changes and human land use are plotted in figure 1(c), which includes the simulations with prescribed atmospheric CO₂ that are used to isolate the biochemical and biophysical temperature changes shown in figure 1(d). The common assumption that CO₂ (once in the atmosphere) leads to a certain radiative warming regardless of the emissions source is represented by the temperature trend from PC(LUC + FF). However, the biophysical effects of land-use change are evident in the divergence in the temperature response between PC(LUC + FF) and LUC + FF, beginning relatively early in the simulation period (~1850). The divergence stops increasing after 1960, when the effect of fossil fuel emissions begins to dominate the overall temperature change in the simulation (as shown by the point at which cumulative FF emissions overtake those from LUC: figure 1(b), yellow line versus purple line).

The importance of albedo changes in determining the temperature response to emissions is further illustrated in the LUC case, where, despite an 18 ppm atmospheric CO₂ increase (figure 1(a), green line), global temperatures decreased slightly over the course of the simulation (figure 1(c), green line). Similarly, in spite of the significantly greater emissions (figure 1(b), red line) and higher atmospheric CO₂ (figure 1(a), red line) in the LUC + FF scenario as compared to the FF case, the actual temperature increase produced in the LUC + FF simulation is slightly less than in the FF scenario (figure 1(c), red line versus purple line). This means that in these simulations the biophysical effect of land-use changes over the historical period are slightly larger than the biogeochemical effect of land-



use CO₂ emissions. This can be seen in figure 1(d), which shows biophysical LUC temperature change of -0.24 °C between 1750 and 2000 for both the LUC and LUC + FF scenarios. By comparison, the biogeochemical effect of net terrestrial emissions was a warming of 0.2 °C in the LUC simulation, and 0.22 °C in LUC + FF, reflecting the slightly higher land-use CO₂ emissions in LUC + FF compared to LUC. This estimate of the biophysical effect of land-use change is comparable to the value produced by a recent inter-comparison of 12 EMICs (Eby *et al* 2013), though is slightly larger than that simulated by an earlier version of the UVic model using a different land-use database (Matthews *et al* 2004).

We now assess the climate response to cumulative emissions in these simulations to determine to what extent the TCRE is a useful metric of the climate response to land-use CO₂ emissions. The overall temperature response to cumulative fossil fuel and land-use change (including both the biophysical and biogeochemical land-use effects) for the UVic ESCM 2.9 is shown in figure 2(a). As shown previously (Matthews *et al* 2009, Leduc *et al* 2015), there is a clear linear temperature response in this model to cumulative

FF emissions, as well as to externally-prescribed FF and land-use emissions in the EMIT simulation. The TCRE of this version of the UVic ESCM (1.72 °C/TtC in the EMIT simulation of this study; see table 3) falls near the median of the range of values (0.8 – 2.4 °C/TtC) across other Earth-system models (Matthews *et al* 2009, their figure 2 and supplementary table 1; Gillett *et al* 2013, Leduc *et al* 2015).

However, the net temperature response to spatially-explicit LUC is notably different. As expected from the temperature changes in figure 1, the net response to cumulative land-use emissions (green and yellow lines in figure 2(a)) follows a slight negative slope, reflecting the higher biophysical compared to biogeochemical effects in these simulations shown in figure 1(d). Consequently, the combined response to both fossil fuel and land-use emissions (LUC + FF; red line) shows a nonlinear relationship between the net temperature change and cumulative emissions, with an initially lower rate of warming, followed by an increased temperature response to increasing cumulative emissions. The lower initial temperature response reflects the earlier historical period when LUC-sources of CO₂ (and associated biophysical cooling)

