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# Potential climate forcing of land use and land cover change

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## Abstract

Pressure on land resources is expected to increase as global population continues to climb and the world becomes more affluent, swelling the demand for food. Changing climate may exert additional pressures on natural lands as present day productive regions may shift, or soil quality may degrade, and the recent rise in demand for biofuels increases competition with edible crops for arable land. Given these projected trends there is a need to understand the global climate impacts of land use and land cover change (LULCC). Here we quantify the climate impacts of global LULCC in terms of modifications to the balance between incoming and outgoing radiation at the top of the atmosphere (radiative forcing; RF) that are caused by changes in long-lived and short-lived greenhouse gas concentrations, aerosol effects and land surface albedo. We simulate historical changes to terrestrial carbon storage, global fire emissions, secondary organic aerosol emissions, and surface albedo from LULCC using the Community Land Model version 3.5. These LULCC emissions are combined with estimates of agricultural emissions of important trace gases and mineral dust in two sets of Community Atmosphere Model simulations to calculate the RF from LULCC impacts on atmospheric chemistry and changes in aerosol concentrations. With all forcing agents considered together, we show that 45 % (+30 %, -20 %) of the present-day anthropogenic RF can be attributed to LULCC. Changes in the emission of non-CO<sub>2</sub> greenhouse gases and aerosols from LULCC enhance the total LULCC RF by a factor of 2 to 3 with respect to the LULCC RF from CO<sub>2</sub> alone. This enhancement factor also applies to projected LULCC RF, which we compute for four future scenarios associated with the Representative Concentration Pathways. We calculate total RFs between 1 to 2 W m<sup>-2</sup> from LULCC for the year 2100 (relative to a preindustrial state). To place an upper bound on the potential of LULCC to alter the global radiation budget we include a fifth scenario in which all arable land is cultivated by 2100. This “worst-case scenario” leads to a LULCC RF of 4.3 W m<sup>-2</sup> ( $\pm 1.0$  W m<sup>-2</sup>), suggesting that not only energy policy but

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land policy is necessary to minimize future increases in RF and associated climate changes.

## 1 Introduction

More than half of the Earth's land surface has been affected by land use and land cover change (LULCC) activities over the last 300 years, largely from the expansion of agriculture (Hurt et al., 2011), leading to numerous climate impacts (Foley et al., 2005). Conversion of land from natural vegetation to agriculture or pasturage releases carbon from vegetation and soils into the atmosphere (Houghton et al., 1983), often quickly through fires, which emit carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), ozone (O<sub>3</sub>)-producing compounds and aerosols (Randerson et al., 2006). Deforested areas have a diminished capacity to act as a CO<sub>2</sub> sink as atmospheric CO<sub>2</sub> concentrations increase (Arora and Boer, 2010; Strassmann et al., 2008). Furthermore, agriculture and pasturage emits CH<sub>4</sub> and nitrous oxide (N<sub>2</sub>O), accelerates soil carbon loss (Lal, 2004), and changes aerosol emissions (Foley et al., 2011). For instance, land management can increase mineral dust aerosol emission by modifying surface sediments and soil moisture (Ginoux et al., 2012), but reduces fire aerosol emissions (Kloster et al., 2012) and emissions of low-volatility products of oxidized biogenic organic compounds that condense to form secondary organic aerosols (SOA; Heald et al., 2008). Changes in the abundance of these atmospheric constituents generate forcings onto the climate system (Fig. 1).

Radiative forcing (RF) is the change in energy balance at the top of the atmosphere due to a change in a forcing agent, such as an atmospheric greenhouse gas. It is a commonly used metric for comparison of a diverse set of climate forcings and can be used to approximate a global surface temperature response (Forster et al., 2007). We adopt the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report (AR4) definition of adjusted RF relative to a preindustrial state (Forster et al., 2007). Here we define preindustrial as the year 1850 and note that large-scale anthropogenic

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land cover change began centuries before 1850, but at smaller rates (Pongratz et al., 2009). We compare the RF of LULCC to the RFs of other anthropogenic activities, which are dominated by fossil fuel burning.

The global LULCC RF and associated climate response are often portrayed as a balance between cooling biogeophysical effects (changes in surface energy and water balance) and the warming biogeochemical effect of increases in atmospheric CO<sub>2</sub> (e.g. Claussen et al., 2001; Brovkin et al., 2004; Foley et al., 2005; Bala et al., 2007; Cherubini et al., 2012). Claussen et al. (2001) found that the cooling from biogeophysical effects of land cover change dominated over the warming from associated CO<sub>2</sub> emissions in high-latitude regions where the land may be snow covered for part of the year, whereas tropical LULCC leads to a warming due to a weaker albedo forcing. This regional contrast in the dominant forcing from deforestation also applies to natural forest disturbances (O'Halloran et al., 2011). On a global scale, model estimates have shown nearly canceling climate responses to historical land cover change biogeophysical effects and CO<sub>2</sub> emissions (Brovkin et al., 2004; Sitch et al., 2005) and a small net warming (0.15°C) from the same effects (Matthews et al., 2004).

These comparisons are highly uncertain in part because reports of historical CO<sub>2</sub> emissions from LULCC cover a wide range of values and are computed with several different methodologies (Houghton et al., 2012; Brovkin et al., 2013). Houghton (2010) estimates that 156 Pg carbon (C) has been emitted by historical LULCC from 1850 to 2005, using an inventory-based method (Houghton et al., 1983, 1999). This approach does not account for the feedback between increasing atmospheric CO<sub>2</sub> and LULCC C emissions, also known as the fertilization feedback (Arora and Boer, 2010), or for the diminished capacity of deforested land to act as a CO<sub>2</sub> sink as atmospheric CO<sub>2</sub> concentrations increase (Strassmann et al., 2008). Alternatively, LULCC C emissions are estimated with model simulations of the terrestrial biosphere with and without LULCC after assessing the difference in C stocks between the two simulations. With this approach the effects of CO<sub>2</sub> fertilization on LULCC C emissions can be accounted for, although there is as yet no consistent method for including feedbacks without using

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5 a fully-coupled carbon cycle model (Arora and Boer, 2010). Gasser and Ciais (2013) propose a framework by which some of these studies may be compared. The results of several studies that calculate a LULCC C flux are summarized by Houghton (2010) and Pongratz et al. (2009). They report a range of previously published C emission estimates for LULCC of 138 PgC to 294 PgC for years 1700 to 2000, including results from the modeling studies of Strassmann et al. (2008) and Shevliakova et al. (2009). Strassmann et al. (2008) account for the impact of CO<sub>2</sub> fertilization and estimate that this negative feedback on C emissions amounts to roughly 25 % of the LULCC C flux. More recently, Lawrence et al. (2012) calculated a net LULCC C flux of 128 PgC for 10 1850 to 2005, and Ciais et al. (2013) suggested a range of 180 ± 80 PgC for the time period 1750 to 2011. Arora and Boer (2010) estimate a substantially smaller historical LULCC C flux between 40 and 77 PgC using a coupled climate-carbon cycle model. Although, the representation of nitrogen-limitation on plant growth, not included in Arora and Boer (2010), may lead to a greater LULCC C flux in otherwise similar model experiments (Arora et al., 2013).

