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Assessing climatic impacts of future land use and land cover change projected with the CanESM2 model

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ABSTRACT: To demonstrate the importance of land use and land cover change (LUCC) on future climate projections, the CanESM2 model experiments recommended by the LUCID project were used. Four fully coupled simulations were performed: with and without LUCC for two scenarios (RCP2.6 and RCP8.5). Model results show that the global LUCC effects are very small because of offsetting regional signals. Future global land-use emissions due to LUCC in the two scenarios are estimated to be 35.7 and 32.1 Pg C, respectively. The largest regional responses are directly associated with the land cover conversion in the tropics and subtropics. As the albedo effect dominates in mid- and high-latitudes, LUCC produces a small cooling or little effect in the western United States and Eurasia as a result of the reduction in needleleaf evergreen trees. LUCC increases temperature by 0.05–0.1 °C in the tropics due to the reduction in evapotranspiration because of the conversion from rainforests to croplands. When compared with greenhouse gases (GHGs) and aerosol influences, LUCC has a second-order effect on the temperature change at the global scale. However, for the CO_2 fluxes, the LUCC and GHG/aerosol effects are equally important and the former is much stronger than the latter over some regions such as Africa and South and North America. The land–atmosphere CO_2 flux can be regionally modulated by LUCC when compared with the effects of GHG/aerosol forcings. Although there is no significant land cover change in higher latitudes, climate responses to LUCC occur over boreal and arctic regions, indicating that atmospheric teleconnection can modify regional climate far away from the areas with LUCC. These results highlight the need to understand the responses of carbon cycle and remote climate to LUCC over longer time scales.

KEY WORDS land use and land cover change; future climate projection; climatic impact

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1. Introduction

Human activities have drastically modified the physical properties of the land surface by transforming the natural ground cover to human use and consequently have significantly altered the global and regional climate (Pielke, 2005). Approximately 30–50% of the Earth's land surface has been directly altered by human activity (Foley *et al.*, 2005). Land use and land cover change (LUCC) represents one of the most important anthropogenic impacts on the Earth system and has been recommended as an important climate forcing (National Research Council, 2005). Climatic impacts of LUCC at local to regional scales can be as large as or even larger than those of sea surface temperature (SST) anomalies (Findell *et al.*, 2009) or atmospheric CO_2 concentration changes (Zhao and Pitman, 2002; de Noblet-Ducoudré *et al.*, 2012) even though the global mean effect is relatively small (e.g. Findell *et al.*, 2007). Despite many studies on this topic, LUCC has been a long-standing scientific issue in the climate change research community because of the involvement of complex biogeophysical and biogeochemical land–atmosphere interactions (Pongratz *et al.*, 2010). Therefore, further investigation of LUCC is warranted to understand the effects on past and future climate change (e.g. Christensen *et al.*, 2007; Pielke *et al.*, 2011).

LUCC affects the climate through changes in land surface properties such as albedo, aerodynamic roughness, leaf area, and vegetation rooting depth (biogeophysical effects) and via changes in CO_2 fluxes between the land and the atmosphere (biogeochemical effects) (Betts, 2000; Bala *et al.*, 2007; Pitman *et al.*, 2009; Lawrence and Chase, 2010). Modelling studies have demonstrated such impacts regionally (Bonan, 1997; Govindasamy *et al.*, 2001; Bounoua *et al.*, 2002; Gao *et al.*, 2003; Oleson *et al.*, 2004; Brovkin *et al.*, 2006; Gao *et al.*, 2007; Bonan, 2008; Anav *et al.*, 2010; Zhang *et al.*, 2010), as well as remotely through atmospheric teleconnections (Avissar and Werth, 2005; Hasler *et al.*, 2009). In tropic regions, deforestation can lead to a local warming because the cooling effect of the albedo change is overwhelmed by the

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reduction in evapotranspiration, while reforestation could lead to a cooling effect via carbon sequestration together with increased evaporation and cloud cover (Betts *et al.*, 2007). In the mid- and high-latitudes, reforestation with the reduced surface albedo has a warming effect on the climate (Betts, 2000). The major LUCC biogeochemical mechanism is the carbon cycle, connected with atmospheric CO_2 concentrations. As a major greenhouse gas in the Earth's atmosphere, CO_2 plays an important role in changing the climate. During the past 150 years, land-use changes caused approximately 35% of CO_2 emissions (Houghton, 2003). Anthropogenic CO_2 emissions to the atmosphere were estimated to be 180 ± 80 Pg C due to land-use changes between 1750 and 2011 (IPCC, 2013).

To quantify the LUCC effects on climate, various modelling groups have used different models, land cover maps, and experimental protocols to explore the regional response and the possible teleconnection effects (Pielke *et al.*, 2011). A project called LUCID (the Land Use Change, Impacts, and Dynamics intercomparison) was recently launched to address the robustness of the possible impacts of LUCC at a local and remote level (Pitman *et al.*, 2009; Boisier *et al.*, 2012; de Noblet-Ducoudré *et al.*, 2012). However, previous model schemes have generally included fixed land coverage, SST, or CO_2 concentrations, ignoring the possible biogeophysical and biogeochemical feedbacks and thereby damping global-scale teleconnections (Chase *et al.*, 2000; Hibbard *et al.*, 2010). Fully coupled model experiments are needed in future studies (Pitman *et al.*, 2009).

Although the anthropogenic influences on the Earth's surface continue to accelerate, the LUCC effects on future climate are still far from known (Mahmood *et al.*, 2010). DeFries *et al.* (2002) proposed a possible land cover scenario for the year 2050 based on results from the IMAGE-2.1 (Integrated Model to Assess the Global Environment) model and found that the future land cover change, likely to occur in the tropics and subtropics, has a warming effect due to physiological rather than the morphological effects. Feddema *et al.* (2005) and Voldoire (2006) also carried out simulations in which land cover was modified based on IMAGE projections and explored the possible changes in future land cover use. However, the interannual evolution of LUCC has rarely been considered in earlier studies. Sitch *et al.* (2005) and Voldoire *et al.* (2007) provided the idea of including land-use changes based on the IMAGE model and suggested a more effective method that takes the time-varying evolution of the land cover changes as an external forcing, as is done for GHG and aerosol concentrations, which helps narrow the uncertainties induced by neglecting future land-use changes.

Recently, Representative Concentration Pathways (RCPs) have been developed for climate change research and assessment for the Coupled Model Intercomparison Project Phase 5 (CMIP5) experiments (Taylor *et al.*, 2009, 2012). Different emission scenarios were considered to better understand the uncertainty in future climate projections. The RCPs for the future were provided by the Integrated Assessment Model (IAM) teams as input into climate models or Earth System Models (ESMs) for climate projections (Moss *et al.*, 2010). In particular, the forcings of future land-use changes in each scenario were introduced into the CMIP5 experiments. To separate the effects of land-use changes on climate, several CMIP5 modelling groups performed additional simulations without LUCC during the period 2006–2100 (Brovkin *et al.*, 2013). Nevertheless, a thorough assessment of the climatic effects due to LUCC at regional and global scales and the relative contribution of LUCC and other forcings to future climate (i.e. greenhouse gases and aerosols) are still necessary.

In this study, we attempt to assess the LUCC effects on the future climate based on fully coupled climate model simulations using the second generation Canadian Earth System Model of the Canadian Centre for Climate Modeling and Analysis (CanESM2; Arora *et al.*, 2011). The CanESM2 experiments have already included simulations driven by land-use changes for each RCP scenario, and additional simulations without land-use changes were required to separate the effects of land use on climate within the LUCID-CMIP5 framework. Brovkin *et al.* (2013) assessed the effects of land-use changes on climate using CMIP5-LUCID results, with emphases on differences in climate and land–atmosphere fluxes (near-surface air temperature, albedo, and land carbon storage) between the ensemble averages of simulations with and without land-use changes by the end of the 21st century. This study quantifies the relative impacts of GHGs/aerosols and LUCC and further analyses the regional effects of LUCC on the underlying physical [e.g. Plant Function Type (PFT) and albedo] and land surface processes. Compared to previous studies of future LUCC simulations (DeFries *et al.*, 2002; Feddema *et al.*, 2005; Sitch *et al.*, 2005; Voldoire *et al.*, 2007), the CanESM2 experiments considered the time-evolving LUCC as a forcing for the future climate projections, which may be more robust than previous studies that used fixed land cover changes or a GCM coupled to the IAM. More details on the model description and simulations, including the land-use scenarios, are presented in Section 2, followed by an analysis of the climate and carbon cycle changes on both global and regional scales in Section 3. The study concludes with a brief summary and discussion in Section 4.