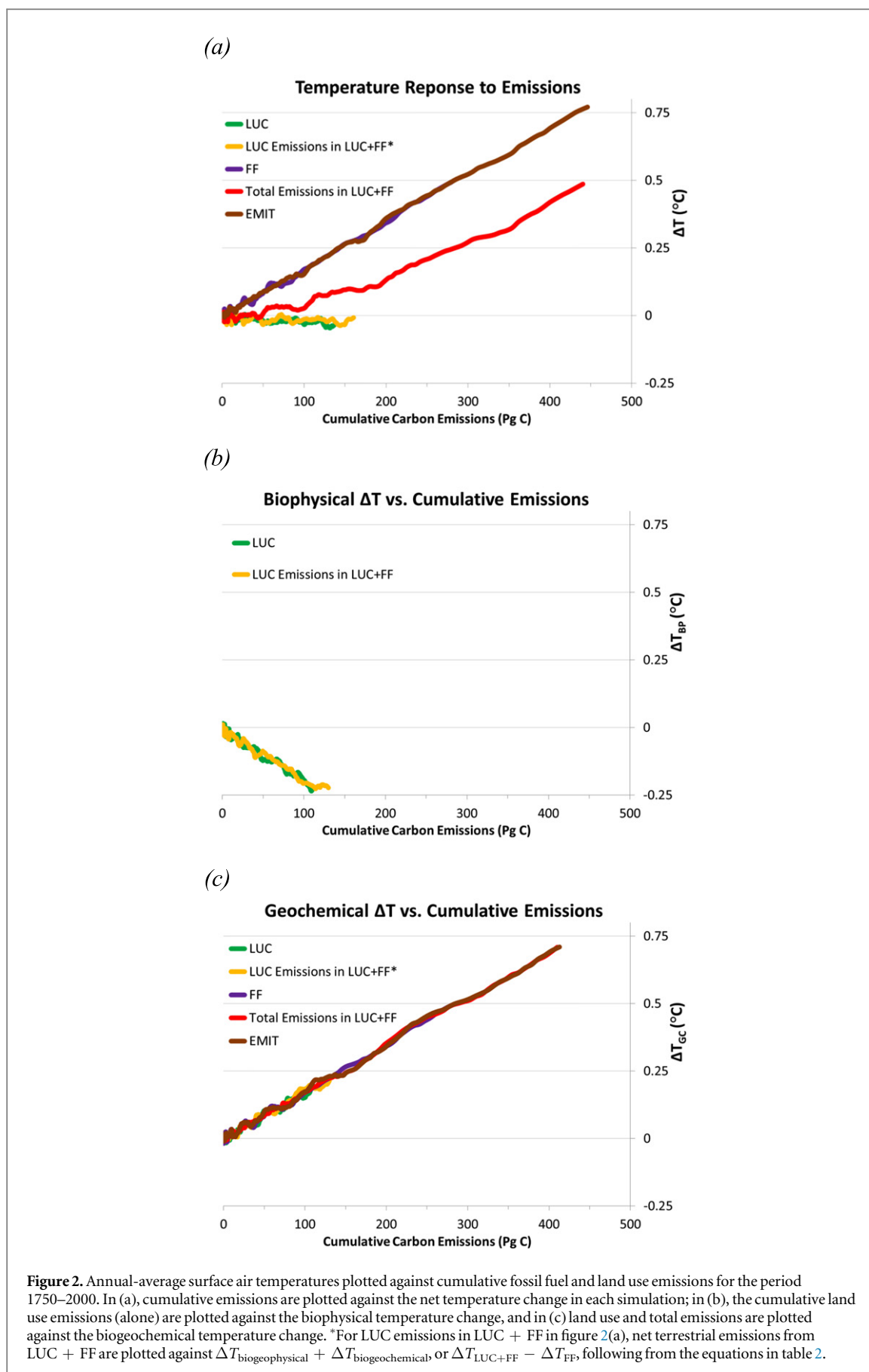


Table 3. The linear slopes of the curves represented in figure 2, with the linear correlation coefficient provided in parentheses. The slopes represent the line of best fit passing through the point (0, 0), i.e., zero emissions associated with no temperature change.

Linear slope of transient climate response to emissions ($^{\circ}\text{C}/\text{Tt C}$) for 1750–2000			
	Total ΔT	Geochemical ΔT	Biophysical ΔT
LUC-only	-0.35 ($r^2 = 0.511$)	$+1.67$ ($r^2 = 0.975$)	-2.02 ($r^2 = 0.972$)
LUC emissions in LUC + FF ^a	-0.22 ($r^2 = 0.113$)	$+1.71$ ($r^2 = 0.984$)	-1.93 ($r^2 = 0.974$)
Total emissions in LUC + FF	$+0.98$ ($r^2 = 0.950$)	$+1.72$ ($r^2 = 0.999$)	—
FF-only	$+1.73$ ($r^2 = 0.994$)	$+1.73$ ($r^2 = 0.994$)	—
EMIT	$+1.72$ ($r^2 = 0.997$)	$+1.72$ ($r^2 = 0.997$)	—

^a For LUC emissions in LUC + FF, the Total $\Delta T = \Delta T_{\text{BP}} + \Delta T_{\text{BGC}}$, which reduces to $T_{\text{LUC+FF}} - T_{\text{FF}}$ following from the equations in table 2.

