Effect of anthropogenic land-use and land cover changes on climate and land carbon storage in CMIP5 projections for the 21st century


1Max Planck Institute for Meteorology, Hamburg, Germany
2Canadian Centre for Climate Modelling and Analysis, Environment Canada, University of Victoria, British Columbia, Canada
3Laboratoire des Sciences du Climat et de l’Environnement, Gif-sur-Yvette, France
4University of Maryland, USA
5University of Hamburg, Germany
6University of Exeter, UK
7Netherlands Royal Meteorological Institute, De Bilt, Netherlands
8Met Office Hadley Centre, Exeter, UK
9National Institute for Environmental Studies, Tsukuba, Japan

*Corresponding author address: Max Planck Institute for Meteorology, Bundesstr. 53, 20146, Hamburg, Germany. Phone: +49 40 41173339, Fax: +49 40 41173350, e-mail: victor.brovkin@zmaw.de
Abstract

The effects of land-use changes on climate are assessed using simulations complementary to the RCP2.6 and 8.5 scenarios performed for the fifth coupled model intercomparison project (CMIP5). This analysis focuses on differences in climate and land-atmosphere fluxes between the ensemble averages of simulations with- and without land-use changes by the end of 21st century. Even though common land-use scenarios were used, the areas of crops and pastures are specific for each Earth System Model (ESM) due to different interpretations of land-use classes. On the global scale, the fossil fuel forcing dominates the land-use forcing and the simulated effects of land-use changes in the experiments with prescribed atmospheric CO₂ concentrations are not significant. However, the biogeophysical effects are significant for regions with land-use changes exceeding 10%. For these regions, two out of five participating models, MIROC-ESM and HadGEM2-ES, reveal statistically significant changes in mean annual surface air temperature for the RCP2.6 scenario. Changes in land-surface albedo, available energy, and latent heat fluxes are small but significant for most ESMs in regions affected by land-use changes. The climatic effects are relatively small, as land-use changes in the RCP2.6 and RCP8.5 scenarios are small in magnitude and mainly limited to tropical and subtropical regions. The relative importance of the climatic effects of land-use changes is higher for the RCP2.6 scenario (low CO₂ forcing), which considers an expansion of biofuel croplands as a climate mitigation option. A robust signal across all models is the loss in global land carbon storage due to land-use changes.
1. Introduction

About one third to one half of the land surface has been modified by humans (Ellis 2011; Vitousek et al. 1997), and this extent is likely to increase in the future to accommodate a growing demand for land (Carpenter et al. 2006). Anthropogenic land-use and land cover change (LULCC) affects climate through alteration of near-surface energy and moisture exchange, as the physical characteristics of the land surface such as albedo, soil moisture, and roughness are changed (the biogeophysical pathway). LULCC also affects climate through changes in atmospheric concentrations of greenhouse gases (GHGs) such as CO₂, CH₄, and N₂O resulting from alteration the land-atmosphere fluxes (the biogeochemical pathway, Arora and Boer 2010; Canadell et al. 2007; Houghton 2003; House et al. 2002; Pongratz et al. 2009; Shevliakova et al. 2009). Numerous biogeophysical and biogeochemical processes are parameterized in the land surface schemes of atmospheric general circulation models (AGCMs), which simulate the exchange of heat, moisture, and CO₂ between the land surface and the atmosphere (e.g., Bonan 2008; Dickinson et al. 1993; Sellers et al. 1997). LULCC has been shown to result in seasonal changes in temperature, precipitation patterns, snow cover in high latitude regions, and atmospheric dynamics (e.g., Bala et al. 2006; Chase et al. 2000; Claussen et al. 2004; Feddema et al. 2005).

The project 'Land-Use and Climate, IDentification of robust impacts (LUCID)' is focused on the biogeophysical effects of LULCC on climate. Pitman et al. (2009) investigated the climatic effect of land cover changes from preindustrial period to present-day using several AGCMs. The models simulated substantial changes in
latent and sensible heat fluxes, albedo, and therefore absorbed shortwave radiation, and near-surface air temperature over the regions with considerable LULCC, but the magnitude of those biogeophysically-induced changes differed considerably among the models. De Noblet-Ducoudré et al. (2012) and Boiser et al. (2012) analyzed the mechanisms that explain those differences, and Pitman et al. (2012) showed that LULCC leads to reduced temperature extremes. Van der Molen et al. (2011) showed that feedbacks in local cloud cover are important to explain differences between tropical and extratropical temperature responses to LULCC.

The LUCID experiments were designed to investigation the LULCC effects on climate using prescribed sea surface temperatures (SSTs) and sea ice, focusing on land-atmosphere interactions. This approach allows isolation of the direct effects of LULCC on the atmosphere from the indirect effects caused by interactions with the other components of climate system, for example, sea ice. However, neglecting these feedbacks may reduce the magnitude of effects of LULLC on climate (e.g., Davin and de Noblet-Ducoudre 2010). On decadal to centennial timescales, the feedbacks through interactive SSTs and sea ice have the potential to enhance the biogeophysical cooling that occurs in response to historical LULCC (Brovkin et al. 2006). Coupled atmosphere-ocean simulations are crucial for future climate change projections, because the ocean plays a dominant role in the climate response to high levels of GHG concentrations. Pitman et al. (2011) have demonstrated that LULCC impacts depend on the background climate. The climatic effect of LULCC in the future scenarios are generally secondary in comparison to the climatic effects of fossil fuel emissions (Sitch et al. 2005), while the magnitude and patterns of LULCC-induced climatic changes are scenario-dependent.
The fifth Coupled Model Intercomparison Project (CMIP5) is a coordinated effort of more than 20 climate modeling groups from around the world to improve our understanding of climate change (Taylor et al. 2012). Integrated Assessment Model (IAM) groups provided the CMIP5 community with four representative concentration pathways (RCPs) of greenhouse gases, aerosols, and land use and land cover changes through the 21st century. The set of RCP scenarios envelopes different scenarios of future land-use changes, which satisfy the demand for food, biofuels and afforestation (or reforestation) to mitigate CO₂-induced climate changes.

In the core set of CMIP5 simulations, Earth System models (ESMs) are driven through the 21st century by a set of RCP scenarios that include land-use changes. To isolate the effect of land-use changes on climate, several CMIP5 modeling groups performed additional LUCID-CMIP5 simulations without anthropogenic land-use changes from 2006 to 2100. The differences between simulations with and without land-use changes reveal climatic effects of LULCC on global and regional scales. In this paper, we examine the biogeophysical effects and changes in the land carbon storage due to LULCC, focusing on two RCP simulations driven by prescribed CO₂ concentrations. These simulations allow to quantify the climatic effect of changes in land cover in comparison to those caused by changes in fossil fuel emissions for the RCP scenarios considered here. The inter-model comparison provides insight into the core research question concerning uncertainty in climatic effects of land-cover changes due to differences in model parameterizations.
2. Experimental setup