2. Model description and methodology

The CanESM2 is a comprehensive and fully coupled climate-carbon model that participated in CMIP5 (Arora *et al.*, 2011). It consists of the atmosphere, ocean, and land surface through the exchange of energy, momentum, water, and trace gases, e.g. CO_2. The horizontal resolution of the atmospheric and land components of CanESM2 is about 2.8°, whereas the physical ocean horizontal resolution is approximately 1.41° (longitude) × 0.94° (latitude). The land component of CanESM2 is the Canadian Terrestrial Ecosystem Model (CTEM) (Arora and Matthews, 2009; Arora and Boer, 2010). CTEM is a dynamic vegetation model that includes photosynthesis, autotrophic and heterotrophic respiration, phenology, allocation, mortality, and land-use changes. Therefore, all parameters (e.g. leaf area index, roughness, albedo, stomatal conductance, and root depths) change as vegetation responds to changes in climate and CO_2. The values of the model parameters used in the CTEM are described in Arora and Boer (2005).

To address the combined effects of human activities (e.g. land-use changes, greenhouse gases, and aerosols) on the carbon-climate system, future land-use scenarios were generated using crop fraction data from the University of New Hampshire (available at http://luh.unh.edu/data.shtml) for four RCPs (Hurtt *et al.*, 2009). When the cropland fraction changes, the fractions of other PFTs were linearly adjusted in proportion to their fractional coverage (Arora and Boer, 2010). The future land-use projections for each RCP were harmonized to ensure a smooth transition from the historical land-use data (1850–2005). Compared to the biophysical LUCC mechanisms, the associated biogeochemical aspects of LUCC, which are typically investigated in the coupled carbon cycle models by injecting the CO_2 emissions directly into the atmosphere in the same manner as fossil fuel emissions, were not well quantified in the models. The approach considered in CanESM-used anthropogenic CO_2 emissions and changing land cover to drive models in which CO_2 was a prognostic variable. The LUCC emissions result interactively from the replacement of natural vegetation by croplands and pastures. Furthermore, changes in surface albedo, terrestrial and oceanic CO_2 fluxes, and storage all interact with and affect one another (Arora and Boer, 2010).

Four experiments were conducted (Table 1). RCP8.5 and RCP2.6 represent a high- and low-emission scenario, respectively. The land-use scenarios produced different future land-use area and land-use transitions corresponding to these two different RCPs. Moreover, additional simulations without land-use changes were performed for the intercomparison of land-use effects on climate as recommended by the LUCID project. For simulations without LUCC (L2A26 and L2A85), the land use and land cover were prescribed from a single year (2005). More information about the land-use changes in each RCP is provided in Section 3. Three ensemble members of the CanESM2 simulations for the period 2006–2100 for each experiment were selected and their ensemble mean was used for the analysis. Evidently, the differences between the simulations with and without LUCC indicate the effects of LUCC. Moreover, *t*-tests were employed to determine if two data sets were significantly different from each other.

3. Results

3.1. Future changes in LUCC and vegetation

Future changes in the estimated global extent of the PFTs are primarily induced by changes in the projected crop areas. Crops are split up into C3 (e.g. wheat, cotton, rice, and soybeans) and C4 (e.g. corn and sugar cane) in the CanESM2 vegetation class map. Figure 1 shows the differences in the fractions of C3 and C4 crops between 2100 and 2005 for RCP2.6 and RCP8.5, respectively. Significant changes in the fraction of C3 crops in RCP2.6 are mainly found in the western United States, South America, Africa, Eurasia, and Indo-China Peninsula (Figure 1(c)), while evident changes in RCP8.5 appear in South America and Central Africa (Figure 1(d)). The major increases in C4 crop ecosystems appear in Central Africa in RCP2.6 and RCP8.5 (Figure 1(e) and (f)). Overall, the future expansion of the cropland in RCP8.5 is narrower in spatial extent and smaller in magnitude than that in RCP2.6.

Figure 2 presents the averaged changes in leaf area index (LAI) for the period 2006–2100 resulting from LUCC (RCP26-L2A26 and RCP85-L2A85). The changes primarily appear in Central Africa and South America, where the land cover expands into the cropland. The global mean values of LAI for the four experiments range from 1.25 (RCP26) to 1.59 (L2A85) in 2100 (Figure 3(a)). By comparing the simulated globally averaged LAI between the two experiments (L2A26 and L2A85) without LUCC, but with different CO_2 concentration forcings, we find that the LAI increases due to CO_2 fertilization effects in response to elevated CO_2 (Pritchard *et al.*, 1999) and such effects are particularly evident in RCP8.5.

Greenhouse gases (GHGs) and LUCC are important forcings in the 21st century climate because the anthropogenic pressure is expected to increase, which could alter the natural vegetation distribution. As an important vegetation parameter, the changes in LAI reflect the combined effects of vegetation dynamics in response to climate change, CO_2 fertilization, and LUCC. At the regional scales, LUCC should be the primary contributor to the LAI changes over the areas with the largest LUCC. For example, South America and Central Africa (Figure 2)

Table 1. Details of the experiments.

Experiment name	Atmospheric CO_2 concentration	Land-use change scenarios	Duration years
RCP85	prescribed atmospheric CO_2 concentration (from RCP8.5 scenario)	Yes	2006–2100
L2A85	prescribed atmospheric CO_2 concentration (from RCP8.5 scenario)	No (land cover map set at yr 2005)	2006–2100
RCP26	prescribed atmospheric CO_2 concentration (from RCP2.6 scenario)	Yes	2006–2100
L2A26	prescribed atmospheric CO_2 concentration (from RCP2.6 scenario)	No (land cover map set at yr 2005)	2006–2100