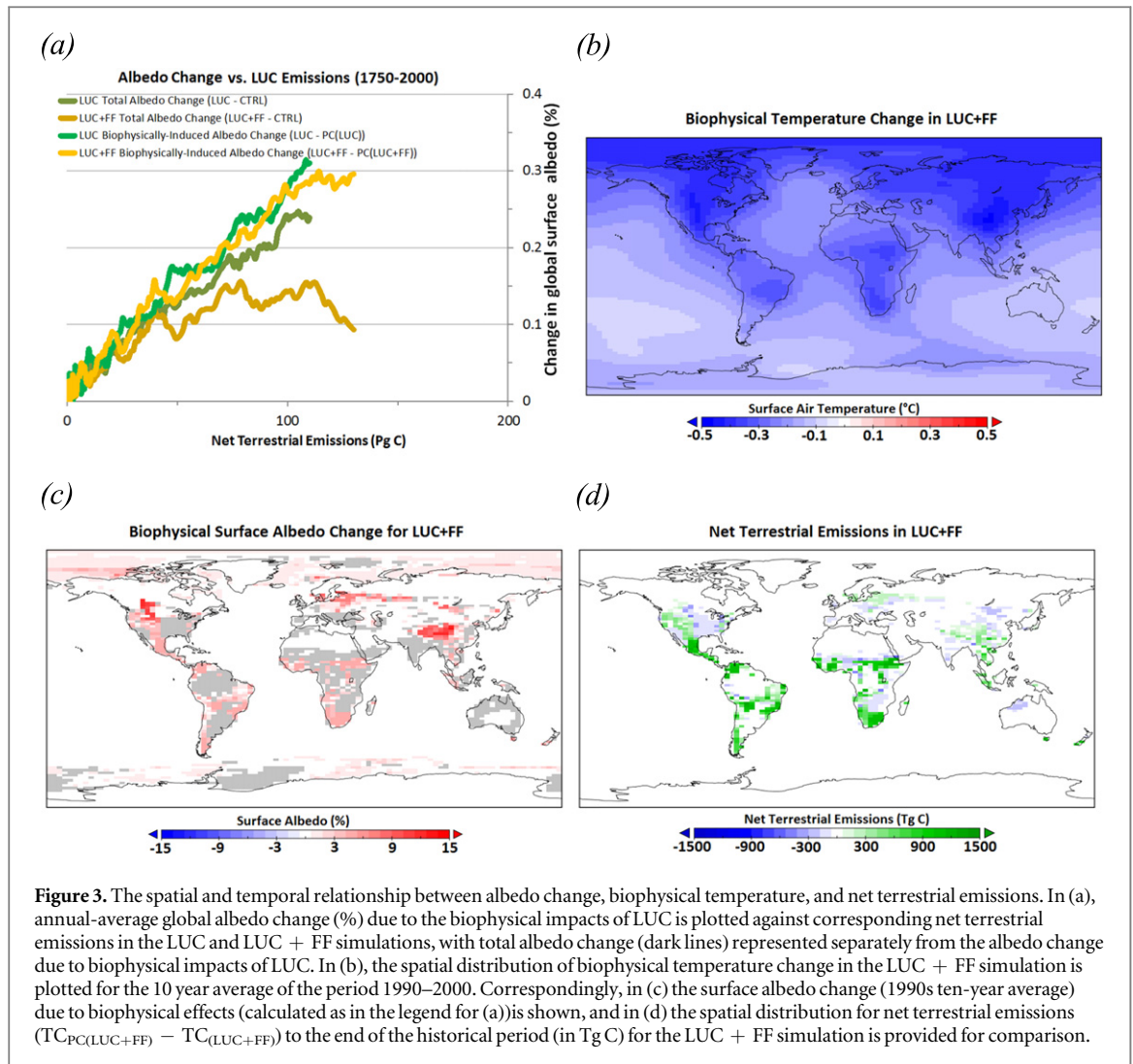
predominate, whereas the larger temperature response emerges with increasing fossil fuel contribution to the total emissions. Thus, the red line (LUC + FF) tracks closer to the green and yellow lines for low emissions values and more closely parallels the purple and brown lines for higher emissions where fossil fuel CO_2 emissions predominate, leading to poorer overall linearity (table 3). By the year 2000, while the slopes of the red (FF + LUC) and brown (EMIT) temperature curves are similar, the overall warming in FF + LUC remains about 30% smaller than when LUC emissions were prescribed externally.

However, despite the very different overall temperature response to land-use CO_2 and fossil fuel CO_2 emissions, figures 2(b) and (c) show that both the isolated biophysical and biogeochemical effects of land-use change can be linearly related to cumulative land-use CO_2 emissions. The net biogeochemical effect of land-use CO_2 emissions (figure 2(c)) follows a positive linear response to cumulative emissions, which is also nearly equivalent to the geochemical warming from fossil fuel CO_2 (table 3). This suggests that the TCRE for fossil fuel emissions can be readily applied to the biogeochemical effect of cumulative land-use emissions.