Two RCP scenarios were considered among the four CMIP5 scenarios of climate change in the 21st century. The RCP8.5 scenario produced by the MESSAGE IAM (Riahi et al. 2011) corresponds to a radiative forcing of more than 8.5 W/m² and a CO₂ concentration of 936 ppm in 2100. It represents the upper 10th percentile of the future scenario range for CO₂ emissions (Moss et al. 2010). In contrast, the RCP2.6 scenario simulated by the IMAGE IAM (van Vuuren et al. 2011) represents pathways in the lower 10th percentile of climate mitigation scenarios (Moss et al. 2010). The RCP2.6 scenario assumes a peak of radiative forcing of 3.1 W/m² around 2050 followed by a decline towards 2.6 W/m² and a CO₂ concentration of 420 ppm in 2100. These two scenarios span the two extremes of projected climate change over the 21st century. Each of these scenarios is supplemented by a set of explicit LULCC data. Despite a strong difference in radiative forcing between these two scenarios, they both include a substantial increase in cultivated land by the end of the 21st century, although for different reasons. In the RCP8.5 scenario, expansion of agricultural land (cropland and pastures) is driven by the food demands of an increasing population, while in the RCP2.6 scenario the climate change mitigation is partly achieved by an increase in the area used for production of bioenergy crops. The total global area used for pastures is more-or-less constant in the RCP2.6 over the 21st century, as the increase in production of animal-based products is met through a shift from extensive to more intensive animal husbandry.

a. Harmonized land-use change scenarios
The IAM land-use scenarios are diverse; each operates with different classes of land cover and land use, different spatial and temporal resolutions, and different assumptions about the historical land-use reconstruction that the future projections are built off. In addition, the data from IAMs is not always in the format required by ESMs. These challenges are addressed using a “harmonized” set of RCP land-use change scenarios developed by Hurtt et al. (2011) that seamlessly connects gridded historical reconstructions of land-use with future projections in a format required by ESMs, while preserving as much information in the future scenarios as possible. The Global Land-use Model (Hurtt et al. 2006) was adapted and extended to produce new estimates of global land-use patterns (fractional content of crop, pasture, urban, primary land, and secondary land in each grid-cell) and underlying annual land-use transitions (i.e., which type of land-use was converted to which different use, and where) at 0.5°×0.5° resolution beginning in 1500, and connecting seamlessly in 2005 to the future projections provided by IAMs to 2100. Although agreement between IAMs on 2005 land-use values was generally good at the global scale, there were still significant regional differences. To address this issue, IAM decadal changes in land-use were aggregated over a 2°×2° grid, and these changes were applied sequentially to the 2005 land-use distribution of HYDE3.1 database (Goldewijk et al. 2011). The resulting 2°×2° grids were then disaggregated into 0.5°×0.5° grids, weighted by available land for crop and pasture increases, and applied proportionally for cropland or pasture decreases, and interpolated temporally to get annual grids. Resulting changes in land-use between 2005 and 2100 are shown in Fig. 1 for cropland (top), pasture (middle), and total agricultural land (bottom).
Two sets of LUCID-CMIP5 simulations, L2A26 and L2A85, were performed with the CMIP5 models using the same forcings as for the RCP26 and RCP85 experiments but with land-use prescribed to the state in 2006 (Tab. 1). To explore the uncertainty related to internal climate variability, an ensemble of several members was performed if computationally affordable. The number of analyzed LUCID-CMIP5 simulations ranges from 1 for the MIROC and IPSL-CM5A models to 3 for the CanESM2 model (Tab. 2).

**b. Implementation of land-use changes**

The harmonized scenarios of land-use change and woody harvest were implemented into the five participating ESMs in different ways following the structure of their land surface models. A brief description of these models is provided in the appendix.

**CanESM2**

CanESM2 includes the changes in crop area from the harmonized land-use change scenarios following the linear approach of Arora and Boer (2010). In this approach the fractional coverage of herbaceous and woody PFTs is reduced by an amount proportional to their existing coverage in order to allow an increase in crop fraction. If the crop fraction decreases, the fractional coverage of natural PFTs is increased while ensuring that these PFTs can potentially exist in a grid cell. The effect of changes in pasture area on land cover is not taken into account. A simple crop model is used over the cropland fraction of a grid cell. That determines
harvest based on temperature or phonological criteria. This typically leads to one annual crop cycle in high- to mid-latitude regions and multiple crop cycles in tropical regions. Harvesting ensures that vegetation biomass does not keep increasing on croplands as CO₂ increases, and prevents croplands from sequestering carbon like forests.

HadGEM2-ES

In the HadGEM2-ES model, the crop and pasture fractions from the harmonized land-use change scenarios are added together and interpreted as a fraction of agricultural land. This agricultural fraction is added as a mask on top of simulated dynamic vegetation to prevent woody vegetation within the agricultural area. Grassland is preferentially used for agriculture. For example, if an area would naturally have 50% tree and 50% grass, but the agriculture fraction is 70%, then the tree fraction is limited to 30%. The vegetation dynamics module simulates growth of grass or not (i.e. allocate bare soil) in the remaining 30% area depending on the prevailing climate. When the agriculture mask increases, natural vegetation is removed. But when agricultural area is reduced, then the vegetation dynamics module simulates re-growth of trees and grasses in that place, provided the climate is suitable.

IPSL-CM5A

In the IPSL-CM5A model, the identical land-cover map is used for both the historical and the future period. It is based on an observed present-day land-cover map (Loveland et al. 2000), that includes natural and anthropogenic vegetation types. The land-use changes are implemented in the following way. Firstly, the
area covered by crops, per year and per grid-cell, is set to the value provided by the harmonized land use-change scenario. The expansion of this crop area proportionally occurs at the expense of all natural vegetation types. This means the percent by which natural grasses and tree areas are reduced is the same for all PFTs. Reciprocally, a reduction of the anthropogenic area implies a proportional increase of all natural vegetation types existing in any given grid-cell. If no information is available on the natural vegetation distribution at a specific location (i.e. 100% anthropogenic types on the original land-cover map used) then the model algorithm searches for the nearest point that has natural vegetation and introduces these vegetation types. The desert extent is kept unchanged from pre-industrial times till the end of the 21st century, with one exception: desert is reduced, if the anthropogenic area is larger than the natural vegetation part of the grid-cell. After this first step where the change in crop area has been handled, grazing is introduced as follows: if the pasture area from the land-use scenario is lower than the area covered with grasses and shrubs, nothing is changed. If the pasture area is larger than the area covered with grasses and shrubs, a part of the forested area is replaced by grassland.

**MIROC-ESM**

In the MIROC-ESM model, each land grid cell is subdivided in 900 cells of the terrestrial ecosystem model. The number of these cells assigned as cropland, pasture, and urban land is defined according to the harmonized land-use fraction. Cells for primary and secondary land are simulated with a dynamic vegetation module, and the fraction of grassland and forest is changing with time. In cells assigned as secondary land, the vegetation dynamics module simulates re-growth
of trees and grasses after the abandonment of cropland and pasture. The conversion of land-use types follows a simple rule of cell arrangement within the grid.

**MPI-ESM**

The MPI-ESM model combines primary and secondary land into one vegetation class (natural vegetation) and considers transitions between 3 vegetation classes (natural vegetation, croplands, pastures). Allocation of new croplands and pastures follows several simple rules (Reick et al. 2012). The demand for pastures is firstly covered by natural grasslands, and only if there is no grassland area left, areas of woody PFTs (trees and shrubs) are allocated to pastures. This rule assumes that using natural grassland as a pasture is an easier way for farmers to manage the land. The demand for croplands is equally shared among all natural PFTs in the land grid cell. MPI-ESM includes a dynamic vegetation model (Brovkin et al. 2009), and the fraction of natural vegetation, such as grassland and forest, is changing with time. This can potentially lead to some changes in cropland and pastures areas when the regional climate becomes unsuitable for any natural vegetation (Reick et al. 2012). Unlike the other models, the MPI-ESM also uses information from the harmonized protocol on wood harvest.