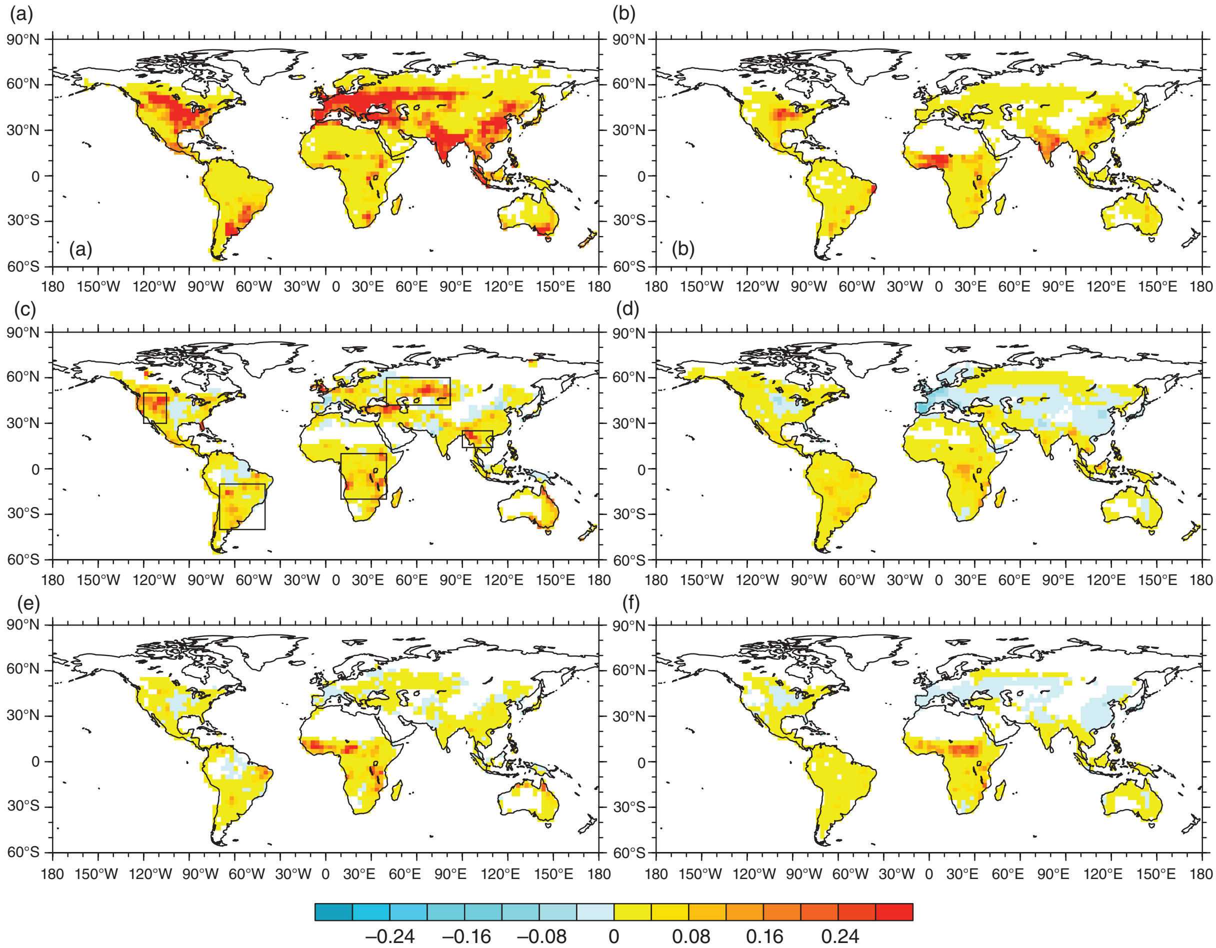

Figure 1. Geographic distributions of (a) C3 and (b) C4 crops in 2005, and the PFT differences between 2100 and 2005: (c) C3 crops for RCP2.6, (d) C3 crops for RCP8.5, (e) C4 crops for RCP2.6, and (f) C4 crops for RCP8.5. Five regions (western United States, South America, Eurasia, Central Africa, and Indo-China Peninsula) are defined as rectangular boxes in Figure 1c.

exhibit the most significant LUCC-induced LAI decreases (Figure 2; Figure 3(b)–(c)). The regional average LAI in 0°–30°S without LUCC shows large increases in RCP8.5 but the opposite in RCP2.6, indicating that the latter has small CO_2 fertilization effects due to the low CO_2 emission scenario and large climatic effects on LAI due to drought-induced stress on vegetation growth as these regions exhibit significant decreases in soil moisture (figure not shown for brevity). Figure 3(c) depicts the changes in LAI between the periods 2091–2100 and 2011–2020 for four RCP-based experiments. The LAI changes vary with latitudes for the L2A26 and RCP26 experiments, while the LAI increases in all five regions due to high atmospheric CO_2 concentrations in the RCP8.5 scenario. The LAI decreases in the tropics (0°–30°S) in the L2A26 experiment reflect drought-enhanced stress on vegetation growth as discussed previously and the larger decrease in RCP26 indicates the additional reduction in LAI due to LUCC. Therefore, the LAI can vary significantly in response to climate change, with and without land-use changes. Consequently, the time evolution of LUCC should be considered with evolving climate in the future.

3.2. LUCC effects on temperature, precipitation, and the carbon cycle

LUCC affects the global climate by releasing and storing carbon in plants and soils and by altering the physical properties of the land surface. Figure 4 shows the time series of the global mean surface air temperature, precipitation, and global land–atmosphere CO_2 flux for four future experiments. There is a large difference in the temperature and precipitation responses from 2006 to 2100 for the two CO_2 concentration scenarios. However, the changes between the LUCC and no-LUCC experiments are very small (RCP26 and L2A26; RCP85 and L2A85), indicating a small global-scale effect of LUCC. Simulated land–atmosphere CO_2 fluxes (Figure 4(c)) show that due to the LUCC in the two scenarios, future global land-use emissions are 35.7 Pg C (RCP26-L2A26) and 32.1 Pg C (RCP85-L2A85), which is about half of approximately 70 Pg C based on Arora *et al.* (2009) during a historical period (1850–2000).

The globally averaged temperature differences due to LUCC are small because of offsetting regional effects. Figure 5 shows the geographic patterns of the mean surface air temperature changes between the LUCC and no-LUCC

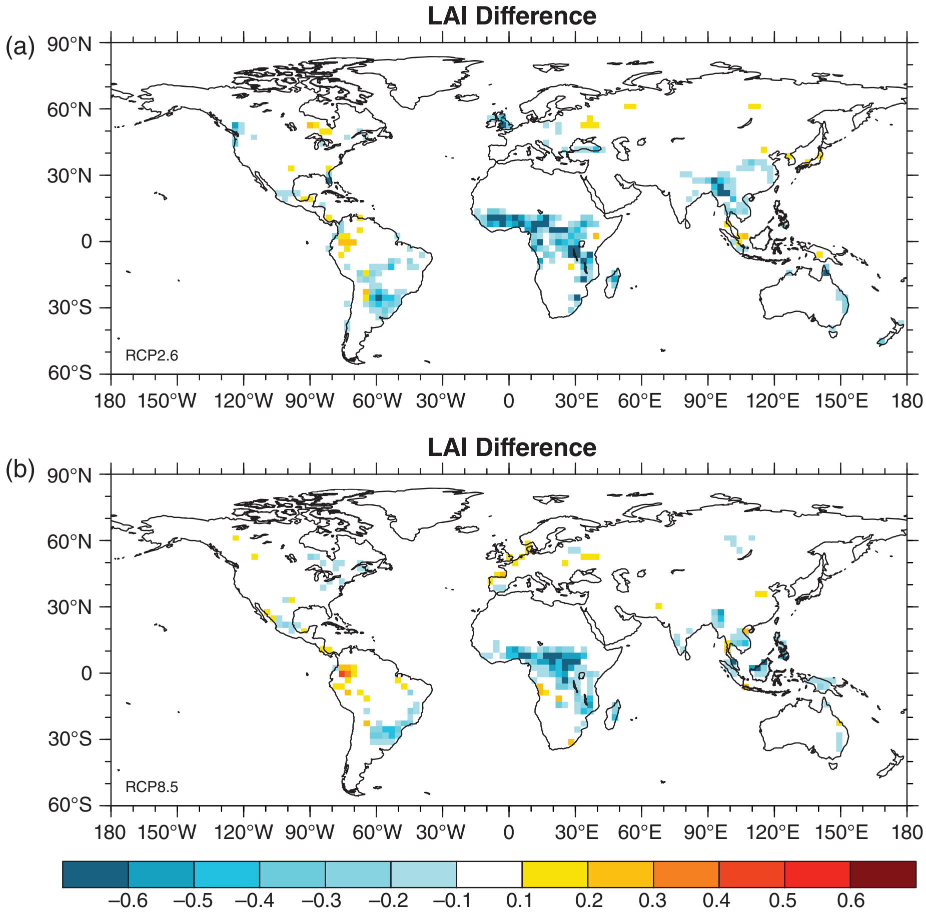

Figure 2. Geographic distribution of changes in leaf area index (LAI) resulting from LUCC averaged over the period 2006–2100 for two land-use scenarios (RCP26-L2A26 and RCP85-L2A85).

experiments in each scenario, averaged from 2006 to 2100. The regions with a statistically significant response ($p = 0.05$) are directly associated with vegetation conversions in the tropics and subtropics in RCP2.6 scenario. For example, the cultivation of crops in Central Africa and Southeast Asia results in a warming effect. For the high greenhouse gas concentration scenario (RCP8.5), there are no significant temperature and precipitation changes related to LUCC (Figures 5 and 6), suggesting that the elevated CO_2 may have modified the climate in a magnitude larger than LUCC and thus mask the LUCC impacts (Friedlingstein *et al.*, 2006; Shao *et al.*, 2013).

Note that we quantify the changes in temperature and other variables between the LUCC and no-LUCC experiments by averaging these variables over the entire period 2006–2100 instead of differencing them between two periods primarily for two reasons. First, the projected climate and its interaction with LUCC evolve with time, which makes it difficult to choose two particular periods objectively. Second, the averaging method can filter out some high-frequency and short-term climate variations as the focus of this study is the persistent and low-frequency climatic signal induced by LUCC.