15 Model estimates of C emissions from soils that have been disrupted by land use are poorly constrained (Houghton, 2010) and introduce major uncertainty into estimates of the LULCC C flux (House et al., 2002). In a review of field studies, Guo and Gifford (2002) conclude that soil C is increased for most conversions of natural land to pasture, and decreased for conversions to cropland. Lal (2004) estimates that cultivation 20 has caused the loss of 78 ± 12 PgC from soils since 1850. Modeling studies suggest that LULCC can cause a net loss of soil C globally, from ~ 13 % of total LULCC C emitted (Strassmann et al., 2008) to ~ 37 % (Shevliakova et al., 2009), or a net gain as in Arora and Boer (2010). In addition, there is a potentially major source of CO<sub>2</sub> 25 from deforestation and forest degradation in tropical peat swamp forests that has only recently been recognized (Hergoualc'h and Verchot, 2011).

Previous studies have shown that land cover change also modifies climate by biogeophysical effects such as changes to surface latent and sensible heat fluxes and to the hydrological cycle (DeFries et al., 2002; Feddema et al., 2005; Brovkin et al.,

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2006; Pitman et al., 2009; Lawrence and Chase, 2010). In general, while important for local or regional climate especially in the tropics (Strengers et al., 2010), these effects are considered minor on a global scale (Lawrence and Chase, 2010) and are difficult to quantify using the RF concept (Pielke et al., 2002). Of these biogeophysical effects of LULCC, land albedo change is recognized as the dominant forcing globally (Betts et al., 2007; Pongratz et al., 2009). The surface underlying a forest may have a different albedo than the canopy that is revealed following forest removal. In high latitude forests, clear-cut areas may become snow-covered in the winter and therefore, highly reflective. Many estimates of the global RF of land albedo change have been published, derived from modeling experiments (e.g. Brovkin et al., 1999, 2004; Betts, 2001; Defries et al., 2002; Betts et al., 2007; Davin et al., 2007; Pongratz et al., 2009; Skeie et al., 2011; Lawrence et al., 2012; Avila et al., 2012) and from satellite retrievals (Myrhe et al., 2005). In all these studies, a representation of the present day land albedo, whether simulated or observed by satellite, is compared to the land surface albedo with preindustrial vegetation, or the potential vegetation. Estimates for the global albedo change RF range from  $-0.10 \text{ W m}^{-2}$  (Skeie et al., 2011) to  $-0.28 \text{ W m}^{-2}$  (Lawrence et al., 2012), with a central estimate from the IPCC of  $-0.20 \text{ W m}^{-2}$  (Forster et al., 2007). The inhomogeneous distribution of forcing from surface albedo changes and short-lived trace gas and aerosol species could lead to non-additive (A. D. Jones et al., 2013), and highly variable local climate responses (Lawrence et al., 2012). Therefore, we use the RF for our assessment of global-scale climate impacts and acknowledge the limits of the RF concept for predicting the diverse and local impacts of land use (Betts, 2008; Runyan et al., 2012).

Additional LULCC forcings are often grouped in with fossil fuel burning and other activities for assessment of the anthropogenic RF (e.g. Forster et al., 2007). Nevertheless, there is some recognition of the importance of evaluating LULCC emissions of non- $\text{CO}_2$  greenhouse gases separately from fossil fuel emissions for targeting emission reduction policies (Tubiello et al., 2013). Less attention is given to forcings from short-lived atmospheric species that are affected by LULCC. Foley et al. (2005) ac-

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knowledge that changes in the concentrations of short-lived species, aerosols and O<sub>3</sub>, from LULCC are important for air quality assessment but do not estimate the impacts of these species on climate. Unger et al. (2010) partition sources of global, anthropogenic RF into economic sectors, including agriculture. They consider non-CO<sub>2</sub> greenhouse gas and aerosol forcing agents but only for present day land use emissions and they do not include land cover change. The full contribution of LULCC to global RF compared to the contribution from other anthropogenic activities remains unquantified.

Here we compute the CO<sub>2</sub> and albedo RF from global LULCC and compare to previous estimates of these values, but we also compute the global LULCC RF from non-CO<sub>2</sub> greenhouse gases (CH<sub>4</sub>, N<sub>2</sub>O, O<sub>3</sub>), and aerosol effects (direct, indirect, deposition on snow and ice surfaces). Individual forcings are computed from the results of terrestrial model simulations forced with historical land cover changes and wood harvesting, and projected land cover changes from five future scenarios. Because the land model used here includes a carbon model, fire module and emissions of volatile organic compounds, we can uniquely account for the complicated interplay between land use and fire (e.g. Marlon et al., 2008; Kloster et al., 2010; Ward et al., 2012). Four of the future scenarios of land cover change correspond to the four Representative Concentration Pathways (RCP) that were developed for the Climate Model Intercomparison Project in preparation for the IPCC 5th assessment report (AR5) (Lawrence et al., 2012; Hurtt et al., 2011; van Vuuren et al., 2011). The low emissions scenario, RCP2.6, includes widespread proliferation of bioenergy crops, while RCP4.5 is characterized by global reforestation as a result of carbon credit trading and emission penalties (Hurtt et al., 2011). The higher emissions scenarios include expansion of crop area at the expense of existing grasslands (RCP6.0; Fujino et al., 2006) or forests (RCP8.5; Riahl et al., 2007; Hurtt et al., 2011). We introduce a fifth, worst-case scenario, in which all arable and pasturable land is converted to agricultural land, either for crops or pasture, by the year 2100. The worst case scenario was not developed within an integrated modeling framework and, therefore, its likelihood of occurrence given economical and additional environmental constraints is difficult to judge. Instead, this scenario gives a theoretical

upper bound on LULCC impacts over this century. The range in outcomes for the global LULCC RF based on these five projections strengthens our understanding of the role that LULCC decision-making will play in future climate.

## 2 Methods: crop suitability calculations for worst case scenario

To estimate the maximum extent of crop and pasture for the worst case future scenario requires criteria that measure the potential of a land area to support agriculture. We follow the methodology of Ramankutty et al. (2002) to define the suitability of the climate and soil properties at model grid point locations for crops or pasture. In that study the authors define suitability based on the growing degree days, moisture index, soil organic carbon content, and soil pH that are characteristic of present day agricultural areas. Areas with a long enough growing season and sufficient water resources to support present day crops, absent irrigation (which is not included in their analysis), are considered suitable based on climate. For both soil organic carbon content and soil pH the authors find an ideal range of values that support agriculture and categorize areas that meet the criteria as suitable based on the soil. We repeat their analysis with temperature and precipitation data from the Climatic Research Unit TS3.10 dataset (Harris et al., 2014), soil data from the International Soil Reference and Information Centre – World Soil Information database (Batjes, 2005) and a simplified moisture index (Willmott and Feddema, 1992).