Only two of the five models, MIROC-ESM and MPI-ESM, account for the transition matrix in the harmonization protocol by Hurtt et al. (2011). This transition matrix provides annual fractions of changes in the land grid cells from one land use class to another. The implementation of this scheme has different consequences for the carbon cycle than for the vegetation cover. For example, a cyclic conversion of
forest to pasture, pasture to cropland, and cropland to forest leads to no changes in land surface fractions covered by the particular PFTs, but however leads to a reallocation of the carbon reservoirs among the PFTs. This results in extra CO$_2$ emissions that result from transitional changes in carbon pools due to simultaneous clearing and regrowth of forest although the net forest cover in the grid cell does not change.

Implementation of cropland into the land surface schemes of ESMs is very simplistic. Out of five models, only CanESM2 explicitly models crop PFTs. Other ESMs treat cropland as grassland with the same albedo and the same or slightly modified carbon cycle parameterization (MPI-ESM assumes different parameters of photosynthesis and phenology for crops). In these ESMs, a change from grassland to pasture does not lead to a significant change in land surface parameters.

ESMs account for changes in pastures in various ways. A spread among models is clearly visible in Fig. 2 for the RCP8.5 scenario which assumes that a substantial part of western Australia is converted to pasture by 2100. Models with dynamic vegetation (HadGEM-ES, MIROC-ESM, MPI-ESM) use this scenario in calculation of land cover changes. CanESM2 does not account for changes in pastures assuming that this change in land-use does not translate into changes in land cover. IPSL-CM5A uses observed vegetation cover and this results in almost no changes in vegetation cover in Australia in RCP8.5. The diversity among the models in crop fractions is also considerable, although most of the patterns are reproduced in the tropics (Fig. 2). The temporal dynamics of crop area changes presented in Fig. 3
(top) show a relatively smaller spread between the models (± 1 SD) in comparison with the pasture changes (Fig. 3, middle). On average, the RCP2.6 simulations show almost twice as high changes in crop areas as the RCP8.5 scenario. In contrast, the average decrease in tree cover in both simulations is very similar, although the spread in simulated tree fraction is more substantial than for the crop fraction (Fig. 3, bottom). Without land use changes in the L2A26 and L2A85 simulations, the models with dynamic vegetation simulate an increase in tree cover in response to climate and CO₂ changes (Fig. 3, bottom).

The implementation of the harmonized scenarios in the land surface schemes is the first step in the interpretation of the land-use changes. The models are different not only in the way land-use change is interpreted in terms of land cover changes, but also in translating these land cover changes into biogeophysical and biogeochemical characteristics of the land surface. These differences among the land surface schemes of the participating models are expected to yield differences in the simulated climatic response to land use changes.

3. Results and discussion

a. Changes in temperature and precipitation

In response to the RCP scenarios, all models simulate an increase in global mean annual temperature (Fig. 4, top). The diversity among the models mainly reflects different sensitivity of the models to CO₂ and other (e.g. aerosol) forcings, with MPI-ESM-LR being the least sensitive (0.5K and 3.8K increase between 2006-2100
for RCP2.6 and 8.5, respectively), while MIROC-ESM being the most sensitive (1.6K and 5.2K for 2.6 and 8.5 scenarios, respectively). The difference in global mean annual temperature between the RCP and LUCID simulations shown in dark and light colors, respectively (Fig. 4, top), is quite small and not statistically significant for any model due to substantial interannual variability simulated by ESMs. In addition, the imposed LULCC changes are quite small and dispersed (no strong coherent change in one region). As a result, the signal-to-noise ratio is too low to be pronounced on the global scale. However, the LULCC effect is significant for two models – CanESM2 and HadGEM2-ES – for the RCP2.6 scenario if the temperature is averaged over the regions with considerable land-use change (where LULCC over the period 2006-2100 exceeds 10% of grid cell area). For these regions, the CanESM2 model simulates an increase of 0.1K in annual mean temperature averaged over 2070-2100 due to LULCC, and HadGEM2-ES – a decrease by 0.1K (Fig. 4, bottom; Tab. 3). It is also notable that the temperature spread in 2100 among the models is less pronounced for the RCP8.5 than for the RCP2.6 scenario (Fig. 4, bottom). This may indicate that the sensitivity of the land temperature in the LULCC regions to the forcing of the RCP8.5 scenario is similar to the global mean, while for the RCP2.6 scenario the differences between the models are larger in these regions of considerable LULCC. The global temperature response in the RCP8.5 is also less diverse among the models than in the RCP2.6 (Fig 4, top).

Spatial plots of significant changes in mean annual temperatures due to land-use changes are shown in Fig. 5. The MPI-ESM, HadGEM2-ES, and IPSL-CM5A models show little response, while CanESM2 shows a significant temperature increase in central Africa and MIROC-ESM in South America in the RCP2.6 scenario. For
tropical and subtropical regions, the seasonality of the response of near surface air
temperature for regions where LULCC exceeds 10% is small (Fig. 6). The
temperature response to changes in LULCC is most pronounced for Australia for
the RCP8.5 scenario characterized by a strong increase in pasture in this region. All
models that account for the pasture changes (MPI-ESM, MIROC-ESM, HadGEM2-
ES) show a decrease in temperature over LULCC>10% regions almost in all
seasons with the strongest cooling of 1K simulated by the MIROC-ESM model. The
model response depends on the manner in which pasture changes are interpreted
in the models. A conversion from the shrubby-type natural vegetation to pasture
(rangeland) in Australia may not be followed by a decrease in shrub cover, as is
assumed in most of the ESMs, which in most cases treat pastures as grasslands.

Similar to temperature, precipitation changes due to LULLC are only statistically
significant in regions where LULCC exceeds 10%. For the RCP2.6 scenario, annual
mean precipitation in these regions is slightly reduced by ca. 10-25 mm/yr in
2071-2100 in MPI-ESM and HadGEM2-ES. A precipitation reduction of the same
magnitude is significant for CanESM2, MIROC-ESM and HadGEM2-ES in the RCP8.5
scenario (Tab. 3).