The LUCC effects on the surface temperature differ significantly for the two scenarios (Figure 5) and some temperature and precipitation changes do not resemble the spatial patterns of LUCC (Figure 6). For example, although there is no significant land cover change in higher latitudes (e.g. Figures 1 and 2), climate responses to LUCC occurred over boreal and arctic regions, which are in line with Voldoire (2006). Two factors may help explain such changes. First, the background climate influences the regional climate responses due to LUCC. Hua and Chen (2013) noted that the greenhouse gas concentrations in 1850 and in the present indicate contrary change tendencies in climate sensitivity through estimations of the radiative forcing associated with LUCC based on different background climatologies. Pitman *et al.* (2011) found that the background climate affects the influence of land cover changes on regional climate, and in the higher latitudes, warmer climate induces changes in snow and precipitation, affecting the snow-albedo feedback and the partitioning between latent and sensible heat fluxes. Second, atmospheric teleconnection can modify regional climate far away from the areas with LUCC. Avissar and Werth (2005) showed that tropical deforestation significantly affects precipitation in mid- and high-latitudes through hydrometeorological teleconnections. Snyder (2010) indicated that the removal of tropical forests weakens deep convective activity and eventually impacts the northern remote areas by modifying the strength of the westerlies. So the changes in precipitation in high latitudes (Figure 6) may reflect the

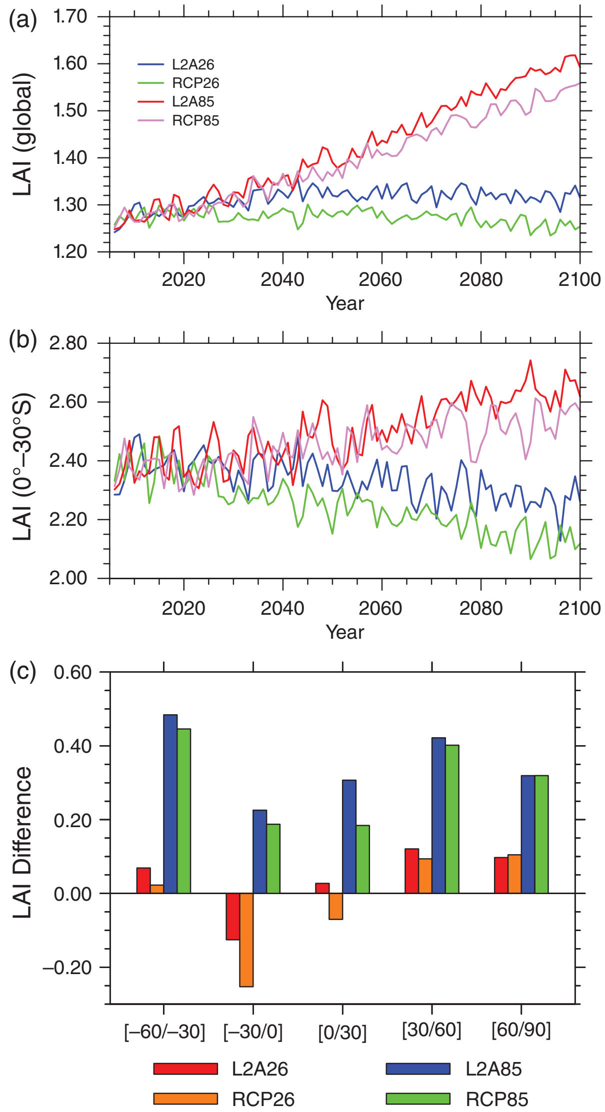

Figure 3. Annual time series of (a) global, (b) latitudinal mean (0°–30°S) LAI for the period 2006–2100, and (c) latitudinal mean changes in LAI in the period 2091–2100 compared to 2011–2020 for four RCP-based experiments. The abscissa in (c) indicates the range of region in latitude.

remote effects of circulation changes resulting from LUCC (Feddema *et al.*, 2005).

Many studies have focused on the impacts of LUCC at the local to regional scales and the possible teleconnections between regional LUCC and climate over remote areas. However, the remote impacts of LUCC on climate are not fully understood (Pielke *et al.*, 2011). As Findell *et al.* (2006) noted, it is difficult to differentiate the extratropical response to LUCC from natural climate variability and other climate forcings. First, climatic responses are not directly linked to local land cover change and can be modified by different climate scenarios. Second, remote effects of LUCC are complicated by the non-linear interactions among the land-use changes, background climate, and natural climate variability. For instance, Mahmood *et al.* (2014) found out that LUCC impacts behave more like a trend similar to greenhouse gas effects, but with great regional variability. This highlights the need to assess the possible range of LUCC impacts on remote climate in future studies.

The replacement of natural vegetation by crops and pastures interactively affects all components of the climate system and has historically led to an increase in atmospheric CO_2. The differences in the land–atmosphere CO_2 fluxes between the two experiments with and without LUCC suggest that there is a net decrease in land–atmosphere CO_2 fluxes caused by LUCC emissions with all components of the coupled carbon model active in both simulations (Arora and Boer, 2010). Figure 7 presents the spatial distribution of the changes in the land–atmosphere CO_2 fluxes (Pg C year^{-1}) for each scenario due to LUCC (RCP26-L2A26 and RCP85-L2A85). The most significant regional responses are directly associated with the land cover conversions. Negligible changes are generally seen in the areas far away from the LUCC where significant changes are found. For example, crop cultivation in Central Africa and Southeast Asia releases CO_2 into the atmosphere, which will affect the climate locally and remotely by changing the atmospheric CO_2 concentration. In return, the land surface carbon sink will be altered by changes in climate such as temperature, precipitation, soil moisture, water vapour, and solar visible radiation (Friedlingstein *et al.*, 2006; Boer and Arora, 2010; Shao *et al.*, 2013).

Climate models require time-evolving concentrations of radiatively active constituents (GHGs and aerosols), and time-evolving paths of LUCC as well (Moss *et al.*, 2010). Each emission scenario (e.g. RCP2.6 and RCP8.5) corresponds to a specific radiative forcing pathway, which can also be represented with an equivalent CO_2 concentration (including all radiative forcing of GHGs and aerosols). Basically, LUCC has a second-order effect compared to the effects of atmospheric CO_2 concentration changes at the global scale (Pitman and Zhao, 2000; Voldoire, 2006). Voldoire (2006) assessed separately the impacts of CO_2 and LUCC independently , although the time-evolving land use and CO_2 concentration were not considered. As a result of only changing in GHG/aerosols concentrations (L2A85-L2A26), the globally averaged surface temperature change is greater than 0.8 °C and this warming effect is statistically significant ($p = 0.05$) across every grid level (Figure 8(a)). Moreover, the precipitation increases in most areas, except for the Amazon and western Africa (Figure 8(b)). Figure 8(c) shows the spatial pattern of changes in land–atmosphere CO_2 fluxes due to GHGs/aerosols. The CO_2 fluxes vary by region and overall, the land acts as a sink for carbon (approximately 1.13 Pg C year^{-1}) due to increasing CO_2 concentrations. Based on the C4MIP model intercomparison (Friedlingstein *et al.*, 2006), a CO_2 increase alone leads to enhanced carbon storage in land.

The magnitude of the LUCC effects compared to the CO_2 effects can be quantified (Pitman and Zhao, 2000; Voldoire, 2006). In the CanESM2 experiments, RCP26-L2A26 (RCP85-L2A85) represents the LUCC effects for the RCP2.6 (RCP8.5) scenario. The impact of GHGs/aerosols can be expressed as

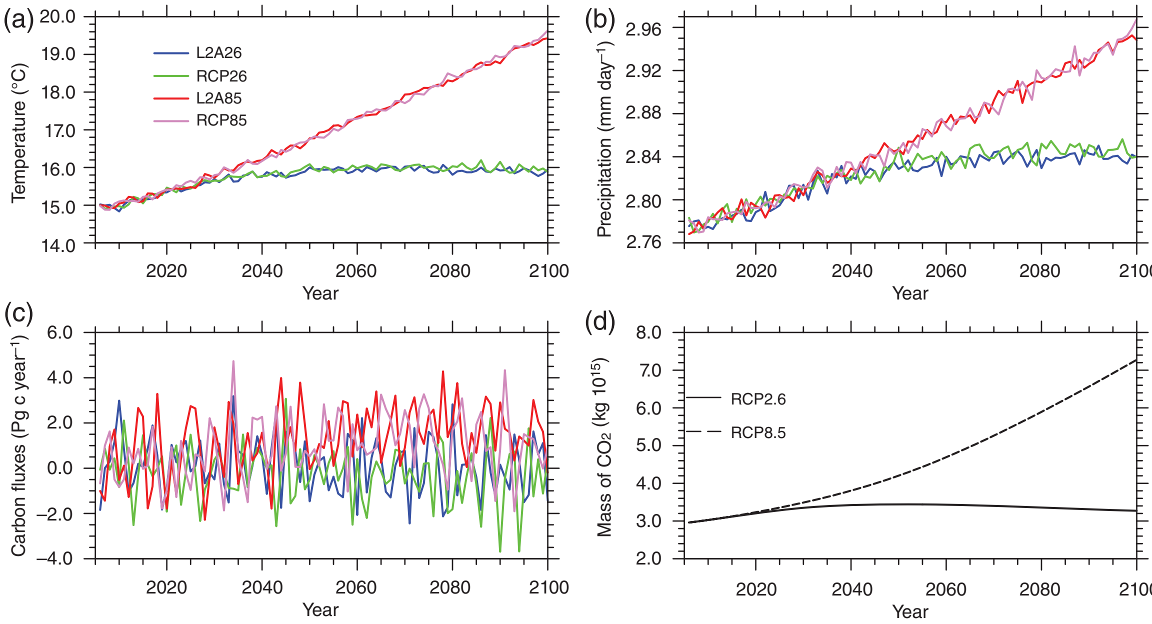

Figure 4. Global mean annual time series of (a) surface air temperature (°C), (b) precipitation (mm day^{-1}), (c) land–atmosphere carbon fluxes for four RCP-based experiments (Pg C year^{-1}), and (d) total atmospheric mass of CO_2 for two RCP scenarios (kg × 10^{15}).