In this approach, sigmoidal functions are fit to probability density functions of gridbox fractional crop area and four environmental factors; growing degree days (GDD), moisture index, soil pH and soil organic carbon density. These functions describe where crops grow in today's world and how well they grow there. The functions are then applied to current global climate and soil datasets to identify areas that could support crops but have yet to, and also some areas where crops outdo their potential based on the local climate and soil, usually due to irrigation.

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We use the Ramankutty et al. (2002) definitions for soil pH, soil carbon, defined as the mass of C per meter squared in the top 30 cm of the non-gravel soil, and for GDD, defined as the number of °C by which daily mean temperature exceeds 5 °C.

For the moisture index we use the Climate Moisture Index (CMI) (Willmott and Fedema, 1992) which is defined using precipitation,  $P$ , and potential evaporation, PE, data as:

$$\text{CMI} = 1 - \text{PE}/P \quad \text{when } P \geq \text{PE}$$

$$\text{CMI} = P/\text{PE} - 1 \quad \text{when } P < \text{PE} \quad (1)$$

$$\text{CMI} = 0 \quad \text{when } P = \text{PE} = 0$$

We use 1979–2009 averages for climate variables and year 2000 crop area data (Ramankutty et al., 2008). For fitting the individual sigmoidal curves, we restrict the data to only those points that are otherwise optimal for crops, as in Ramankutty et al. (2002). For example, when fitting the CMI data, we restrict the crop area data to regions where the GDD, soil C, and soil pH support crops. This isolates grid points that could be CMI limited.

Following Ramankutty et al. (2002), we fit a single sigmoidal curve to the GDD data, and the CMI data, a double sigmoidal curve to the soil C data and explicitly define a pH limit function. The expressions for these functions from Ramankutty et al. (2002) are given below with new coefficients computed for our study:

$$f_1(\text{GDD}) = \frac{1}{[1 + e^{a(b-\text{GDD})}]} \quad (2)$$

$$f_2(\alpha) = \frac{1}{[1 + e^{c(d-\alpha)}]} \quad (3)$$

Where  $a = 0.0037$ ,  $b = 1502$ ,  $c = 10.16$ , and  $d = 0.3544$ .

$$g_1(\text{C}_{\text{soil}}) = \frac{a}{[1 + e^{b(c-\text{C}_{\text{soil}})}]} \frac{a}{[1 + e^{d(h-\text{C}_{\text{soil}})}]} \quad (4)$$

Where  $a = 22.09$ ,  $b = 3.759$ ,  $c = 1.839$ ,  $d = 0.0564$ , and  $h = 106.5$ .

$$g_2(\text{pH}_{\text{soil}}) = \begin{cases} -1.64 + 0.41\text{pH}_{\text{soil}} & \text{if } \text{pH}_{\text{soil}} \leq 6.5 \\ 1 & \text{if } 6.5 < \text{pH}_{\text{soil}} < 8 \\ 1 - 2(\text{pH}_{\text{soil}} - 8) & \text{if } \text{pH}_{\text{soil}} \geq 8 \end{cases} \quad (5)$$

These functions are multiplied together to create suitability indices: the product of the  $f$  functions gives the climate suitability index and the product of the  $g$  functions gives the soil suitability index. Natural land that is “suitable” for crops based on these criteria is converted to cropland (on a linear year-to-year basis) between years 2006–2100. We assume area that is suitable for crops based on climate, but not soil characteristics, can support grass and is used for pasturing animals. This assumption leads to the replacing of most tropical forests by crops or grasslands. The global potential crop area computed here for present day climate is 4180 Mha and the potential pasture area is 3110 Mha, compared to reported year 2010 utilized areas of 1570 Mha for crops and 2030 Mha for pasture (Hurt et al., 2011). Since the potential crop area depends on climate, it is likely to change in the future. One estimate, using a business-as-usual greenhouse gas emissions scenario, yields a 16% increase of the 1961–1990 potential crop area by 2070–2099, mainly in high latitudes (Ramankutty et al., 2002). We did not include climate-dependent trends in potential crop area in this study but note here that doing so may increase the year 2100 RF of the worst case scenario LULCC. Further information on how the potential crop and pasture area is translated into LULCC is given in Sect. 3.1.1. As discussed below, emissions of  $\text{CH}_4$  and  $\text{N}_2\text{O}$  from agriculture in the worst case scenario are based on emissions of these gases per area of crop/pasture in the RCP8.5 scenario and scaled by the differences in crop and pasture area between RCP8.5 and the worst case scenario. We do not consider possible future changes in natural emissions of  $\text{CH}_4$  and  $\text{N}_2\text{O}$ . Other calculations are done similarly to the RCPs, as discussed below in Sect. 3.

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### 3 Methods: radiative forcing calculations

Our approach to computing the RFs begins with estimating emissions of trace gases and aerosols from a diverse set of LULCC activities, many of which are illustrated schematically in Fig. 1. We model the following LULCC activities with a global terrestrial model; wood harvesting, land cover change, and changes in fire activity, including deforestation fires. Changes in the terrestrial model carbon cycle driven by the historical and projected LULCC are used to derive the RF of surface albedo change, and emissions of CO<sub>2</sub>, SOA, smoke, and mineral dust from LULCC. We assemble emissions from additional LULCC activities; agricultural waste burning, rice cultivation, fertilizer applications, and livestock pasturage, from available datasets corresponding to the RCP LULCC projections. Altogether, we consider LULCC emissions of non-methane hydrocarbons (NHMCs), NO<sub>x</sub>, CH<sub>4</sub>, N<sub>2</sub>O, CO<sub>2</sub>, NH<sub>3</sub>, SOA, black carbon (BC), organic carbon (OC), SO<sub>2</sub>, and mineral dust. From these emissions we calculate the change in concentrations of forcing agents between years 1850 to 2010 and 1850 to 2100 for all future projections. The different lifetimes of the forcing agents means that a single model approach cannot easily capture changes in all the forcing agents (Unger et al., 2010) and, therefore, a combination of models and methodologies are used here (Fig. 2). Note that RFs due to fossil fuels and other anthropogenic activities are calculated in this study for RCP4.5 emissions with identical methodology to that used for LULCC emissions.

Here we describe the methods for computing the various RFs, organized in four sections, corresponding to the rows in Fig. 2:

1. First the *LULCC activities* included in the analysis are outlined (Sect. 3.1).
2. This is followed by an explanation of the sources of the *emissions* data (Sect. 3.2).
3. Then the methods and models used to *compute concentration changes* are described (Sect. 3.3).
4. Next, the methods for *calculating the RFs* are explained (Sect. 3.4).