The land-use changes in the analyzed RCP scenarios (ca. 6 to 8×10^6 km^2) is about
10-30% of the historical LULCC between 1500 and 2005 estimated by Hurtt et al.
(2011), being 15.6×10^6 km^2 of cropland and 33.4×10^6 km^2 of pastures. A
substantial part of historical LULCC occurred in the mid-latitudes of Eurasia and
North America, where snow-masking effects of forest leads to a biogeophysical
cooling effect of deforestation. The magnitude of this cooling differs among the
models. ESMs of intermediate complexity suggest a global cooling effect of 0.1 to 0.3K (Brovkin et al. 2006), while ESMs of full complexity reveal a less pronounced effect. Pongratz et al. (2010) found the cooling biogeophysical effect of LULCC over the last millennium to be 0.03 and 0.04 K averaged over the global and land, respectively. Lawrence et al. (2012) reported 0.1K cooling over the land for the historical period of 1850 to 2005. The scale of biogeophysical effects in RCPs scenarios found in our study is limited to 0.1K changes over land with LULCC >10%. This is consistent with a cooling of 0.1K over agricultural regions found in the study by Pongratz et al. (2010). Therefore, regional climatic effects of future land-use changes could be comparable to the effects of the past land-use changes, when projected regional land-use changes are considerable. On a global scale, the biogeophysical effects of the RCP scenarios are smaller not only due to their lower magnitude in comparison to historical LULCC, but also due to the dominant geographical location of RCP land-use changes in tropics and subtropics, where snow-masking effect of forests does not play a role and negative feedbacks via cloud cover may be stronger. A large uncertainty in biogeophysical effects in the tropics is related to the effects of land-use on evapotranspiration, air humidity and clouds (Davin and de Noblet-Ducoudre 2010; Van der Molen et al. 2011) which vary strongly among ESMs.

b. Changes in albedo, available energy, and latent heat flux

In response to changes from natural ecosystems to crops or pastures, a fraction of tree and/or grass PFTs is replaced by agricultural vegetation, which in most cases has a higher albedo. These changes in land surface albedo for areas affected by
LULCC are statistically significant for all models on an annual basis (Tab. 3). The difference in annual albedo between RCP and LUCID simulations by 2070-2100 is most substantial in the MPI-ESM (0.007), HadGEM2-ES (0.006) and IPSL-CM5A (0.004) models (Fig. 7). This increase in albedo in tropical regions leads to a substantial reduction in available energy (Fig. 8b), defined as $Q_S(1-\alpha) + Q_{Ld}$, where $Q_S$ is the shortwave radiation incident at the land surface, $\alpha$ is the surface albedo, and $Q_{Ld}$ is the downwelling infrared radiation at the surface. This is not always reflected in temperature changes (Fig. 5). The seasonality of the albedo differences is small (Fig. 8a), presumably because seasonal changes in albedo in the tropics and subtropics are small in parameterizations of land surface processes in the models. This is different from seasonal changes in snow-covered regions in mid- and high latitudes where the snow-masking effect of forests is important to consider (e.g., Bonan 2008).

Land use-induced changes in latent heat fluxes differ among the models. Most ESMs show a statistically significant decrease of latent heat flux for regions of considerable LULCC (Fig. 9). Decrease in the latent heat flux for areas with LULCC exceeding 10% in South America is pronounced in the MPI, HadGEM2-ES, and IPSL-CM5A models (Fig. 10). These are models with a significant increase in albedo and reduction in available energy, and reduction in latent heat flux does not cause an increase in temperature (the HadGEM2-ES model shows a reduction of temperature by 0.1K in RCP2.6). In contrast, the MIROC-ESM model in RCP2.6 has almost no reduction in latent heat flux in South America in all seasons except MAM, while it simulates an increase in temperature by 0.1K. Differences in albedo in
response to land cover changes among models can lead to these opposite climatic
effects, although their magnitude remains small.

Simulating an interactive ocean response is important to account for feedbacks
though SSTs and sea ice. This is inherent to the LUCID-CMIP5 simulations. The
drawback of using an interactive ocean component is that it does increase the
variability of simulated climate and decreases the signal-to-noise ratio in
sensitivity experiments using small forcings, such as LULCC. In this study, this
drawback was partly accounted for by executing ensemble simulations for three
ESMs. To account for changes in background climate in the case of global warming,
Pitman et al. (2011) performed LUCID simulations with SSTs and sea ice
prescribed from atmosphere-ocean simulations generated for a 2xCO₂
concentration scenario. They conclude that estimating future biophysical changes
due to LULCC requires an accurate simulation of changes in snow cover and
rainfall in the regions of LULCC, particularly at mid- and high latitudes. While the
approach with prescribed SSTs and sea ice is appropriate for analysis of regional
land-atmosphere interactions, a net estimate of global LULCC effect on climate,
especially in tropics, requires simulating dynamic ocean response (Davin and de
Noblet-Ducoudre 2010).

c. Changes in land carbon storages

A robust signal across models is the loss in global land carbon storage due to
LULCC (Fig. 11). In nearly all simulations with and without LULCC global
terrestrial carbon stocks increase, although with substantial spread (Fig. 11, top).
This increase can be explained by the effect of CO$_2$-fertilization that tends to enhance the uptake of CO$_2$ by terrestrial plants and that more than compensates the carbon losses associated with changes in temperature and precipitation (Arora et al. 2012; Friedlingstein et al. 2006). In the RCP scenarios, this carbon gain is offset substantially by emissions resulting from clearing of natural vegetation (Fig. 11, top).

The difference between net land carbon storage in the RCP and LUCID simulations, as shown in Fig. 11, is an estimate of net land-use emissions which accounts for both carbon loss due to clearing of vegetation and carbon gain due to regrowth of vegetation after abandonment of management. The experimental setup of LUCID-CMIP5 simulations allows biogeophysical climatic changes associated with local LULCC to affect terrestrial carbon storage. This is usually not considered in quantifications of net land-use emissions. Net land-use emissions have been quantified for the historical time period (e.g., Houghton et al. 2012; Pongratz et al. 2009) and the SRES future scenarios (Sitch et al. 2005; Strassmann et al. 2008). These previous studies have revealed large uncertainties in emission quantification, on the order of +/-50%, partly since the manner in which land-use change emissions are calculated varies widely amongst the different models and approaches (Arora and Boer 2010). These uncertainties arise from differences in implementation of LULCC data, inclusion or exclusion of specific land-use processes such as wood harvest (see Tab. 2), and different climate-carbon cycle representation in ESMs (Houghton et al. 2012). When the MPI model is excluded, the spread across models in LUCID-CMIP5 is of the same order of magnitude as these previously defined uncertainties.
The large loss in global carbon storage in both scenarios of the MPI-ESM is a result of an overestimation of initial carbon stocks in this model in the tropics and drylands, so that carbon loss due to clearing is overestimated. Another reason of higher carbon losses may also be the use of transition land-use matrices (Tab. 1). The MIROC-ESM, which also uses transitional matrices, is the model which yield second highest net land-use emissions. Consideration of transition land-use change matrices implies that rotational LULCC is accounted for instead of only net changes, which results in additional land-use change emissions above those resulting from net changes in crop and pasture area.

There are some robust features in the pattern of changes in carbon stocks. For instance all models simulate a carbon loss in the tropical rainforests, especially over central Africa and eastern South America (Fig. 12). In these regions, strong LULCC coincides with high initial carbon stocks. Smaller regions show carbon gains, but the pattern varies across models. Increased carbon stocks by 2100 result partly from abandonment of agriculture (see for instance the RCP8.5 scenario in regions such as North America). In other cases a change from natural vegetation to managed land may increase carbon stocks, e.g. due to larger root mass under grasslands/pasture; the realism of the representation of such processes in ESMs is, however, limited.