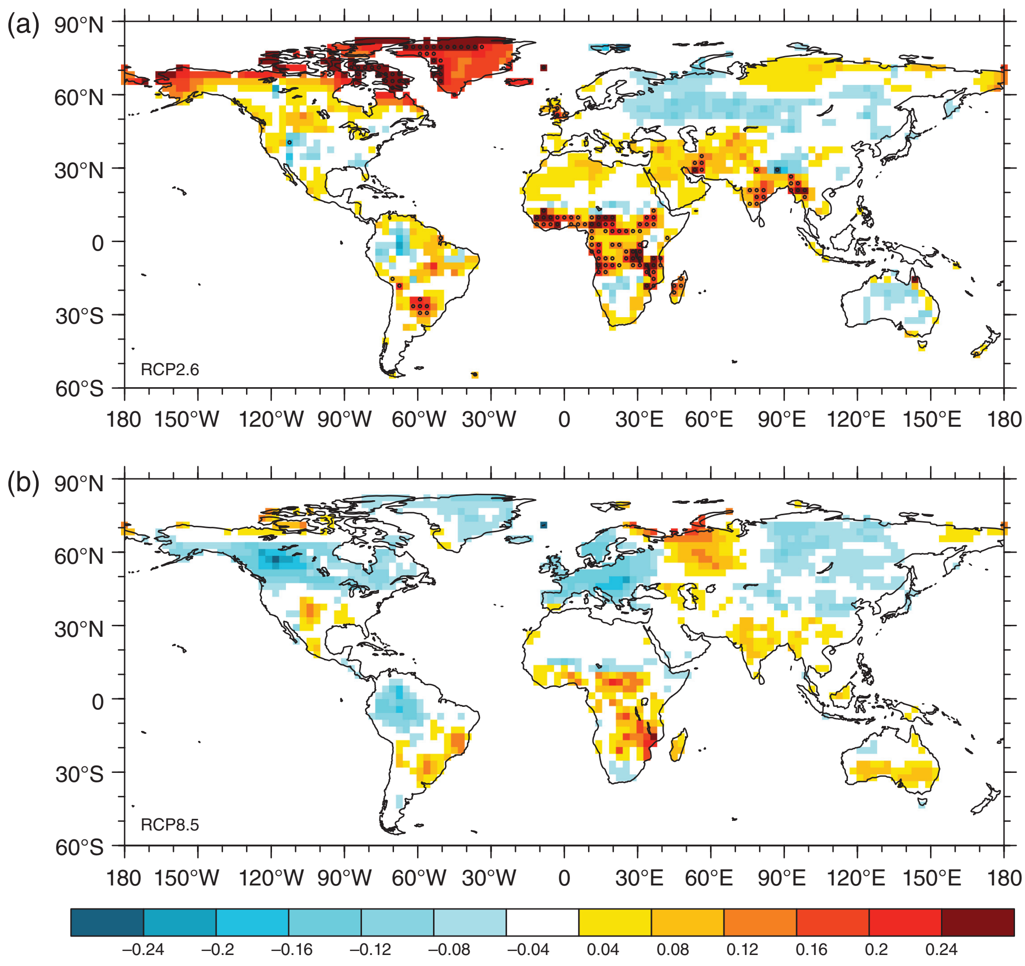

Figure 5. Geographic distributions of change in surface air temperature (°C) resulting from LUCC (RCP26-L2A26 and RCP85-L2A85), averaged over the period 2006–2100. The hollow dots are statistically significant at the 0.05 level.

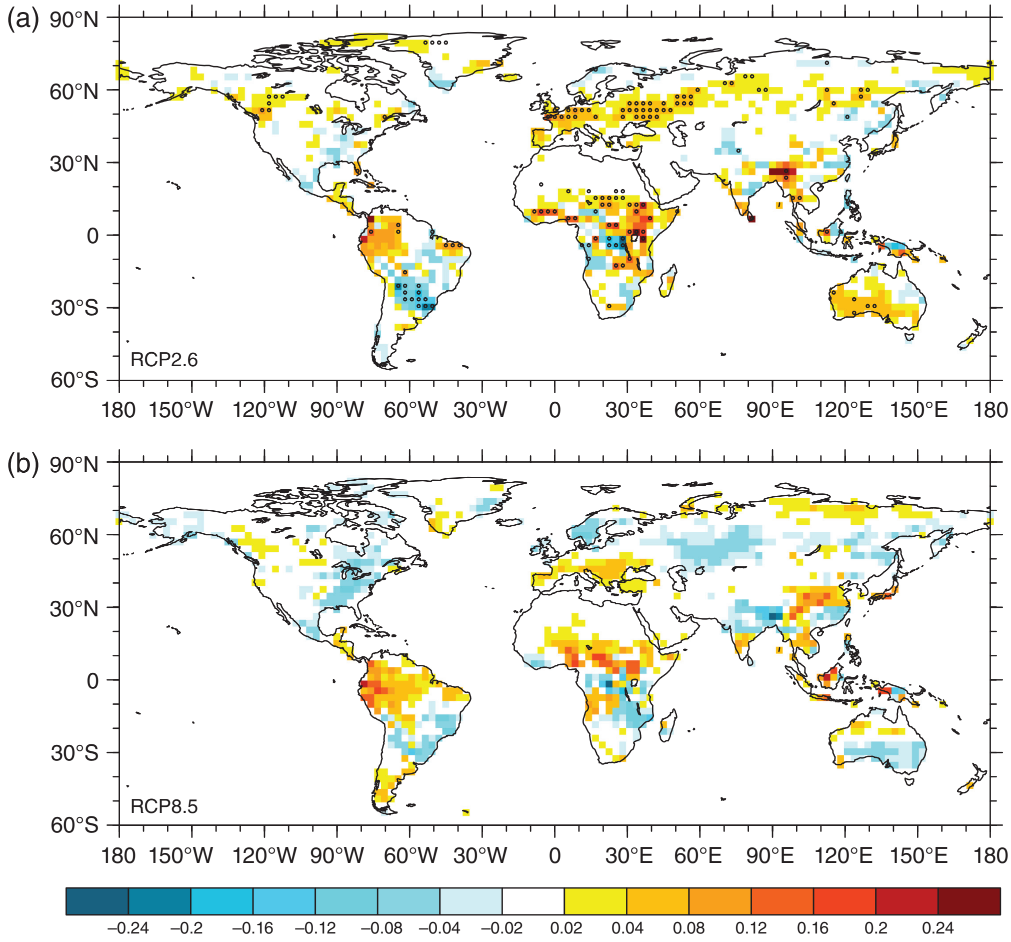

Figure 6. Geographic distribution of changes in precipitation (mm day^{-1}) resulting from LUCC (RCP26-L2A26; RCP85-L2A85), averaged over the period 2006–2100. The hollow dots are statistically significant at the 0.05 level.

L2A85 minus L2A26. Similar to the method used in de Noblet-Ducoudré *et al.* (2012), we average the results of the land-use change experiments for the two scenarios, i.e. 0.5(RCP26-L2A26 + RCP85-L2A85), to represent the LUCC impact. The ratio of the LUCC impact to the GHG/aerosol impact can be expressed as: 0.5(RCP26-L2A26 + RCP85-L2A85)/(L2A85-L2A26). For temperature, the magnitude of the ratio is less than 20% (Figure 9(a)), indicating that the GHG/aerosol effects are dominant on the temperature. However, for the CO_2 fluxes, the LUCC and GHG/aerosol effects are equally important and the former is much stronger than the latter over some regions such as Africa and South and North America where the ratio exceeds 1 (Figure 9(b)). The land–atmosphere CO_2 flux can be regionally modulated by LUCC when compared with the effects of GHG/aerosol forcings. Again, the direct LUCC effects are seen over the regions where LUCC has occurred, while remote effects are observed over other regions through atmospheric teleconnection. Interestingly, Chase *et al.* (2001) also found that the ratio of the absolute value of the vegetation change anomalies and that of the CO_2/aerosol anomalies are significant over much of the higher northern latitudes. This is an indication that teleconnections due to changes in large circulation play an important role in the overall climatic effects of LUCC and CO_2/aerosol (Pitman and Zhao, 2000; Chase *et al.*, 2001).