With respect to the biophysical temperature change (figure 2(b)), despite some variations, land use emissions follow similar negative slopes (table 3) in LUC and LUC + FF for the historical period (i.e., increasing emissions are associated with larger biophysical temperature decreases). While biophysical temperature changes are influenced by roughness length, evapotranspiration, and other modifications of the Earth's surface due to ecosystem conversion, figure 3(a) suggests that the linear relationship between biophysical temperature and land use emissions is dominated by surface albedo changes in both the LUC and LUC + FF simulations. Though total albedo change in both simulations is increasingly influenced by the effects of geochemical warming (which decreases surface albedo due to reduced snow and ice cover) for greater LUC emissions, the biophysical component of the albedo change follows the linear relationship established in figure 2(b) (for the

LUC + FF simulation, the albedo-emissions regression yields a slope of 2.65 $^{\circ}\text{C}/\text{Tt C}$ and r^2 of 0.969, to compare to table 3). The albedo difference between the LUC and LUC + FF simulations (figure 3(a), yellow line versus green line) are related to the greater sequestered fossil fuel carbon in the terrestrial emissions of LUC + FF, which lead to reduced albedo change sensitivity to terrestrial emissions (as shown for temperature in table 3).

The regional distribution of albedo changes (figure 3(b)) demonstrates that the resulting biophysical temperature change is not limited to areas experiencing land use conversion but has a global impact due to a high latitude amplification of land use-related cooling by the ice-albedo feedback, with biophysical cooling leading to more snow in mid and high latitude regions and greater Arctic sea ice extent (not shown, see albedo changes figure 3(c)). Similarly, mid-latitude and high altitude regions undergoing LUC (such as central North America and central Eurasia in figure 3(d)) tend to experience greater local albedo changes (figure 3(c)), due in part to the greater cold-season effect of snow on grassy (i.e., agricultural and pastoral) surfaces (compared to forested regions, where snow has a smaller impact on surface albedo due to taller vegetation masking the snow albedo). In addition, most other regions demonstrating biomass gains (figure 3(d), blue-shaded grid cells) experience a decrease in albedo (figure 3(c), gray-shaded grid cells). Thus, the linearity between albedo and net terrestrial emissions is partly related to the way the net LUC emissions totals are calculated in this study as the sum of afforestation (which decreases both albedo and net terrestrial emissions) and deforestation (which increases albedo and net terrestrial emissions). For these simulations, the strongly linear response (table 3) of biophysical temperature to net terrestrial emissions for the historical period suggests that, for certain TCRE applications, an additional linear scaling factor can be used to represent the biophysical land-use effects.



3.2. Twenty-first century change and harmonized RCPs: 2000–2100

From 2006 to 2100, harmonized spatial land use patterns (Eby *et al* 2013) and fossil fuel CO₂ emissions (Meinshausen *et al* 2011) were used to perform simulations for the RCP scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5). The results are plotted in figure 4, with the temperature change and emissions plotted relative to the year 2000 to highlight changes during the 21st century alone. Each of the panels in figure 4 are also plotted with different temperature and emissions scales so as to be able to show the relative differences between simulations for a given RCP scenario, due to the very different overall emissions across the four RCPs. These plots show several common features as compared to the historical runs. In all cases, there is a consistent linear temperature response to externally-prescribed emissions (brown and purple lines), and in all cases the combined response to fossil fuel and land-use CO₂ produced by spatially-explicit LUCs is decreased as a result of the inclusion of biophysical land-use effects (red lines). There is also a consistent pattern of enhanced net terrestrial emissions when fossil fuel emissions are

included (yellow versus green lines), which can be understood in general as the re-emission by land-use change of fossil fuel emissions that had been previously sequestered in the terrestrial biosphere due to CO₂ fertilization (calculated as the difference in net terrestrial emissions between the LUC + FF and LUC experiments). Furthermore, the relative importance of this effect increases according to the magnitude of fossil fuel emissions across the four RCP simulations; this re-emission of fossil fuel CO₂ accounts for 40% (45 Pg C) of total 21st century LUC + FF terrestrial emissions in RCP2.6, 45% (46 Pg C) in RCP4.5, 51% (69 Pg C) in RCP6.0, and 57% (82 Pg C) in RCP8.5.