Three of four models simulate a stronger carbon loss due to LULCC in RCP8.5 than RCP2.6, despite almost identical forest cover changes in both scenarios. The likely reason is that in RCP8.5 more tropical rainforest with high carbon stock is cleared,
while in RCP2.6 also clearing of natural vegetation in the extra-tropics occurs strongly for use in bio-energy. In the extra tropics lower carbon stocks prevail, and some of these areas are regrowing forest in RCP8.5. Note that another effect would tend to act in the opposite direction: Almost all expansion of agricultural land in the RCP2.6 scenario is realized as expansion of croplands, while in the RCP8.5 scenario both croplands and pastures increase. Pasture, however, tends to be treated as natural grasslands in ESMs. Therefore, smaller carbon stock changes can be expected in the pasture-rich RCP 8.5 scenario.

Lawrence et al. (2012) reported results from simulations of biogeochemical effects of LULCC in the RCP scenarios using the Community Climate System model (CCSM4). They have not performed simulations without land-use change as in the LUCID-CMIP5 protocol but estimated changes in total land carbon and land-use emissions from the RCP simulations. For RCP2.6 and 8.5, their model simulates a net release of 18.6 and 30.3 PgC during 2006-2100, respectively, from land ecosystems to the atmosphere. Comparing with the response of LUCID-CMIP5 models (Fig. 11b), the CCSM4 results are at the low end.

The L2A85 and L2A26 simulations were performed with prescribed atmospheric CO2 concentrations, therefore they do not provide a direct estimate of biogeochemical effects of LULCC emissions. Gillett et al. (2012) calculate transient response to cumulative emissions (TRCE, °K/EG C) which is defined as the ratio of global mean warming to cumulative emissions at CO2 doubling using results from 1% yr⁻¹ CO2 increase simulations for 12 participating CMIP5 models. Here, we multiply net land-use changes emissions (Fig. 11) by their corresponding model's
TRCE to translate them into equivalent temperature changes. The methodology provides coarse estimates but nevertheless gives a first-order estimate of the temperature effect associated with the biogeochemical pathway of land-use change. For RCP 8.5, the changes are below 0.1K for all models except for the MPI-ESM (Tab. 4), which as mentioned above, overestimates the carbon release due to land-use change. For RCP 2.6, the effect is more pronounced due to lower background CO₂ concentration. For HadGEM2-ES and CanESM2, the temperature changes are below 0.1K, but MIROC-ESM and MPI-ESM yield more substantial changes of 0.14 and 0.33K, respectively. This suggests that the biogeochemical effect of land use-changes is more substantial in absolute and relative terms for the climate change mitigation scenario.

The geographical location of the land-use changes is essential for their climatic effects. Claussen et al. (2001), Bala et al. (2007), and Bathiany et al.(2010) performed large-scale deforestation/afforestation experiments using ESMs of different complexity. They concluded that boreal deforestation cool the climate because the biogeophysical cooling dominates over the biogeochemical warming, while tropical deforestation warms the climate due to the dominant biogeochemical effect. A limited climatic effect of LULCC in our simulations does not confirm or reject these large-scale results because of rather small land cover changes in the RCP scenarios.

4. Conclusions
The LUCID-CMIP5 experiments were designed to evaluate climatic effects of future land-use change scenarios using ESMs participating in the CMIP5. The analysis here was limited to experiments with prescribed atmospheric CO₂ concentrations. We investigated a difference in climate and land carbon storage between the average of ensemble members with- and without land-use changes by the end of 21st century. A variety among responses of five ESMs to land-use forcing indicated an uncertainty due to differences in model parameterizations under an extreme range of projected CO₂ forcings.

On the global scale, simulated biogeophysical effects of land-use changes projected in the RCP2.6 and RCP8.5 scenarios were not significant. However, these effects were significant for regions with land-use changes exceeding 10%. Two out of five participating models, MIROC and HadGEM2-ES, revealed small (0.1K) but statistically significant changes in regional mean annual surface air temperature for the RCP2.6 scenario. Changes in land surface albedo, available energy, and latent heat fluxes were small but significant in most ESMs for regions with considerable land-use changes. The small scale of climatic effects of LULCC in the RCP scenarios is likely explained by the relatively small scale of land-use changes and their dominance in the tropical and subtropical regions where the difference between biogeophysical parameters of land cover types is less pronounced than in mid- and high latitudes. This conclusion on the small scale of biogeophysical effects is valid only for the studied RCP scenarios. For example, changes in land cover of larger scale located in regions with seasonal snow cover would lead to larger climatic effects.
In both the RCP2.6 and RCP8.5 scenarios, land-use change leads to a reduction in land carbon storage. The difference between experiments with- and without land-use change ranges between 19 and 205 PgC, with the high number generated by MPI-ESM is likely overestimating the carbon release due to too high initial carbon stock. The spread in the LULCC-induced CO$_2$ emissions is due to differences in parameterizations of land carbon processes such as CO$_2$ fertilization, regrowth strength, initial carbon storage, and wood harvest implementation. ESM spread in future carbon cycle changes is dominated by uncertainty in land carbon uptake (Arora et al. 2012; Jones et al. 2012). Jones et al. (2012) discuss that model representation of land-use change is an important contribution to future land carbon spread between models. The LUCID-CMIP5 simulations help quantify this spread.

Interpreted in terms of global temperature increase, the warming due to land-use emissions is likely to be limited by 0.1K in three out of five models, while it is it higher in the two other models that account for transitions in land-use. While this warming effect is negligible for the RCP8.5 scenario with an increase of global mean temperature by 3.8 to 5.2K, it is relevant for the climate mitigation scenario RCP2.6 with a global warming of 0.5 to 1.6K in 21st century. Note that the experiments reported here were performed with prescribed CO$_2$ concentrations, and a full assessment of biogeochemical effects of RCP land-use scenarios is beyond the scope of this study.

The LUCID-CMIP5 experiments demonstrated different responses of ESMs to the land-use forcing, which is in line with findings of previous intercomparison
experiments in the LUCID framework (e.g., de Noblet-Ducoudre et al. 2012; Pitman et al. 2009). The diversity of the model responses is caused by a number of reasons. Firstly, the models varied in interpretation of harmonized land-use change scenarios (crops, pastures, primary and secondary land) in terms of land cover (PFTs) used in ESMs. Some ESMs (HadGEM2-ES, MIROC, MPI-ESM) include modules of vegetation dynamics which makes allocation of land to cropland and pasture dynamically changing with climate changes. Thus, the rules of land-use changes interpretation in models with dynamic vegetation are more sophisticated in comparison with models with prescribed land cover and have a larger number of degrees of freedom (Reick et al. 2012). Secondly, ESMs treat changes in land cover using different parameterizations of land surface processes. For example, models with significant albedo response (HadGEM2-ES, IPSL-CM5A, MPI-ESM) tend to cool the land surface due to land-use changes, at least in the RCP2.6 scenario, while a model with smaller albedo changes (MIROC) shows an increase in the land temperature for the same scenario. A way forward to reduce uncertainty in projections of climate response to land-use changes is now under intensive debate in the land-surface modeling community (Pielke et al. 2011).

Although the model responses to the forcing varied substantially, we can draw several robust conclusions out of the model experiments. Firstly, the fossil fuel forcing dominates over the land-use forcing in the RCP projections in the 21st century when considering large-scale averages. This is different from the historical period when the land use-forcing, especially via CO$_2$ emissions due to land-use, were of similar order of magnitude to the fossil fuel forcing. However, even for the high emission forcing, the land-use change affects climate on a regional scale.
Secondly, for low CO₂ emission scenarios, such as RCP2.6, the relative role of land-use forcing is significant. The regional biogeophysical changes are of the order of 0.1K. The global biogeochemical effects are in the order of 0.1K as well, and some models suggest an increase in global temperature in the range of 0.1-0.3K, which is comparable with 0.5-1.6K warming in the 21st century simulated for the RCP2.6 scenario. Besides, this scenario involves land-use changes for biofuel crop production. Therefore, a further analysis of climatic effects of land-use changes is essential for assessment of climate mitigation scenarios and regional climate adaptation.