3.3. Regional effects of LUCC

Our results indicate that regional climate differs significantly in response to LUCC and so the LUCC effects over several chosen regions are examined next. The subregions selected are the western United States, South America, Eurasia, Central Africa, and Indo-China Peninsula (Figure 1(c)). As cropland expansion is larger in the RCP2.6 scenario than that in the RCP8.5 scenario (Hurtt *et al.*, 2011), we only focus on the areas where LUCC is significant in the RCP2.6 scenario. Figure 10 shows the projected changes in the fraction of various PFTs during the period 2005–2100. In the western United States, there is a relatively rapid increase in land conversion to C3 crops (Figure 10(a)), where the crops gradually increase between 2005 and 2040 and nearly stabilize afterward (Figure 10(b), (c), and (e)). Over Eurasia, the broadleaf drought deciduous trees are replaced by crops mainly in the 2020s and 2030s. The broadleaf trees that dominate in the tropical areas (Figure 10(b), (c), and (e)) decrease much more rapidly compared to other PFTs. While the areas of needleleaf evergreen trees that dominate in the temperate or boreal regions (Figure 10(a)) are replaced by croplands.

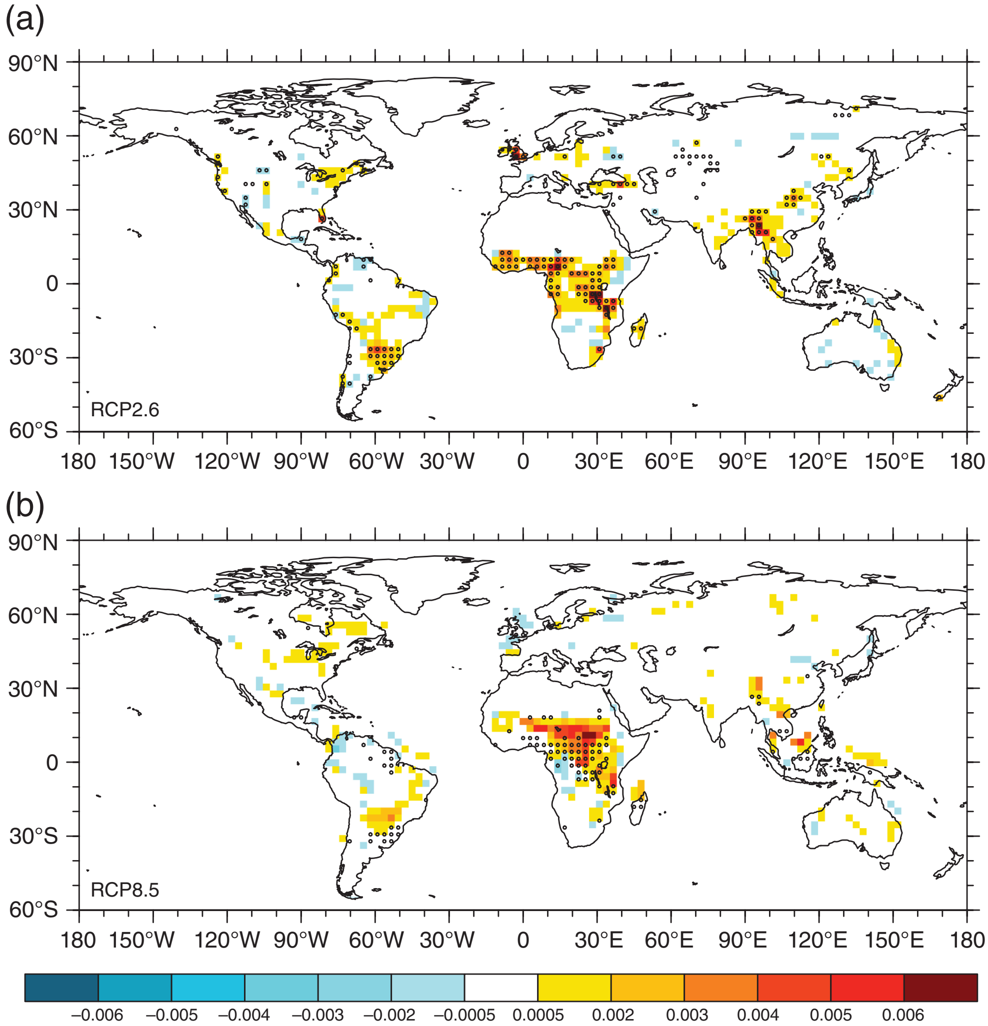

Figure 7. Geographic distribution of changes in land–atmosphere carbon fluxes (Pg C year^{-1}) resulting from LUCC (RCP26-L2A26; RCP85-L2A85), averaged over the period 2006–2100. The hollow dots are statistically significant at the 0.05 level.

LUCC affects global and regional climate via feedback between the land surface and the atmosphere by modifying the energy, momentum, and moisture fluxes via changes in surface albedo, roughness, leaf area, etc., and by changing atmospheric CO_2 concentration via changes in biomass. These processes relate to biogeophysical and biogeochemical mechanisms, respectively. Modelling studies suggest that through this biogeophysical pathway, past LUCC generally warms the surface in tropical areas but cools it in boreal lands (Claussen *et al.*, 2001; Bounoua *et al.*, 2002). LUCC effects in the tropics are dominantly controlled by evapotranspiration rather than by albedo, while albedo evidently drives the LUCC influences in boreal regions (Betts, 2000; Bala *et al.*, 2007). The important biochemical mechanism of LUCC for global climate is the influence on the carbon cycle and thus on the atmospheric CO_2 concentration.

We examine the changes of regional averaged land surface variables to understand the LUCC effect on the regional climate. As the significant land cover conversions occur in different periods, we focus on the period in the first half of the 21st century when the LUCC is the largest (Table 2). Among various biogeophysical effects of LUCC, two factors have been shown to have important effects on the surface energy and water cycle: (1) an increase in the surface albedo leading to a reduction in solar radiation absorbed by the land surface and (2) a decrease in evapotranspiration due to a reduction in the forest cover and surface roughness length. Therefore, the partitioning of the net radiation into sensible and latent heat fluxes will change. As the albedo effect dominates in the mid- and high-latitudes (Betts, 2000), in the western United States, LUCC produces a cooling effect of −0.02 °C, which is expected as a result of the reduction in needleleaf evergreen trees by changing the albedo rather than by the warming effect due to the decrease in evapotranspiration. Although LUCC also increases the albedo in Eurasia, its effect is small because the net radiation is positive compared to other regions. In the tropics (Figure 10(b), (d), and (e)), a warming effect of 0.05–0.1 °C is observed. The reduction in evapotranspiration (latent heat flux) indicates that the warming effect due to the conversion from rainforests to croplands is more important than the albedo effects (Betts, 2000; Bala *et al.*, 2007).