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Changes in terrestrial carbon storage, fire activity and biogenic trace gas emissions due to dynamic land cover are simulated using version 3.5 of the Community Land Model (CLM) (Oleson et al., 2008; Stockli et al., 2008) with active carbon and nitrogen cycles (CN) (Thornton et al., 2009) coupled to a process-based fire model (Kloster et al., 2010). This process based carbon model simulates the complicated interplay between land use, land use change, fires, land carbon uptake and loss, and emissions of volatile organic compounds (Thornton et al., 2009; Kloster et al., 2010; Guenther et al., 2006). To isolate the impacts of LULCC we simulate the CLM land surface processes separately for each of the LULCC dynamic PFT scenarios and compare it to an identical simulation with no PFT changes. All CLM simulations use 1.9° latitude by 2.5° longitude spatial resolution and a 30 min timestep.

Simulations of historical LULCC run from year 1850 to 2005 and future simulations from year 2006 to 2100. We follow the methods of Kloster et al. (2012) for historical and future atmospheric forcing, including meteorology, CO<sub>2</sub> concentrations and N deposition. Twelve future CLM simulations are run, two for each future LULCC scenario (RCP2.6, RCP4.5, RCP6.0, RCP8.5, worst case scenario, and No-LULCC) forced from the atmosphere with temperature, precipitation, wind, specific humidity, air pressure, and solar radiation data from the results of two fully-coupled CMIP3 simulations. The two sets of atmospheric forcing were selected for their divergent predictions of future temperature and precipitation (Kloster et al., 2012).

### 3.1.2 Fires

Fire area burned in CLM is controlled by available biomass, fuel moisture and ignition events, all expressed as probabilities, and adjusted by surface wind speeds (Kloster et al., 2010). Fire emissions from the area burned are contingent upon the available biomass and are partly determined by PFT-dependent combustion completeness. In addition to wildfires, deforestation fires occur in the model and are represented as an immediate release of a portion of the carbon lost during deforestation. In our analysis, deforestation fires do not impact the overall CO<sub>2</sub> RF but do speed up the timing of the

release of carbon that would otherwise occur by decomposition. Deforestation fires do, however, contribute small amounts of CH<sub>4</sub>, N<sub>2</sub>O, O<sub>3</sub> precursor gases, and aerosols to the atmosphere that would not have been released through decomposition.

Global burned area is reduced, both historically and in the future, by LULCC in our simulations (for RCP4.5, which includes large scale reforestation, the reduction is only a few percent and LULCC actually leads to a small increase in global fire emissions). This result matches our current understanding of the impact of LULCC on wildfires (Kloster et al., 2012; Marlon et al., 2008).

### 3.1.3 Agricultural activities

Additional emissions from LULCC activities associated with agriculture were taken from the integrated assessment model emissions for the different RCPs (e.g. van Vuuren et al., 2011) and are estimated based on RCP8.5 for the worst case scenario, as described below. These activities are fertilizer application, soil modification, livestock pasturage, rice cultivation and agricultural waste burning.

## 3.2 Emissions

This section describes the sources and accompanying computations for LULCC emissions of all relevant trace gas and aerosol species (Fig. 2). For non-LULCC related emissions (such as those from fossil fuel burning) we use the emission inventories from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) (Lamarque et al., 2010) for historical time periods, with future emissions from RCP4.5 (Wise et al., 2009). These datasets include emissions of non-methane hydrocarbons (NMHCs), NO, NH<sub>3</sub>, SO<sub>2</sub>, and organic carbon (OC) and black carbon (BC) aerosols.

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to the carbon emissions from fires to determine the contribution of fires to the various chemical species (see Fig. 2) including NMHCs, CH<sub>4</sub>, N<sub>2</sub>O, NH<sub>3</sub>, BC, OC, and SO<sub>2</sub> (Kloster et al., 2010; Ward et al., 2012). Fire emissions of BC and OC are reduced by 13% due to LULCC in year 2010 and reduced for projected LULCC in the year 2100, except for RCP4.5 (8% increase; Table 2).

### 3.2.3 Dust emissions

Agricultural activities have been linked to increased wind erosion of soils and greater dust emission in semi-arid regions (Ginoux et al., 2012). To address the impact of LULCC on dust emissions in our CAM simulations we introduce a modified soil erodibility dataset for each scenario. For each model grid box, a new soil erodibility value is set equal to the sum of the original soil erodibility and the fraction of the grid box that is cultivated land. We then introduce a parameter that weights the cultivated fraction in the soil erodibility computation such that the fraction of the dust flux resulting from cultivation in the year 2000 for eight regions (N. America, S. America, N. Africa, S. Africa, W. Asia, C. Asia, E. Asia, and Australia) is comparable to recently reported, satellite-derived values for each region (Ginoux et al., 2012). The weighting parameter for cultivated land was tuned with three iterations of four-year global atmospheric model simulations (using the a similar model setup to that described in Sect. 3.3.5), comparing the results for the tuned and un-tuned soil erodibility to the Ginoux et al. (2012) estimates for each region after each iteration. From this tuning we estimate reasonable weighting parameters for the cultivated fraction of land in each of the eight regions. The weighting parameters are applied to the timeseries of historical and projected crop area to create timeseries of soil erodibility that are modified by cultivation.

Ginoux et al. (2012) estimate that 25% of present day, global dust emissions are caused by anthropogenic activities. We estimate an increase in year 2010 global dust emissions from historical LULCC of about 20% (Table 2). Once these relationships between land use and dust are developed in the current climate, the natural dust source, along with changes in vegetation and climate are allowed to interact with the prognostic

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dust scheme to predict changes in dust (Mahowald et al., 2006; Albani et al., 2014). The extreme expansion of crop and pasture area in the worst case scenario causes global dust emissions, from natural and human-impacted sources, to more than triple by the year 2100 using this methodology (Table 2).

### 3.2.4 SOA emissions

Biogenic emissions of isoprene, monoterpenes, carbon monoxide (CO) and methanol depend on leaf area index (LAI) and, therefore, also on LULCC. We compute biogenic trace gas emissions using an offline version of the Model of Emissions of Gases and Aerosols from Nature (MEGAN) (Guenther et al., 2006) with a forced diurnal cycle for temperature and solar radiation (Ashworth et al., 2010). The monthly average LAI output from CLM are used for each scenario to produce the biogenic emissions with LAI scaled globally such that predicted year 2000 isoprene emissions match present day global estimates from Heald et al. (2008).