Appendix. Model descriptions

Brief descriptions of the physical atmosphere and ocean components and the land carbon cycle component of the participating ESMs are provided below.

Canadian Centre for Climate Modelling and Analysis’ (CCCma) CanESM2

CanESM2 has evolved from the first generation Canadian earth system model (CanESM1) (Arora et al. 2011; Christian et al. 2010) of the Canadian Centre for Climate Modelling and Analysis (CCCma) and described in (Arora et al. 2011). The vertical domain of the atmospheric component of CanESM2 (CanAM4) extends to 1 hPa with the thicknesses of the model’s 35 layers increasing monotonically with height. The physical ocean horizontal resolution is approximately 1.41° (longitude) × 0.94° (latitude) in CanESM2.
Terrestrial ecosystem processes are modelled using the Canadian Terrestrial Ecosystem Model (CTEM) which simulates carbon in three live vegetation pools (leaves, stem, and root) and two dead pools (litter and soil organic carbon) for nine plant functional types (PFTs) - needleleaf evergreen and deciduous trees, broadleaf evergreen and cold and dry deciduous trees, and C\textsubscript{3} and C\textsubscript{4} crops and grasses (Arora and Boer 2010).

Institut Pierre Simon Laplace's (IPSL) IPSL-CM5A-LR

The IPSL-CM5A (Dufresne and Co-authors 2012) is the new generation Earth System Model developed at the Institut Pierre Simon Laplace. The atmosphere and land models of IPSL-CM5ACM5 are updated versions of those used in IPSL-CM4 (Marti et al. 2010), namely, the atmospheric general circulation model LMDZ (Hourdin et al. 2006) and the ORCHIDEE land-surface model (Krinner et al. 2005). The atmospheric and land components use the same regular horizontal grid with 96x96 points, representing a resolution of 3.6°x1.8°, while the atmosphere has 39 vertical levels. The oceanic component is NEMOv3.2 (Madec 2008) with a horizontal resolution of 2° to 0.5° and 31 vertical levels.

The land component ORCHIDEE (Krinner et al. 2005) simulates, with a daily time step, processes of photosynthesis, carbon allocation, litter decomposition, soil carbon dynamics, maintenance and growth respiration, and phenology for 13 different plant functional types.

Japan Agency for Marine-Earth Science and Technology’s (JAMSTEC) MIROC-ESM
The MIROC-ESM (Watanabe et al. 2011) is based on the global climate model MIROC (Model for Interdisciplinary Research on Climate). The MIROC-AGCM has a spectral dynamical core and uses a flux-form semi-Lagrangian scheme for the tracer advection. The grid resolution is approximately 2.81° with 80 vertical levels between the surface and about 0.003 hPa. The physical ocean component of MIROC-ESM (COCO 3.4) has longitudinal grid spacing of about 1.4°, while the latitudinal grid intervals gradually vary from 0.5 degrees at the equator to 1.7° near the North/South Pole with 44 levels in the vertical.

A terrestrial ecosystem component with dynamic vegetation SEIB-DGVM (Sato et al. 2007) adopts an individual-based simulation scheme that explicitly captures light competition among trees. Vegetation is classified into 13 plant functional types (PFTs), consisting of 11 tree PFTs and 2 grass PFTs. The dynamics of the two soil organic carbon pools (fast- and slow-decomposing) is based on the Roth-C scheme (Coleman et al. 1997).

*Max Planck Institute for Meteorology’s (MPI) MPI-ESM-LR*

The Earth System model developed at the Max Planck Institute for Meteorology in Hamburg, Germany, (MPI-ESM) includes the atmospheric model ECHAM6 in T63 (1.9° x 1.9°) resolution with 47 vertical levels described by Stevens et al. (2012), the oceanic model MPI-OM at approx. 1.6° resolution with 40 vertical layers (Jungclaus et al. 2006), and the land-surface model JSBACH (Raddatz et al. 2007) sharing the horizontal grid of the atmospheric model. This grid set-up is a low-resolution version (LR) of the model used for centennial-time scale simulations in CMIP5. A detailed description of the model and an evaluation of the model...
performance regarding temperature and precipitation fields is given by Giorgetta et al. (2012).

The land surface model of MPI-ESM, JSBACH (Raddatz et al. 2007), simulates fluxes of energy, water, momentum, and CO$_2$ between land and atmosphere. Each land grid cell is divided into tiles covered with up to 12 plant functional types. A module for vegetation dynamics (Brovkin et al. 2009) is based on the assumption that competition between different PFTs is determined by their relative competitiveness expressed in annual net primary productivity (NPP), as well as natural and disturbance-driven mortality (fire and wind disturbance).

*UK Met Office's (UKMO) HadGEM2-ES*

HadGEM2-ES (Collins et al. 2011) couples interactive ocean biogeochemistry, terrestrial biogeochemistry and dust, interactive atmospheric chemistry and aerosol components into an update of the physical model HadGEM1 (Johns et al. 2006). The physical model contains a 40 level 1×1°, moving to 1/3° at the equator, ocean and a 38 level 1.875°×1.25° atmosphere (Martin et al. 2011). HadGEM2-ES has been set-up and used to perform CMIP5 simulations as described by Jones et al. (2011).

The terrestrial carbon cycle is represented by the MOSES2 land surface scheme (Essery et al. 2003) which simulates exchange of water, energy and carbon between the land surface and the atmosphere, and the TRIFID dynamic global vegetation model (Cox 2001) which simulates the coverage and competition between 5 plant functional types (broadleaf tree, needleleaf tree, C$_3$ and C$_4$ grass...
and shrub) and 4 non-vegetated surface types (bare soil, urban, lakes and land-ice). The soil carbon component has been updated based on the 4-pool RothC soil carbon model (Jones et al. 2005).

Acknowledgements

We acknowledge the World Climate Research Programme’s Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups for producing and making available their model output. We thank Karl Taylor and Charles Doutriaux for help with setting up the CMOR tables for the LUCID-CMIP5 experiments. We appreciate a support by the staff of the German Climate Computing Center (DKRZ), in particular by Stephanie Legutke and Estanislao Gonzalez, in performing the LUCID-CMIP5 simulations and in making the model results available via DKRZ ESG gateway. CDJ was supported by the Joint DECC/Defra Met Office Hadley Centre Climate Programme (GA01101).
References


Bathiany, S., M. Claussen, V. Brovkin, T. Raddatz, and V. Gayler, 2010: Combined biogeophysical and biogeochemical effects of large-scale forest cover changes in the MPI earth system model. *Biogeosciences*, 7, 1383-1399.


Giorgetta, M., and e. al., 2012: Climate variability and climate change in MPI-ESM CMIP5 simulations. *JAMES*, submitted.


Lawrence, P. J., and Coauthors, 2012: Simulating the Biogeochemical and Biogeophysical Impacts of Transient Land Cover Change and Wood Harvest in the Community Climate System Model (CCSM4) from 1850 to 2100. *Journal of Climate*, **25**, 3071-3095.