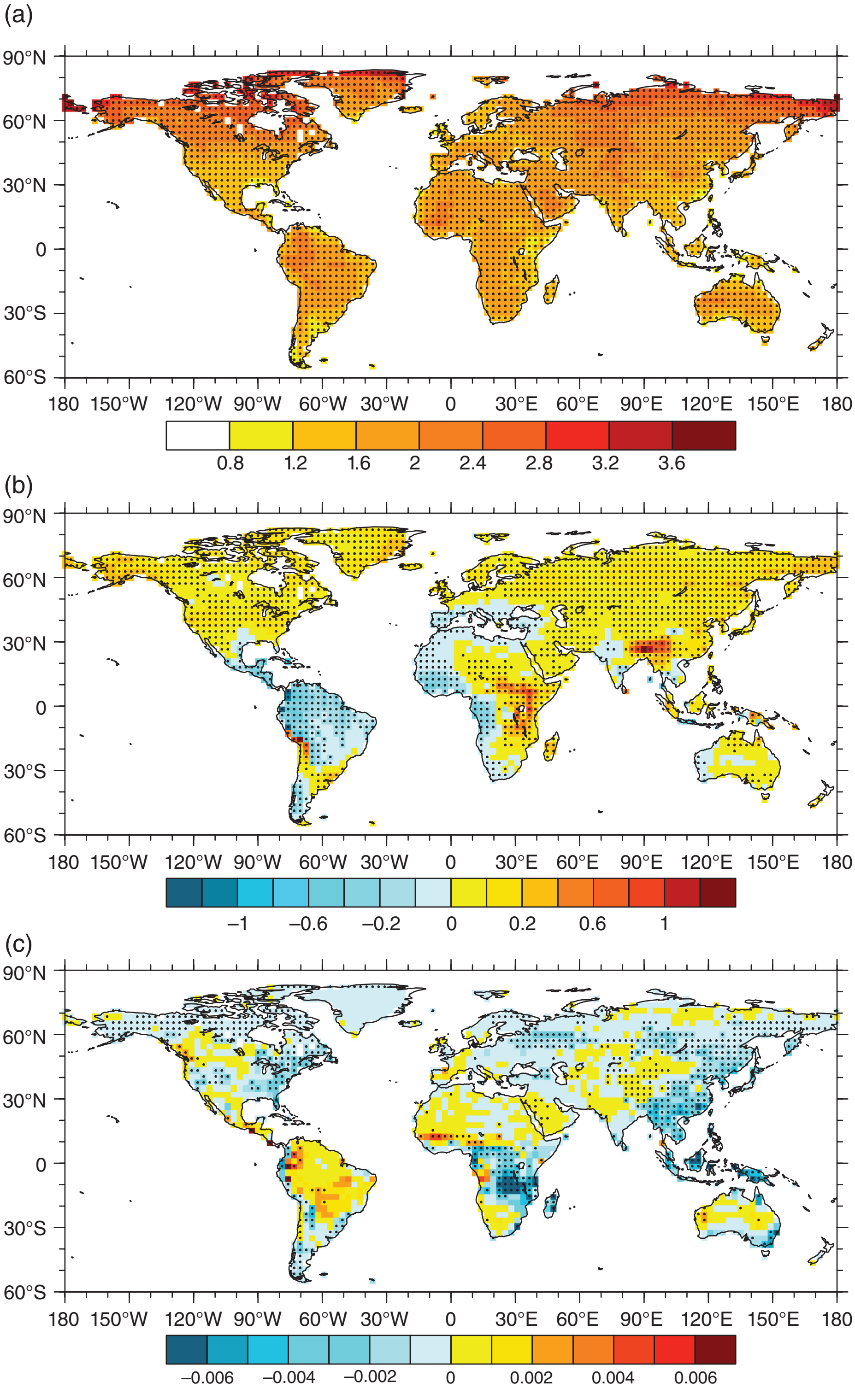

Figure 8. Geographic distribution of changes in (a) surface air temperature (°C), (b) precipitation (mm day^{-1}), and (c) land–atmosphere carbon fluxes (Pg C year^{-1}) resulting from GHGs/aerosols (L2A85-L2A26), averaged over the period 2006–2100. The hollow dots are statistically significant at the 0.05 level, and all grid points in (a) have statistically significant anomalies.

Basically, trees have larger LAI and roughness lengths than crops, and so replacing trees by crops reduces LAI and surface roughness and consequently evapotranspiration. The impact of tropical LUCC predicts an increase in precipitation in the Indo-China Peninsula and Central Africa. In contrast, South America shows a decrease in rainfall, as predicted in other climate projections (e.g. Spracklen *et al.*, 2012). Further attribution of the precipitation response to tropical LUCC is still under debate and thus beyond the scope of this paper, as changes in SST, local to regional circulation, and land surface properties also play a role (Aragão, 2012; Cook *et al.*, 2012).

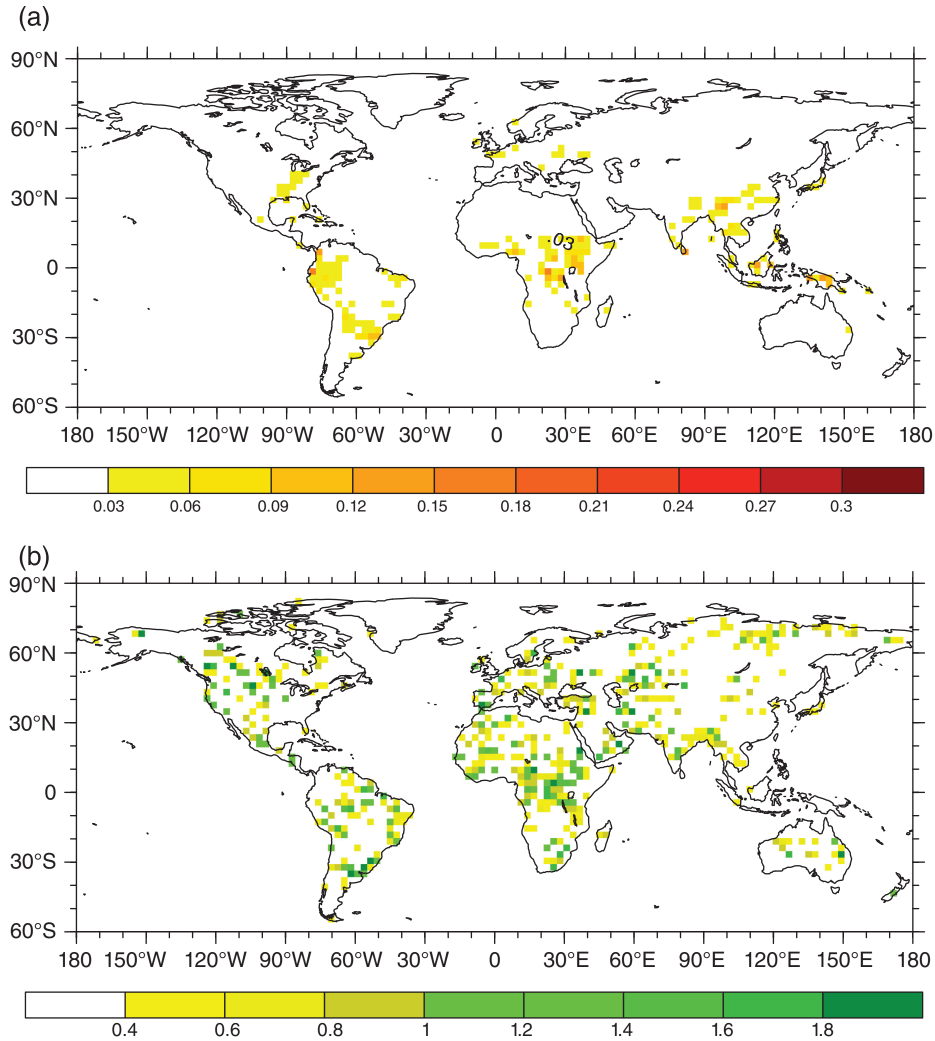

Figure 9. Geographic distribution of the ratio of the magnitude of the LUCC response to the GHG/aerosol change. (a) surface air temperature and (b) land–atmosphere CO_2 fluxes), averaged over the period 2006–2100. The impact of GHGs/aerosols can be expressed as L2A85 minus L2A26, while LUCC is represented by averaging the results for land-use change experiments for two scenarios, i.e. 0.5(RCP26–L2A26 + RCP85–L2A85). Consequently the ratio of the LUCC effect over the GHGs/aerosol effect can be quantified as follows: $\frac{0.5(\text{RCP26}-\text{L2A26}+\text{RCP85}-\text{L2A85})}{\text{L2A85}-\text{L2A26}}$.

4. Discussion and conclusion

In this study, the CanESM2 model results recommended by the LUCID project are used to assess the effects of future LUCC on climate. First, compared to previous studies, using fixed land cover change, the time-evolving LUCC as a climate forcing in the model simulations was considered to capture the effects climate–LUCC interactions. Second, both the biogeophysical and biogeochemical effects of LUCC were examined in the future climate projections. Finally, the relative contribution of impacts of GHGs/aerosols and LUCC to future climate change was quantified.