There are some interesting differences from the historical simulations. In the LUC + FF simulation, the net temperature response to land-use changes is now positive (table 4), reflecting an increase in the biogeochemical relative to biophysical effects of land-use change over the 21st century. Furthermore, the total temperature response in the LUC + FF simulation follows an overall more linear response to cumulative combined fossil fuel and land-use emissions, owing in part to this decreased overall prominence of the biophysical land-use effect. It can also be seen that, as the

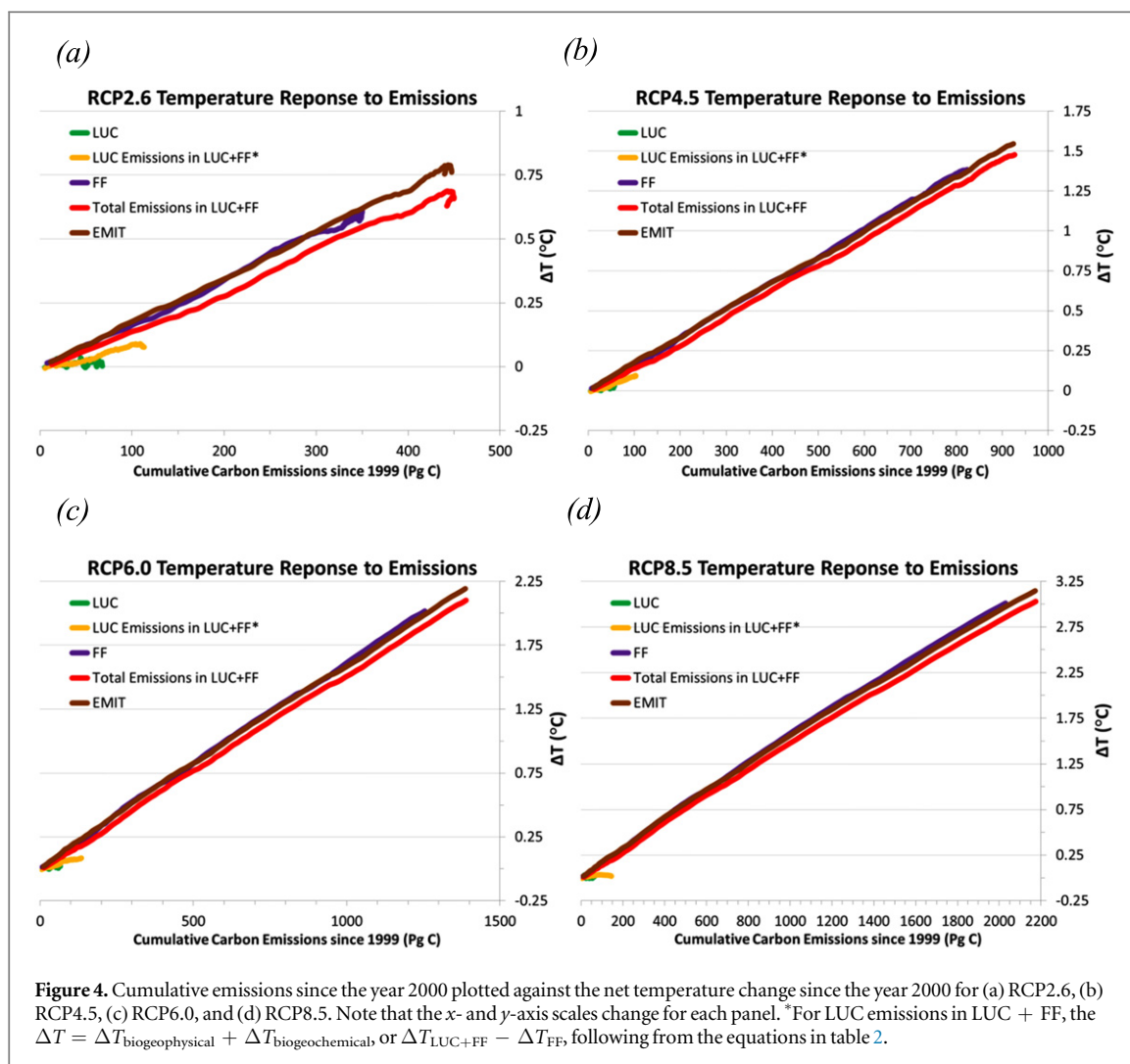


Figure 4. Cumulative emissions since the year 2000 plotted against the net temperature change since the year 2000 for (a) RCP2.6, (b) RCP4.5, (c) RCP6.0, and (d) RCP8.5. Note that the x- and y-axis scales change for each panel. *For LUC emissions in LUC + FF, the $\Delta T = \Delta T_{\text{biogeophysical}} + \Delta T_{\text{biogeochemical}}$ or $\Delta T_{\text{LUC+FF}} - \Delta T_{\text{FF}}$, following from the equations in table 2.