Some biogenic NMHCs, notably monoterpenes and isoprene, can undergo gas to particle phase transitions in the atmosphere after oxidation (Heald et al., 2008) and contribute to changes in aerosol concentrations. The rate of secondary aerosol production depends on the concentrations of the gas precursors, but also the oxidation capacity of the troposphere (Shindell et al., 2009). Both criteria are predicted in our atmospheric chemistry model simulations, described in Sect. 3.3.1. Emissions of biogenic SOA precursors (mainly isoprene) are approximately unchanged by LULCC in the year 2010 but are reduced by projected changes in land cover for the future RCP between 6 to 16 % (Table 2). For comparison, Wu et al. (2012) calculate a ~ 10 % decrease in isoprene plus monoterpene emissions from LULCC between 2000 and 2100 using the IPCC A1B future emissions scenario.

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### 3.2.5 CO<sub>2</sub> emissions

The anthropogenic contribution to the concentration of atmospheric CO<sub>2</sub>, used to compute the RF at years 2010 and 2100, depends on the history of anthropogenic CO<sub>2</sub> emissions up to that point. We estimate yearly LULCC emissions to the atmosphere as being equivalent to the global annual change in terrestrial carbon storage due to LULCC. Therefore, sources as well as sinks of CO<sub>2</sub> associated with LULCC are accounted for in the CO<sub>2</sub> emissions.

LULCC emissions of CO<sub>2</sub>, computed from the CLM simulations, are decreased in the simulations without changing land cover. Decreased atmospheric CO<sub>2</sub> will also lead to lower terrestrial carbon storage through the CO<sub>2</sub>-fertilization feedback, but our simulations do not capture this feedback since we prescribe the same CO<sub>2</sub> forcing in CLM regardless of the LULCC. Arora and Boer (2010) show that this form of “double-counting” land carbon storage can lead to overestimates of 20th century LULCC carbon emissions (by  $\sim 0.33 \text{ PgCyr}^{-1}$ ). However, a recent model intercomparison study suggested that including nitrogen (N)-limitation dramatically reduces terrestrial carbon pool sensitivity to changes in CO<sub>2</sub> concentration (Arora et al., 2013). Land carbon uptake in coupled models using the CN version of CLM was only 40 % as sensitive to changes in CO<sub>2</sub> concentration and surface temperature increases (known as the climate change feedback) compared to the model used by Arora and Boer (2010). Therefore we adjusted the yearly LULCC carbon emissions downward by  $0.14 \text{ PgCyr}^{-1}$  to account for the CO<sub>2</sub> fertilization feedback.

Other model parameters, including aerosol and biogenic NHMC fluxes, depend on LAI, which would also be impacted by the different CO<sub>2</sub> fertilization. However, due to the non-linearity of the aerosol and ozone response we do not apply an adjustment to these RFs but note here that the magnitude of the year 2010 aerosol, O<sub>3</sub> and indirect CH<sub>4</sub> RFs may be small overestimates.

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### 3.2.6 N<sub>2</sub>O emissions

N<sub>2</sub>O has both industrial and agricultural sources, in addition to a large natural source from soils and oceans. Total anthropogenic N<sub>2</sub>O emissions have been estimated for the historical time period and projected for RCP4.5 (Meinshausen et al., 2011a). Additional information regarding natural emissions and also agricultural emissions are needed to partition the anthropogenic N<sub>2</sub>O emissions into LULCC and non-LULCC components and estimate the associated RFs. We follow the methodology of Meinshausen et al. (2011b) in which the N<sub>2</sub>O budget is balanced for a historical time period to extract the natural emissions from the total anthropogenic emissions. Natural emissions of N<sub>2</sub>O decrease from about 11 to 9 TgN(N<sub>2</sub>O) yr<sup>-1</sup> using this method between the years 1850 and 2000. We maintain the year 2000 emissions, 9 TgN(N<sub>2</sub>O) yr<sup>-1</sup>, for the years 2000 to 2100. Future land cover change, particularly the worst case scenario, could lead to further decreases in natural N<sub>2</sub>O emissions. However, not enough is known about global natural N<sub>2</sub>O emissions to justify changing the future emission rate for this analysis (Syakila and Kroeze, 2011).

Anthropogenic emissions of N<sub>2</sub>O have been partitioned into agricultural (LULCC) and other anthropogenic (primarily fossil fuel) sources, which have been further partitioned into animal production and cultivation sources for years prior to 2006 (Syakila and Kroeze, 2011). We compute the global N<sub>2</sub>O emitted per area covered by crop or pasture in the year 2000 using these estimates. Our estimate for year 2010 N<sub>2</sub>O emissions from agriculture, 4.3 TgN(N<sub>2</sub>O) yr<sup>-1</sup>, is at the lower end of previously reported values compiled by Reay et al. (2012), ranging from 4.2 to 7 TgN(N<sub>2</sub>O) yr<sup>-1</sup>. The year 2000 ratios of emission per area are applied to future changes in crop or pasture area to compute future LULCC N<sub>2</sub>O emissions for all scenarios. This assumes no future trends in the rates per cultivated land area of the major agricultural N sources: N fertilizer application and animal waste management (Syakila and Kroeze, 2011). Our approach results in increased N<sub>2</sub>O emissions from agriculture between years 2010 and 2100 for RCP2.6, RCP8.5, and the worst case scenario (Table 2). Emissions decrease

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(year 2100) concentrations. We compare the concentration with all anthropogenic CH<sub>4</sub> sources/influences to the concentration with either LULCC or other anthropogenic sources/influences removed to compute the change in concentration for each case. The lifetime of CH<sub>4</sub> in the atmosphere (~ 9 years) means our simulations are too short to directly simulate the changes in CH<sub>4</sub> concentration. Instead we use approximations based on the known emissions of CH<sub>4</sub> and changes in the quick-adjusting main chemical sink for CH<sub>4</sub> – the hydroxyl radical (OH).

If we remove direct emissions of CH<sub>4</sub> from a particular source such as LULCC, a new steady state concentration can be approximated using the following expression from Ward et al. (2012):

$$\Delta[\text{CH}_4] = F \cdot \Delta E / E_0 \cdot [\text{CH}_4]_0 \quad (6)$$

such that a percentage change in CH<sub>4</sub> emissions,  $E$ , leads to a percentage change in concentration,  $[\text{CH}_4]$ , times the ratio of the perturbation lifetime to the initial lifetime,  $F$ . We do not calculate  $F$  from our simulations but use  $F = 1.4$  as recommended by the IPCC (Prather et al., 2001).

Changes in global OH concentration can be used to approximate the change in CH<sub>4</sub> lifetime caused by a change in emissions (Naik et al., 2005). Here we use the OH concentrations predicted in the CAM4 simulations for each case. The impact of non-LULCC emissions on CH<sub>4</sub> lifetime is taken as the difference between the year 2010 or 2100, and year 1850 CH<sub>4</sub> lifetime in the simulations with no LULCC emissions. Estimated this way, the CH<sub>4</sub> lifetime decreases by more than two years between 1850 and 2010 and by one and a half years between 1850 and 2100.