Strassmann, K. M., F. Joos, and G. Fischer, 2008: Simulating effects of land use changes on carbon fluxes: past contributions to atmospheric CO2 increases
and future commitments due to losses of terrestrial sink capacity. *Tellus Series B-Chemical and Physical Meteorology, 60*, 583-603.


Table 1. List of model experiments

<table>
<thead>
<tr>
<th>Simulation acronym</th>
<th>Atmospheric GHGs, aerosols</th>
<th>Land-use</th>
<th>Simulated years</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CMIP5</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RCP26</td>
<td>Transient scenario (RCP 2.6)</td>
<td>Transient scenario (RCP 2.6)</td>
<td>2006-2100</td>
</tr>
<tr>
<td>RCP85</td>
<td>Transient scenario (RCP 8.5)</td>
<td>Transient scenario (RCP 8.5)</td>
<td>2006-2100</td>
</tr>
<tr>
<td><strong>LUCID-CMIP5</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L2A26</td>
<td>Transient scenario (RCP 2.6)</td>
<td>Fixed to yr 2006</td>
<td>2006-2100</td>
</tr>
<tr>
<td>L2A85</td>
<td>Transient scenario (RCP 8.5)</td>
<td>Fixed to yr 2006</td>
<td>2006-2100</td>
</tr>
</tbody>
</table>
### Table 2. Brief description of models participated in the LUCID-CMIP5 simulations

<table>
<thead>
<tr>
<th>ESM</th>
<th>CanESM2</th>
<th>IPSL-CM5A-LR</th>
<th>MIROC-ESM</th>
<th>HadGEM2-ES</th>
<th>MPI-ESM-LR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Atmosphere/land</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>resolution</td>
<td>~2.8°</td>
<td>3.75°x1.90° (T39)</td>
<td>~2.8° (T42)</td>
<td>~1.6°</td>
<td>~1.9° (T63)</td>
</tr>
<tr>
<td><strong>Land surface</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>component</td>
<td>CTEM</td>
<td>ORCHIDEE</td>
<td>SEIB-DGVM</td>
<td>JULES</td>
<td>JSBACH</td>
</tr>
<tr>
<td><strong>Number of PFTs</strong></td>
<td>9</td>
<td>13</td>
<td>13</td>
<td>5</td>
<td>12</td>
</tr>
<tr>
<td><strong>Dynamic vegetation</strong></td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Fire module</strong></td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Crop PFT</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>No¹</td>
<td>No</td>
<td>No²</td>
</tr>
<tr>
<td><strong>Pastures</strong></td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Wood harvest</strong></td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Usage of land-use</strong></td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>transitions (Hurtt et al. 2011)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Ensemble members</strong>,</td>
<td>3/3</td>
<td>-</td>
<td>1/1</td>
<td>3/2</td>
<td>3/2</td>
</tr>
<tr>
<td>RCP26/L2A26</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Ensemble members</strong>,</td>
<td>3/3</td>
<td>3/1</td>
<td>1/1</td>
<td>3/2</td>
<td>3/2</td>
</tr>
<tr>
<td>RCP85/L2A85</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹ Uses grasses PFT parameters for crops, but harvested annually
² Crops differ from grasses in parameters of photosynthesis and phenology
Table 3. Differences between RCP and LUCID simulations in annual mean climate characteristics averaged for land regions with LULCC exceeding 10%. Only statistically significant results (p<0.05) are presented.

<table>
<thead>
<tr>
<th>Model</th>
<th>Scenario</th>
<th>Surface air temperature [K]</th>
<th>Precipitation (mm/day)</th>
<th>Albedo ($\times 100$)</th>
<th>Available energy (W m$^{-2}$)</th>
<th>Latent heat flux (W m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CanESM2</td>
<td>2.6</td>
<td>0.12</td>
<td>0.01</td>
<td>0.02</td>
<td>0.5</td>
<td>-0.1</td>
</tr>
<tr>
<td></td>
<td>8.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HadGEM2-ES</td>
<td>2.6</td>
<td>-0.09</td>
<td>-0.07</td>
<td>0.58</td>
<td>-1.3</td>
<td>-1.4</td>
</tr>
<tr>
<td></td>
<td>8.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>IPSL-CM5A-LR</td>
<td>8.5</td>
<td>-</td>
<td></td>
<td>0.39</td>
<td>-1.7</td>
<td>0.3</td>
</tr>
<tr>
<td>MIROC-ESM</td>
<td>2.6</td>
<td>-</td>
<td></td>
<td>0.15</td>
<td>-2.3</td>
<td>-2.8</td>
</tr>
<tr>
<td></td>
<td>8.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MPI-ESM-LR</td>
<td>2.6</td>
<td>-</td>
<td>-0.02</td>
<td>0.73</td>
<td>-1.6</td>
<td>-0.7</td>
</tr>
<tr>
<td></td>
<td>8.5</td>
<td></td>
<td></td>
<td>0.59</td>
<td>-</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Table 4. Estimated biogeochemical effect of land-use changes

<table>
<thead>
<tr>
<th>Model</th>
<th>RCP scenario</th>
<th>Cumulative net land-use emissions, PgC, year 2100</th>
<th>Transient climate sensitivity to emissions, K/TtC, (Gillett et al. 2012)</th>
<th>Estimated global annual temperature increase, K, year 2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>CanESM2</td>
<td>2.6</td>
<td>39</td>
<td>2.365</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>8.5</td>
<td>34</td>
<td></td>
<td>0.08</td>
</tr>
<tr>
<td>HadGEM2-ES</td>
<td>2.6</td>
<td>19</td>
<td>2.105</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>8.5</td>
<td>25</td>
<td></td>
<td>0.05</td>
</tr>
<tr>
<td>IPSL-CM5A-LR</td>
<td>8.5</td>
<td>37</td>
<td>1.585</td>
<td>0.06</td>
</tr>
<tr>
<td>MIROC-ESM</td>
<td>2.6</td>
<td>65</td>
<td>2.151</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>8.5</td>
<td>62</td>
<td></td>
<td>0.13</td>
</tr>
<tr>
<td>MPI-ESM-LR</td>
<td>2.6</td>
<td>175</td>
<td>1.604</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>8.5</td>
<td>205</td>
<td></td>
<td>0.33</td>
</tr>
</tbody>
</table>
Figure captions

Figure 1. Differences between years 2100 and 2005 in fractions of cropland (top), pasture (middle), and cropland plus pasture (bottom) in the RCP scenarios. Left: RCP2.6, right: RCP8.5.

Figure 2. Maps of changes in total crop and pasture fraction (%) in the RCP26 (left) and RCP85 (right) simulations between 2006 and 2100 for all LUCID-CMIP5 models. The fractions are specific for each model due to different interpretation of land-use change scenarios by land surface models.

Figure 3. Changes in global areas of crops (top), pastures (middle), and tree cover (bottom) between 2006 and 2100, 10^6 km^2. Shown is 10-yr moving average over all models and ensemble members of the RCP and LUCID simulations. Bold lines are for mean values, dashed lines and shaded areas – for variability in fractions in ensemble simulations. Although land-use was fixed in the LUCID simulations, small changes in crop and pasture areas occurred in models with vegetation dynamics.