Table 4. The linear slopes of cumulative emissions versus total ΔT curves with the historical period and RCP scenarios together (1750–2100). The linear correlation coefficient is provided in parentheses. As in table 3, the slopes represent the line of best fit passing through the point (0, 0), i.e., zero emissions associated with zero temperature change.

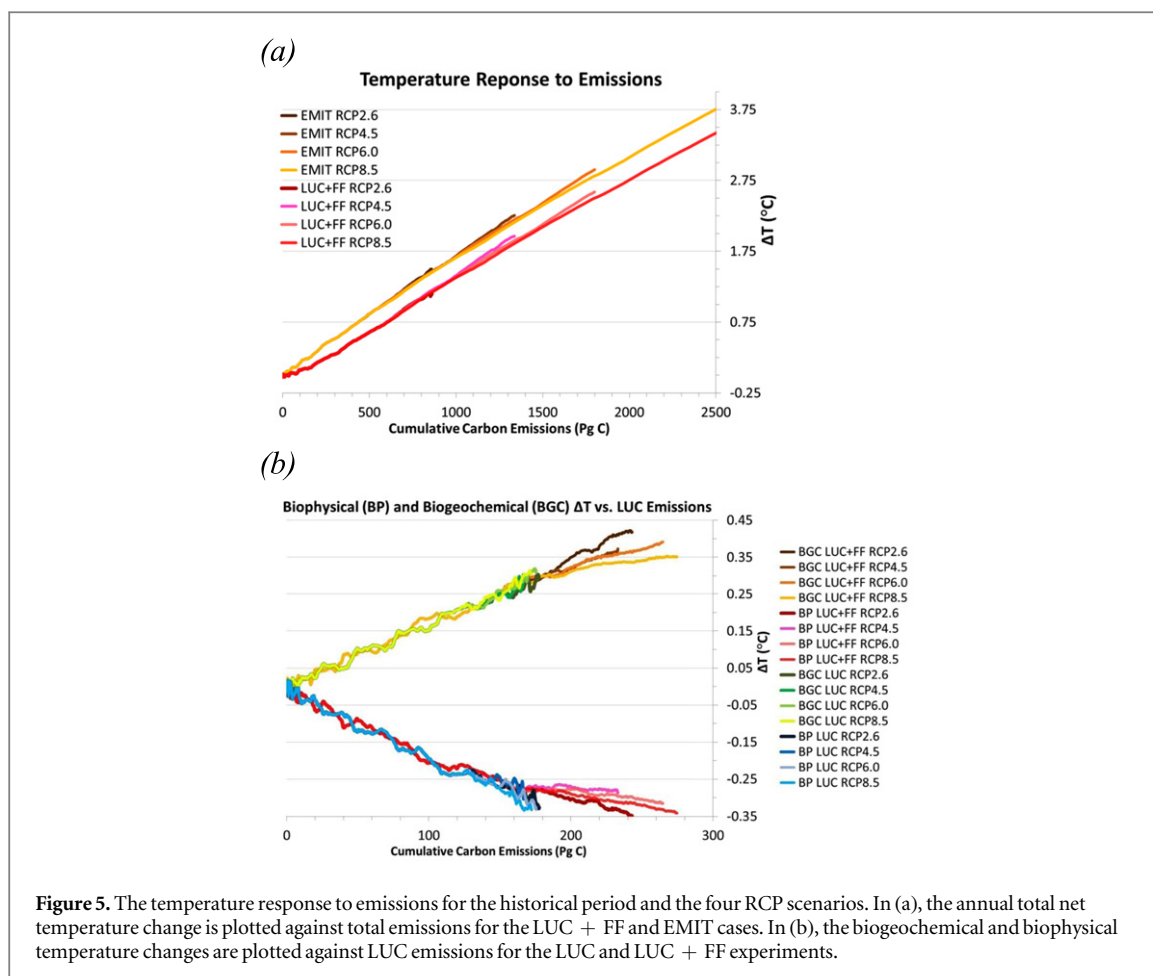
Linear slope of transient climate response to emissions ($^{\circ}\text{C}/\text{Tt C}$) calculated with total ΔT for 1750–2100				
	With RCP2.6	With RCP4.5	With RCP6.0	With RCP8.5
LUC-only	-0.18 ($r^2 = 0.153$)	-0.10 ($r^2 = 0.287$)	-0.13 ($r^2 = 0.212$)	-0.20 ($r^2 = 0.254$)
LUC emissions in LUC + FF ^a	$+0.18$ ($r^2 = 0.435$)	$+0.20$ ($r^2 = 0.454$)	$+0.17$ ($r^2 = 0.442$)	$+0.04$ ($r^2 = 0.088$)
Total emissions in LUC + FF	$+1.37$ ($r^2 = 0.994$)	$+1.41$ ($r^2 = 0.991$)	$+1.40$ ($r^2 = 0.994$)	$+1.37$ ($r^2 = 0.997$)
FF-only	$+1.74$ ($r^2 = 0.999$)	$+1.72$ ($r^2 = 0.999$)	$+1.67$ ($r^2 = 0.999$)	$+1.58$ ($r^2 = 0.998$)
EMIT	$+1.73$ ($r^2 = 0.999$)	$+1.70$ ($r^2 = 0.999$)	$+1.65$ ($r^2 = 0.999$)	$+1.56$ ($r^2 = 0.998$)