We compute the change in concentration due to the change in CH<sub>4</sub> lifetime,  $\tau$ , with respect to reaction with OH using this expression (Naik et al., 2005):

$$\Delta[\text{CH}_4] = F \cdot [\text{CH}_4]_0 \cdot \frac{\Delta\tau}{\tau_0} \quad (7)$$

Here we also use  $F = 1.4$  to account for the positive feedback between CH<sub>4</sub> and OH (Naik et al., 2005).

### 3.3.3 CO<sub>2</sub> concentration

CO<sub>2</sub> is chemically inert in the atmosphere but, over time, the airborne fraction of emitted CO<sub>2</sub> decreases as ocean and land uptake of carbon occurs. Therefore, the most recent CO<sub>2</sub> emissions will have the highest airborne fraction. We apply a CO<sub>2</sub> pulse response function (Enting et al., 1994) to compute the airborne fraction of the yearly pulse emissions at the year 2010 or 2100, following previously used methods (e.g. Randerson et al., 2006; Ward et al., 2012). This weighting is especially important for non-LULCC emissions, which have been largest over the most recent decades.

### 3.3.4 N<sub>2</sub>O concentration

Nitrous oxide is a long-lived greenhouse gas with a lifetime in the troposphere of over 100 years. Therefore, we use a simple atmospheric box model that can be run quickly for many model years to diagnose changes in N<sub>2</sub>O concentration that result from LULCC and other anthropogenic emissions. The box model uses an expression of N<sub>2</sub>O mass balance to predict changing concentrations,  $C$ , with time given yearly emissions,  $E$ , and a dynamic N<sub>2</sub>O lifetime,  $\tau$  (Kroeze et al., 1999):

$$\frac{dC}{dt} = \frac{E}{S} - \frac{C}{\tau} \quad (8)$$

Here,  $S$  is a conversion factor ( $4.8 \text{ Tg N ppbv}^{-1}$ ) and  $t$  is time (years). The N<sub>2</sub>O lifetime is dependent on its own concentration, which we account for here following Meinshausen et al. (2011b) and using a year 2000 reference state:

$$\tau = \tau_0 \left( \frac{C}{C_0} \right)^{-0.05} \quad (9)$$

We run the box model from simulation year 1850 through 2100 with natural and anthropogenic emissions, but with emissions from the source of interest, either LULCC or

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other anthropogenic activities, removed. We assume that the decrease in natural N<sub>2</sub>O emissions (Syakila and Kroeze, 2011) is attributable to LULCC. This decreases the net LULCC emissions of N<sub>2</sub>O.

### 3.3.5 Aerosols concentrations

5 We use CAM version 5 (Liu et al., 2011) with the three-mode Modal Aerosol Model (MAM3) (Liu et al., 2012), including the two-moment microphysical scheme (Morrison and Gettelman, 2008) and aerosol/cloud interactions for stratiform clouds, to simulate aerosol dynamics on a global scale. The more recent version of CAM is used here, as opposed to CAM4, to allow use of MAM3, which is not available for CAM4. Unfortunately chemistry was not yet available in CAM5 at the time of this study, so that different versions of the model had to be run for chemistry and aerosols. Since we use CAM4 and CAM5 to model concentration changes for separate forcing agents (trace gases in CAM4 and aerosols in CAM5), differences in physics between the two models do not affect our results. CAM5 is setup with horizontal grid spacing of 1.9° latitude by 2.5° longitude with 26 vertical levels and a timestep of 30 min. Each simulation is branched from a two-year spinup using year 2000 climate conditions (air temperature, sea surface temperature, solar forcing, etc.). Model setup is identical for all simulations except for aerosol emissions, which are specific to the case (LULCC vs. no-LULCC, year 2010 vs. year 2100). In CAM5, aerosols are both radiatively and microphysically active. This enables simulation of aerosol indirect effects but leads to different model climates for different initial aerosol emissions. To isolate the impacts of aerosols on the RF we integrate CAM5 for four years post-spinup and use the annual average for analysis. This smooths out the interannual variability in the model climate state to minimize its impact on the RF (Wang et al., 2011).

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centrations (Naik et al., 2005). The changes in peroxy radical concentrations, an end result of the changes in emissions of  $O_3$  precursors caused by LULCC or other anthropogenic activities, feeds back onto  $O_3$ , a response which is approximated with the following expression (Naik et al., 2005):

$$5 \quad (\Delta O_3)_{\text{primary}} = \frac{\Delta[\text{CH}_4]}{[\text{CH}_4]} \cdot 6.4 \text{ DU} \quad (10)$$

We use a value of  $0.032 \pm 0.006 \text{ W m}^{-2} \text{ DU}^{-1}$  (Forster et al., 2007) to compute the additional RF of  $O_3$  caused by this process, known as the primary mode response.

### 3.4.2 $\text{CO}_2$ , $\text{CH}_4$ , $\text{N}_2\text{O}$

10 After changes in the long-lived greenhouse gas concentrations due to LULCC or other anthropogenic emissions are calculated, simple expressions from the IPCC TAR (Ramaswamy et al., 2001) can be used to estimate the adjusted radiative forcing ( $\Delta F$ ). For  $\text{CO}_2$ :

$$15 \quad \Delta F = 5.35 \cdot \ln \left( \frac{C}{C_0} \right) \quad (11)$$

Here  $C_0$  is the atmospheric  $\text{CO}_2$  concentration in the unperturbed state (with no LULCC emissions, or no emissions from other anthropogenic activities) and  $C$  is the perturbed atmospheric  $\text{CO}_2$  concentration containing both all anthropogenic contributions. In this way the  $\text{CO}_2$  saturation effect of the different perturbed  $\text{CO}_2$  concentrations on the RF is taken into account.

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Likewise, the adjusted RF for the changes in CH<sub>4</sub> and N<sub>2</sub>O concentrations can be computed with the following expressions (Ramaswamy et al., 2001):

$$\Delta F = 0.036 \left( \sqrt{M} - \sqrt{M_0} \right) - [f(M, N_0) - f(M_0, N_0)] \quad (12)$$

$$\Delta F = 0.12 \left( \sqrt{N} - \sqrt{N_0} \right) - [f(M_0, N) - f(M_0, N_0)] \quad (13)$$

$$f(M, N) = 0.47 \cdot \ln[1 + 2.01 \times 10^{-5} (M \cdot N)^{0.75} + 5.31 \times 10^{-15} M (M \cdot N)^{1.52}] \quad (14)$$

using the average tropospheric concentrations of CH<sub>4</sub> (ppb) and N<sub>2</sub>O (ppb) in the perturbed state with LULCC or other anthropogenic emissions removed ( $M$  and  $N$ , respectively), and in the unperturbed, reference state ( $M_0$  and  $N_0$ , respectively). Equation (12) corresponds to CH<sub>4</sub> and Eq. (13) corresponds to N<sub>2</sub>O.