Model results show that the changes between the LUCC and no-LUCC experiments are very small, indicating a small global-scale effect of LUCC because of offsetting regional signals. The land acts as a global-scale carbon source due to the LUCC, and future global land-use emissions in the two scenarios are estimated to be 35.7 Pg C (RCP26-L2A26) and 32.1 Pg C (RCP85-L2A85). The largest regional responses are directly associated with the land cover conversion in the tropics and subtropics. The higher cropland expansion scenario (RCP2.6) was selected to investigate the regional effects of perturbing land use. As the albedo effect dominates in the mid- and high-latitudes, LUCC produces a small cooling effect of −0.02 °C in the western United States, which is expected as a result of the reduction in needleleaf evergreen trees by changing the albedo rather than by the warming effect due to the decrease in evapotranspiration. LUCC increases temperature by 0.05–0.1 °C in the tropics due to the reduction in evapotranspiration, indicating that the warming effect due to the conversion from rainforests to croplands is more important than the changes in surface albedo.

When compared with GHGs and aerosol influences, LUCC has a second-order effect at the global scale in line with previous studies (Pitman and Zhao, 2000; Voldoire, 2006). The ratio of the impact of LUCC to the impact of GHGs/aerosols reveals that the magnitude of the LUCC effect is no more than 20% of that of the GHGs/aerosols,

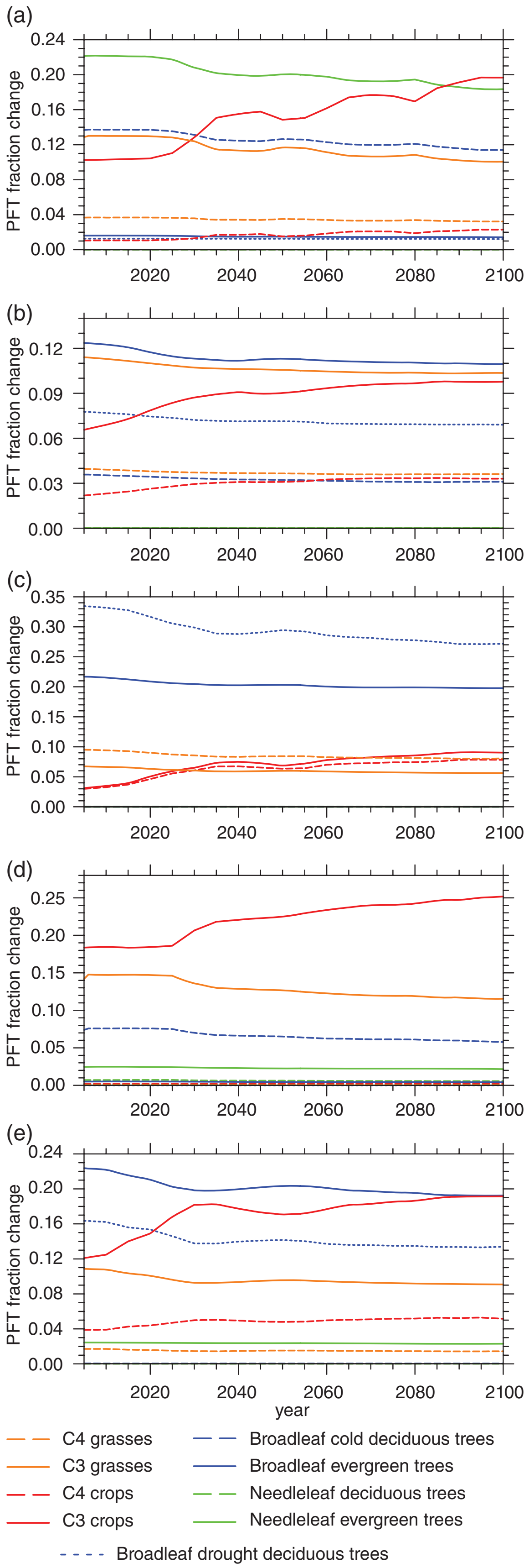

Figure 10. Regional mean annual time series of the PFT fraction changes from RCP2.6 in five regions: (a) Western United States, (b) South America, (c) Eurasia, (d) Central Africa, and (e) Indo-China Peninsula for the period 2005–2100.

indicating that the GHG/aerosol effects are dominant on the future temperature change. However, for the CO_2 fluxes, the LUCC and GHG/aerosol effects are equally important and the former is much stronger than the latter over some regions such as Africa and South and North America. The land–atmosphere CO_2 flux can be regionally modulated by LUCC when compared with the effects of GHG/aerosol forcings. Through the uptake of CO_2 from the atmosphere, the land plays an important role in the global carbon cycle. These results highlight the need to understand the carbon cycle response due to LUCC over long-time scales.

Brovkin *et al.* (2013) reported results of net land carbon storage from RCP and LUCID simulations. The difference between experiments with and without land-use change, which is an estimate of the net land-use emissions, ranged between 19 and 205 Pg C, with large uncertainties for different ESMs. These uncertainties arise because the associated biogeochemical aspects of LUCC were not well quantified and some models typically did not consider the net land-use emissions. Therefore, the calculated emissions from land-use changes vary widely for different models and approaches (Arora and Boer, 2010). In CanESM2, the approach of calculating LUCC-related emissions uses anthropogenic CO_2 emissions and changing land cover to drive the coupled climate-carbon cycle model in which CO_2 is a prognostic variable. Compared with the response in the LUCID-CMIP5 simulations in Brovkin *et al.* (2013), the global land-use emissions in our results are of the same order of magnitude as the changes in total land carbon storages in the CanESM2 model.

Based on the fully coupled ESM simulations, we explored the importance of the climate forcing of land-use and land cover processes in future climate projections. This is a new approach to evaluate the LUCC effects as recommended by LUCID. However, some limitations exist in our study. First, no significant LUCC appears at the high latitudes but the climate responses are quite opposite in the two future scenarios. This emphasizes the need to assess the possible LUCC impacts due to teleconnections and climate feedbacks (e.g. snow-albedo and ice-albedo feedback; carbon-climate feedback). Second, regarding the effects of biogeophysical and biogeochemical mechanisms for the historical LUCC, the climate response remains contradictory (Brovkin *et al.*, 2004; Matthews *et al.*, 2004). Moreover, for the future climate response due to LUCC, the biogeophysical warming (cooling) effects must be separated from the biogeochemical effects. Third, the changes in regional CO_2 fluxes resulting from LUCC can be compared with those induced by GHGs/aerosols in the CanESM2 experiments. However, uncertainties in magnitude and location exist. Also the GHGs-induced warming could lead to a shift in natural vegetation type/cover in the future (Shi *et al.*, 2012), which should be considered. We demonstrated that LUCC has an important role on the global carbon cycle and so similar experiments to explore and quantify the impact of future LUCC against GHG/aerosol perturbations would be valuable. Furthermore, the model lacks nitrogen (N) limitation, which may

Table 2. Changes of regionally averaged land surface variables during the significant PFTs changes periods.

Selected region	Year interval	Albedo ($\times10^{-4}$)	T (°C)	Pr (mm day^{-1} $\times10^{-1}$)	Net R (W m^{-2})	LH (W m^{-2})	CO_2 flux (Pg C year^{-1})
Western United States	2020–2040	0.29	−0.02	−0.03	−0.68	−0.18	0.01
South America	2006–2040	2.35	0.06	−0.28	−0.25	−0.68	0.06
Central Africa	2020–2040	4.13	0.05	0.42	−0.63	−0.13	0.20
Eurasia	2025–2040	2.95	0.00	0.07	0.05	0.12	−0.01
Indo-China Peninsula	2010–2030	8.53	0.10	0.73	−0.45	−0.46	0.07

significantly moderate how the carbon cycle changes and overestimate the terrestrial carbon uptake in the future (Sokolov *et al.*, 2008; Thornton *et al.*, 2009). Additional climate simulations that include carbon–nitrogen cycle interactions in the land components may reduce the uncertainty in predictions of future atmospheric CO_2 concentrations and the associated anthropogenic climate change (Thornton *et al.*, 2009). Fourth, because our results are from a single modelling study with limited ensemble members, a multi-model analysis (Brovkin *et al.*, 2013) will allow for the robustness of LUCC and model uncertainties to be better accounted for. However, it is difficult to implement the same land cover forcing in all the models, due to the different parameterization schemes and the lack of model consistency in representing land cover types (Pitman *et al.*, 2009; Brovkin *et al.*, 2013). Finally, a better representation of evapotranspiration and precipitation will reduce the uncertainties because the background climate affects various regional responses through the water and carbon cycles, especially in remote areas (Pitman *et al.*, 2011). It is important to obtain in-depth knowledge of model performance in simulating climate change and relevant biophysical and biochemical processes (Mahmood *et al.*, 2010).

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