^a For LUC emissions in LUC + FF, the total ΔT is the sum of the biogeochemical and biophysical temperatures changes due to terrestrial biosphere changes, which is equal to $T_{\text{LUC+FF}} - T_{\text{FF}}$, following from the equations in table 2.

overall fraction of total emissions that comes from fossil fuels increases from RCP2.6 (74%) to RCP8.5 (93.3%), the overall temperature response also becomes more similar to the linear temperature response to externally-prescribed emissions (figure 4, table 4). In addition, RCP4.5 has a less pronounced spatial extent of land-use changes compared to the other scenarios, with less land-use CO_2 emissions (103 Pg C, 11% of the total emissions) by the end of the century. For comparison, cumulative land-use emissions

were 26% of the total 21st century emissions in RCP 2.6 (113 Pg C), 9.7% (135 Pg C) in RCP6.0 and 6.7% (144 Pg C) in RCP8.5.

In figure 5, we combine the historical and future simulations to show the net temperature response to cumulative CO_2 emissions in the case of externally prescribed (EMIT simulations) versus dynamically-calculated (LUC + FF simulations) land-use CO_2 emissions (figure 5(a)). Also plotted are the biophysical-only and biogeochemical-only temperature



response to net terrestrial emissions (figure 5(b)). As can be seen in figure 5(a), in all cases there is a slight negative deviation from a linear temperature response to cumulative emissions with increasing total emissions, which has also been shown in previous analyses of the TCRE (Gillett *et al* 2013, Herington and Zickfeld 2014, Leduc *et al* 2015). The divergence between the EMIT and LUC + FF simulations is especially notable for lower emissions values, where LUC emissions and the associated biophysical cooling have a more prominent effect. Correspondingly, the temperature response to cumulative emissions in EMIT and LUC + FF largely parallel each other at higher cumulative emissions which are dominated by fossil fuel CO_2 .

Figure 5(b) shows the individual response of biophysical and biogeochemical land-use effects to cumulative land use CO_2 emissions. In the simulations with spatially-explicit land-use changes, but no fossil fuel emissions (LUC simulation), both the biogeochemical and biophysical effects of land-use change can be well described as a linear (positive and negative respectively) function of cumulative emissions. Again, this suggests that the TCRE for externally prescribed (i.e. fossil fuel) CO_2 can be used to also estimate the biogeochemical warming associated with land-use CO_2 emissions, and that an additional linear scaling

factor can be used to incorporate the corresponding biophysical effects of land-use change. The linearity appears to hold less well for the LUC + FF simulations, which again can be seen to have higher land-use CO_2 emissions associated with the re-emission of previously sequestered fossil fuel CO_2 emissions. In the case of the biogeochemical effect, however, the deviation from linearity seen in the LUC + FF simulations is actually consistent with the overall negative deviation of the temperature response relative to a constant TCRE at very high cumulative emissions (Leduc *et al* 2015), recalling that the land-use emissions in the LUC + FF simulations occur in conjunction with increasing fossil fuel emissions and are therefore subject to the same diminishing temperature response at high total emissions.

For the case of biophysical effects, the increase in albedo associated with land-use change does not depend on whether land use occurs in conjunction with fossil fuel emissions. Accordingly, the LUC simulations (figure 5(b), blue-shaded lines) suggest a very linear biophysical cooling response to cumulative CO_2 emissions, as discussed for the historical period in section 3.1. However, this biophysical linearity breaks down for the LUC + FF simulations (figure 5(b), red-shaded lines). Most of difference in land use emissions between the LUC and LUC + FF simulations results

from fossil fuel carbon absorbed by the terrestrial biosphere and then re-emitted to the atmosphere during land cover change. Plotting the biophysical cooling from LUC + FF against the LUC emissions from LUC (not shown) for each of the RCP scenarios provides a linear trend, indicating that much of the biophysical nonlinearity seen in figure 5(b) for the 21st century LUC + FF simulations results from the high proportion (40%–57%) of biosphere-sequestered fossil fuel carbon in the LUC + FF net terrestrial emissions.