### 3.4.3 Aerosol effects

Aerosols impact radiative transfer directly by scattering and absorbing shortwave and some longwave radiation, and also indirectly by their effects on clouds. We compute the direct effect of changes in aerosols from LULCC by running the CAM5 radiation online in a diagnostic mode separately from the prognostic radiation in the model. The radiation package is run at every timestep through the model atmosphere with all aerosols and again with aerosols removed from interactions with radiation. The difference in top-of-atmosphere net radiative flux when aerosols are removed is the all-sky direct radiative effect. We compute this effect for shortwave and longwave interactions.

Indirect effects are defined here as the change in total cloud forcing between the simulations with and without LULCC (referenced to 1850), where total cloud forcing is the sum of the longwave and shortwave cloud forcing. This quantity is assessed after the direct effects of aerosols have been removed with the online diagnostics. Therefore, the sum of the direct effects and indirect effects of aerosols is equal to the total radiative change caused by aerosols in the CAM5 simulations.

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In CAM5, the indirect effects of aerosols on clouds includes the first indirect effect by which aerosols, acting as cloud condensation nuclei, lead to changes in cloud droplet size and, as a consequence, cloud albedo. CAM5 also simulates aerosol/cloud interactions that are considered secondary indirect effects. These include aerosol impacts on stratiform cloud lifetime and height, and the semi-direct effect. The semi-direct effect refers to the change in cloud fraction that results from the warming of an air layer by aerosol absorption of shortwave radiation (Lohmann and Feichter, 2005). Aerosol impacts on convective clouds are not included in our simulations.

These aspects of the CAM5 microphysics may lead to bias in our RF calculations when compared to the model consensus RFs from the IPCC AR4 (Forster et al., 2007). The IPCC central estimate for the indirect aerosol effect includes only the first indirect effect (aerosol impact on cloud albedo though changes in cloud droplet size). For this reason, and because models generally disagree on the magnitude of the aerosol effects (Forster et al., 2007), we use the IPCC AR4 central estimate aerosol direct and indirect effects for calculating the year 2010 RF and use our model results to determine the proportion of the total anthropogenic aerosols effects due to LULCC. Using the RFs from the IPCC AR4 results in a  $\sim 25\%$  decrease in the year 2010 LULCC aerosol direct and indirect RF magnitudes compared to our model. We apply the same scaling to the aerosol effects in all future scenarios. Central estimates of the aerosol effective RF, both direct and indirect, from the IPCC AR5 report total  $-0.9 \text{ W m}^{-2}$  (Myhre et al., 2013). Our calculations of LULCC RFs would be nearly unchanged if we used the AR5 values for aerosol forcings, but we estimate that the proportion of total anthropogenic RF from LULCC would be decreased by roughly 5%.

In addition to these effects in the atmosphere, light-absorbing aerosols, particularly BC and dust, can decrease the albedo of the Earth's surface when they are deposited onto snow and ice surfaces. The Snow, Ice, and Aerosol Radiative (SNICAR) model (Flanner and Zender, 2006) is run online with CAM5 to simulate this process and estimate the RF. For all cases the RF of aerosol deposition onto snow and ice surfaces is between 0 and  $0.03 \text{ W m}^{-2}$ . Note that we only capture aerosol deposition on snow and

ice covering land and not over sea. This will reduce our estimates of the RF compared to estimates including sea-ice, although the RF from aerosol deposition onto sea-ice is thought to be less important than deposition onto land-covering snow and ice (Flanner et al., 2007).

#### 5 3.4.4 Land surface albedo

LULCC activities change vegetation cover and type, affect forest canopy coverage, and alter wildfire activity, all of which impact land surface albedo. The albedo changes, apart from those caused by fires, are simulated by CLM. Monthly averages for solar radiation incident upon the surface (after accounting for attenuation by monthly average cloud cover) are multiplied by the surface albedo with LULCC and without LULCC for each model grid point. The RF equals the global annual average difference between the outgoing solar radiation with LULCC and without LULCC. The impact of the albedo changes may be further moderated by changes in cloudiness (Lawrence and Chase, 2010), which we did not consider in this analysis.

15 For albedo changes from wildfire activity, post-fire albedo response curves (Ward et al., 2012) are applied to the difference in burned area with LULCC and without LULCC at each grid point. Fires lead to negative (cooling) RF from albedo changes on a global average (Ward et al., 2012). Since historical and projected LULCC reduced burned area in CLM, the result was a small but positive RF in all cases, acting in the  
20 opposite direction of the overall negative LULCC albedo change RF.

#### 3.4.5 Aerosol biogeochemical feedbacks

The importance of aerosol biogeochemical feedbacks onto CO<sub>2</sub> concentrations is beginning to be recognized and known impacts have recently been quantified (Mahowald, 2011). We consider changes to terrestrial uptake of carbon by the addition of nutrients (N, phosphorous (P), and iron (Fe)) transported by aerosols, and also by modifications  
25 of climate.

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N deposition from anthropogenic sources fertilizes vegetation growth and increases the drawdown of  $\text{CO}_2$ , causing a present day RF of  $-0.12$  to  $-0.35 \text{ W m}^{-2}$ . We multiply this forcing by the ratio of N emissions ( $\text{NH}_3$ ,  $\text{NO}_x$ ) from LULCC or other anthropogenic activities for each case to year 2010 total anthropogenic N emissions.

Fertilization can also be enhanced by deposition of P and Fe from fire emissions. Changes in Amazonian fire activity have led to an estimated  $-0.12$  to  $0 \text{ W m}^{-2}$  RF from increased  $\text{CO}_2$  drawdown due to fertilization by P. Deposition of fire-emitted Fe to the oceans could be responsible for a RF of  $-0.02 \pm 0.02 \text{ W m}^{-2}$  (Ward et al., 2012). We scaled these RFs by the changes in fire activity due to LULCC in the Amazon (for P) and globally (for Fe) for all cases. These result in small RFs (less than  $\pm 0.05 \text{ W m}^{-2}$ ) such that N dominates these biogeochemical feedbacks.

Finally, changes in global surface temperature caused by the previously described RFs of LULCC and non-LULCC activities lead to a response in carbon uptake by the terrestrial biosphere and the ocean (Mahowald, 2011). Moreover, aerosols affect vegetation by redistributing precipitation and changing the ratio of diffuse to direct radiation incident on the surface. While not very well understood, these biogeochemical feedbacks can be estimated by coupled carbon-climate models that suggest a roughly linear response of between 0 and 40 ppm  $\text{CO}_2$  for a RF of  $1.4 \text{ W m}^{-2}$  (Mahowald et al., 2011). We sum the total RF of LULCC for all cases from greenhouse gases, aerosol effects and albedo changes, to estimate the impact of the potential changes in climate on atmospheric  $\text{CO}_2$ . In all cases, since the total RF from LULCC is positive, the RF of the feedback onto  $\text{CO}_2$  concentrations is also positive.