Figure 4. 10-yr moving average of changes relative to year 2006 in annual near-surface air temperature, K, averaged for ensemble simulations globally (top) or for land grid cells where LULCC exceeded 10% of cell area (bottom). Bold and dashed lines are for 2.6 and 8.5 scenarios, dark and light colors are for RCP and LUCID experiments, respectively.
Figure 5: Maps of difference in mean annual near-surface air temperature, K, between ensemble averages of the RCP and LUCID simulations for 2.6 (left) and 8.5 (right) scenarios. The differences are averaged for years 2071-2100; only statistically significant changes (p<0.05) are plotted.

Figure 6: Box-and-whisker plots for differences in mean seasonal near-surface air temperature, K, between ensemble averages of the RCP and LUCID simulations for 2.6 (open) and 8.5 (closed) scenarios and for land grid cells where LULCC exceeded 10% of cell area. The plots are based on the data for years 2071-2100 averaged for Africa (left), South America (middle), and Australia (right). The bottom and top of boxes are for the 25th and 75th percentile, lower/upper whiskers are for 1.5-interquartile ranges of lower/upper quartiles. Black line is for the median; red dot is for the mean. DJF, MAM, JJA, and SON are for the seasons.

Figure 7: Maps of difference in mean annual surface albedo (*100) between ensemble averages of the RCP and LUCID simulations for 2.6 (left) and 8.5 (right) scenarios. The differences are averaged for years 2071-2100; only statistically significant changes (p<0.05) are plotted.

Figure 8: A. Box-and-whisker plots for differences in seasonal land surface albedo (*100) between ensemble averages of the RCP and LUCID simulations for 2.6 (open) and 8.5 (closed) scenarios and for land grid cells where LULCC exceeded 10% of cell area. The plots are based on the data for years 2071-2100 averaged for Africa (left) and South America (right). Red dots are for the mean.
DJF, MAM, JJA, and SON are for the seasons. B. The same as A), but for available energy (W/m²).

Figure 9: Maps of difference in mean annual surface upward latent heat flux (W/m²) between ensemble averages of the RCP and LUCID simulations for 2.6 (left) and 8.5 (right) scenarios. The differences are averaged for years 2071-2100; only statistically significant changes (p<0.05) are plotted.

Figure 10: Box-and-whisker plots for differences in seasonal surface upward latent heat flux (W/m²) between ensemble averages of RCP and LUCID simulations for 2.6 (open) and 8.5 (closed) scenarios and for land grid cells where LULCC exceeded 10% of cell area. The plots are based on the data for years 2071-2100 averaged for Africa (left) and South America (right). Red dots are for the mean. DJF, MAM, JJA, and SON are for the seasons.

Figure 11: 10-yr moving average of changes in total carbon storage (PgC), top, and of differences in total land carbon storage between ensemble averages of the RCP and LUCID simulations, bottom. Bold and dashed lines are for 2.6 and 8.5 scenarios, respectively.

Figure 12: Maps of difference in land carbon storage (kgC/m²) between ensemble averages of the RCP and LUCID simulations for 2.6 (left) and 8.5 (right) scenarios. The differences are averaged for years 2091-2100; only statistically significant changes (p<0.05) are plotted.
Figure 1. Differences between years 2100 and 2005 in fractions of cropland (top), pasture (middle), and cropland plus pasture (bottom) in the RCP scenarios. Left: RCP2.6, right: RCP8.5.
Figure 2. Maps of changes in total crop and pasture fraction (%) in the RCP26 (left) and RCP85 (right) simulations between 2006 and 2100 for all LUCID-CMIP5 models. The fractions are specific for each model due to different interpretation of land-use change scenarios by land surface models.
Figure 3. Changes in global areas of crops (top), pastures (middle), and tree cover (bottom) between 2006 and 2100, $10^6$ km$^2$. Shown is 10-yr moving average over all models and ensemble members of the RCP and LUCID simulations. Bold lines are for mean values, dashed lines and shaded areas – for variability in fractions in ensemble simulations. Although land-use was fixed in the LUCID simulations, small changes in crop and pasture areas occurred in models with vegetation dynamics.
Figure 4. 10-yr moving average of changes relative to year 2006 in annual near-surface air temperature, K, averaged for ensemble simulations globally (top) or for land grid cells where LULCC exceeded 10% of cell area (bottom). Bold and dashed lines are for 2.6 and 8.5 scenarios, dark and light colors are for RCP and LUCID experiments, respectively.
Figure 5: Maps of difference in mean annual near-surface air temperature, K, between ensemble averages of the RCP and LUCID simulations for 2.6 (left) and 8.5 (right) scenarios. The differences are averaged for years 2071-2100; only statistically significant changes (p<0.05) are plotted.
Figure 6: Box-and-whisker plots for differences in mean seasonal near-surface air temperature, K, between ensemble averages of the RCP and LUCID simulations for 2.6 (open) and 8.5 (closed) scenarios and for land grid cells where LULCC exceeded 10% of cell area. The plots are based on the data for years 2071-2100 averaged for Africa (left), South America (middle), and Australia (right). The bottom and top of boxes are for the 25th and 75th percentile, lower/upper whiskers are for 1.5-interquartile ranges of lower/upper quartiles. Black line is for the median; red dot is for the mean. DJF, MAM, JJA, and SON are for the seasons.
Figure 7: Maps of difference in mean annual surface albedo (*100) between ensemble averages of the RCP and LUCID simulations for 2.6 (left) and 8.5 (right) scenarios. The differences are averaged for years 2071-2100; only statistically significant changes (p<0.05) are plotted.
Figure 8a. Box-and-whisker plots for differences in seasonal land surface albedo (*100) between ensemble averages of the RCP and LUCID simulations for 2.6 (open) and 8.5 (closed) scenarios and for land grid cells where LULCC exceeded 10% of cell area. The plots are based on the data for years 2071-2100 averaged for Africa (left) and South America (right). Red dots are for the mean. DJF, MAM, JJA, and SON are for the seasons.
Figure 8, b. The same as a), but for available energy (W/m$^2$).
Figure 9: Maps of difference in mean annual surface upward latent heat flux (W/m²) between ensemble averages of the RCP and LUCID simulations for 2.6 (left) and 8.5 (right) scenarios. The differences are averaged for years 2071-2100; only statistically significant changes (p<0.05) are plotted.
Figure 10: Box-and-whisker plots for differences in seasonal surface upward latent heat flux (W/m²) between ensemble averages of RCP and LUCID simulations for 2.6 (open) and 8.5 (closed) scenarios and for land grid cells where LULCC exceeded 10% of cell area. The plots are based on the data for years 2071-2100 averaged for Africa (left) and South America (right). Red dots are for the mean. DJF, MAM, JJA, and SON are for the seasons.
Figure 11: 10-yr moving average of changes in total carbon storage (\(\Delta\)), top, and of differences in total land carbon storage between ensemble averages of the RCP and LUCID simulations, bottom. Bold and dashed lines are for 2.6 and 8.5 scenarios, respectively.
Figure 12: Maps of difference in land carbon storage (kgC/m²) between ensemble averages of the RCP and LUCID simulations for 2.6 (left) and 8.5 (right) scenarios. The differences are averaged for years 2091-2100; only statistically significant changes (p<0.05) are plotted.