Focusing more specifically on the individual cases, the LUC + FF RCP2.6 scenario (figure 5(b), dark red line) has the smallest fraction (40%) of biosphere-sequestered fossil fuel carbon in the net terrestrial emissions, and it is the closest curve to the linear LUC scenarios. The LUC + FF RCP4.5 simulation (figure 5(b), magenta line) has 10 Pg C less terrestrial emissions than RCP2.6, but with a greater proportion (45%) of sequestered fossil fuel carbon, and it demonstrates the most biophysical nonlinearity of all the LUC + FF simulations. From LUC + FF RCP6.0 (figure 5(b), dark pink line) to LUC + FF RCP8.5 (figure 5(b), red line), the biophysical linearity gradually increases again despite greater proportions (51%–57%) of fossil fuel sequestered carbon in the net terrestrial emissions. This is, in part, because the biophysical temperature change ($\Delta T_{BP} = T_{LUC+FF} - T_{EMIT}$, from table 2) is dependent on temperature change in response to fossil fuel emissions. As the temperature sensitivity to CO₂ decreases for higher emissions scenarios (figure 5(a), brown/orange lines), the magnitude of ΔT_{BP} correspondingly increases. Therefore, the reduced geochemical influence on transient temperature changes for higher emissions scenarios contributes to the gradually steeper biophysical slope from RCP4.5 to RCP8.5 in the LUC + FF simulations, in a similar manner as the deviation from linearity for the biogeochemical warming effect (figure 5(b), brown/orange shaded lines).

4. Conclusions

Recent literature has highlighted the strong linearity between temperature change and cumulative carbon emissions, both in the observational record, and in a range of Earth system models (Matthews *et al* 2009, Gillett *et al* 2013). This relationship, as defined by the TCRE metric, represents a simple, yet powerful, framework for understanding contemporary climate change and informing climate mitigation targets (Friedlingstein *et al* 2014). However, these studies consider only the radiative effect of land use carbon emissions in the atmosphere, thus neglecting the additional radiative influence of anthropogenic land use change (LUC, i.e., horticulture, agriculture, and pasture) at the Earth's surface. By increasing global surface albedo and thus allowing more incoming solar radiation to be reflected back to space, human land use

has both a cooling (biophysical) and a warming (biogeochemical) effect on the climate, with the former able to reduce the temperature sensitivity to total cumulative carbon emissions.

In this paper, we incorporated spatial human land use patterns (from HYDE 3.1) into the UVic ESCM (v. 2.9) in order to evaluate the combined biogeochemical and biophysical influence of LUC in the model on the climate response to cumulative carbon emissions for the period from 1750 to 2100. We found that the biophysical cooling in our simulations was of comparable magnitude to the biogeochemical warming over the historical period, with the result that the net temperature response to land-use change did not follow the linear TCRE relationship associated with externally-prescribed emissions. Prior to 1950 in particular, when land use emissions predominated over fossil fuel emissions, this led to a net warming response to all emissions that was substantially lower than what would be expected from the TCRE. As fossil fuels and industry became the dominant emissions source (largely for the higher emissions values reported for the 20 to 21st centuries), the slope of temperature-emissions relationship increased gradually and therefore more closely paralleled the TCRE for fossil fuel emissions alone. It is worth noting that we have included only CO₂ emissions from fossil fuel combustion in our study; further research analyzing the climate effect of non-CO₂ gases and aerosols emitted with industrial CO₂ emissions would also be useful, in order to diagnose their influence on the transient temperature response (Rogelj *et al* 2015), in a similar manner to what we have done here for the non-CO₂ effects of LUC.

Our simulations indicate that the biogeochemical effect of land-use CO₂ cumulative emissions is equivalent to the temperature response to cumulative fossil fuel emissions, with a consistent linear response well represented by a constant TCRE value. Furthermore, we also found that the biophysical effect of land-use change can also be well represented by a linear scaling factor, due to a strong linear relationship between albedo and net terrestrial emissions, though we did find evidence that this linearity became less robust when combined with high fossil fuel CO₂ emissions owing to the effect of enhanced land-use emissions associated with CO₂ fertilization of the terrestrial biosphere. Overall therefore, we conclude that the TCRE remains a useful metric to estimate the biogeochemical effect of cumulative land-use CO₂ emissions, but that the additional biophysical cooling should also be accounted for as this has a non-trivial effect on the overall temperature response to changing spatial patterns of human land-use.

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