The total RFs of these biogeochemical feedbacks are included with the  $\text{CO}_2$  RF in the tables and figures since they impact climate through changing  $\text{CO}_2$  concentrations.

### 3.5 Uncertainty

The uncertainty in these RF estimates arises largely from the uncertainty in modeling the effects of aerosols and modeling the impacts of climate,  $\text{CO}_2$  changes, and LULCC on the carbon cycle. Our model predicts less uptake of anthropogenic carbon in natural

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land ecosystems compared to other land models, and thus could be underestimating the impact of land use on these regions (C. Jones et al., 2013). We compute the uncertainty in the total anthropogenic RF for each forcing agent with additional uncertainty associated with the partitioning of each RF into LULCC and other anthropogenic contributions, and with future fire emissions (Appendix A). For emissions from the worst case scenario we assume that our scaling assumptions (Sect. 3.2.1) are valid and do not introduce additional uncertainty, although the level of understanding of how emissions would scale under such an extreme scenario is low. Future projections incorporate future policy choices and human responses, which introduce considerable uncertainty into calculation of emissions (Unger et al., 2010). We do not attempt to quantify this uncertainty but create a broad range in possible outcomes for LULCC RF by using the RCP scenarios, designed to cover a diverse set of pathways, and extending these with the worst case scenario.

## 4 Results

### 4.1 Land use impacts on radiative forcing

We estimate a RF in the year 2010 from LULCC of  $0.9 \pm 0.5 \text{ W m}^{-2}$ , about 45 % (+30 %, –20 %) of the present day total anthropogenic RF (Fig. 5, Table 3). By separating the total anthropogenic RF (sum of LULCC and other anthropogenic activities) into contributions by forcing agent we can compare our calculations to the central estimates of Forster et al. (2007) (Fig. 5) and the reported RFs of van Vuuren et al. (2011) (Table 4). Our calculations of the total, present day, anthropogenic RF correspond closely to the van Vuuren et al. (2011) values, slightly overestimating the  $\text{CO}_2$  RF, and underestimating the magnitudes of the albedo RFs and  $\text{CH}_4$  RF compared to Forster et al. (2007).

The major contributors to the present-day LULCC RF are increases in atmospheric  $\text{CO}_2$  and  $\text{CH}_4$ . Deforestation, driven largely by the demand for additional agricultural land, leads to an estimated net decrease in global forest area of roughly 5.5 million







in space with the concentration, although, these heterogeneities are moderate for  $O_3$ . The RF at 80 % of grid points is within  $\pm 0.07 \text{ W m}^{-2}$  of the global mean RF (Table 5).

While the positive RF from non-LULCC greenhouse gas emissions is offset to some extent by concurrent emissions of aerosols, LULCC causes both increases and decreases in aerosol emissions resulting in nearly neutral aerosol RFs for the present day (Fig. 5). The contrasting changes in aerosol sources from LULCC are evident by the spatial variability in AOD caused by historical LULCC, ranging between  $-0.18$  to  $0.29$  (Table 5). Global average aerosol optical depth (AOD) is increased by LULCC in 2010 and in 2100 for the RCP4.5, RCP6.0 and worst case scenario scenarios, and decreased by RCP2.6 and RCP8.5 LULCC, but in all cases the change is less than 0.01. The RF from aerosol deposition onto snow and ice surfaces is negligible on a global average ( $0.01 \text{ W m}^{-2}$  for historical LULCC) but exceeds  $\pm 1 \text{ W m}^{-2}$  in some locations (Table 5). We also consider the impacts of aerosols and trace gas species on atmospheric  $CO_2$  due to bio-fertilization by deposition of P, Fe and N emitted from fires, and N from agriculture ( $NH_3$ ,  $NO_x$ ,  $N_2O$ ). For present day emissions of these species from LULCC activities (and land cover change impacts on fires), the drawdown of  $CO_2$ , enhanced particularly by agricultural emissions of N, leads to a negative RF of  $-0.10 \text{ W m}^{-2}$  that nearly compensates for the positive RF from the greenhouse effect of agricultural  $N_2O$  emissions ( $0.14 \text{ W m}^{-2}$ ), a noteworthy aspect of agricultural emissions that was also suggested by Zaehle et al. (2011).

Estimates for the global RF from albedo changes range from  $-0.10$  (Skeie et al., 2011) to  $-0.28 \text{ W m}^{-2}$  (Lawrence et al., 2012), with a substantial percentage, potentially 25 %, caused by preindustrial LULCC (Pongratz et al., 2009). Further estimates (Betts, 2001; Betts et al., 2007; Davin et al., 2007) fall near the IPCC AR4 central estimate of  $-0.2 \text{ W m}^{-2}$  (Forster et al., 2007). The RF from albedo changes is near zero in most locations but has a high magnitude, up to  $5 \text{ W m}^{-2}$ , in some localities on an annual average (Table 5), similar to the findings of Betts et al. (2007). Our estimate for the global RF from historical land surface albedo change,  $-0.05 \text{ W m}^{-2}$ , is at the higher end of the range of previously published estimates, yet still within the 90 % con-

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5 confidence interval around the central estimate of Forster et al. (2007). Reductions in fire area burned that result from historical LULCC act to decrease the magnitude of the surface albedo change forcing, although by less than  $0.01 \text{ W m}^{-2}$  for the present day. The use of a less altered, more natural background state than our year 1850 landscape would likely increase the magnitude of this forcing (Sitch et al., 2005; Pongratz et al., 2009). Finally, the surface albedo RF may be further modified by changes in cloudiness (Lawrence and Chase, 2010), which we did not simulate here.

## 4.2 Future radiative forcings from land use and land cover change

10 Future LULCC according to the range of RCP scenarios considered, is projected to cause an increased RF compared to the present ( $1.0$  to  $2.3 \text{ W m}^{-2}$ ) (Fig. 6), although as a percentage of the projected total anthropogenic RF (as computed for RCP4.5), land use is less important in year 2100 (Table 3). Despite diverging trajectories for forest area and crop area for RCP2.6, RCP4.5 and RCP6.0 in the 21st century (Fig. 3), the year 2100 LULCC RFs are similar between these scenarios (Fig. 6). The RCP8.5 RF is characterized by relatively high contributions from  $\text{CO}_2$  and  $\text{CH}_4$  resulting in a total LULCC RF that is double the average of the other three RCP scenarios. The difference between RCP8.5 and the other scenarios suggests that decisions regarding global land policy similar to those used to develop the RCPs could reduce or increase global anthropogenic RF by  $1 \text{ W m}^{-2}$  by 2100.

20 The LULCC projections for all four RCP scenarios include future decreases in global deforestation rates compared to recent historical rates (Fig. 7). A recent satellite assessment of global forest area gain and loss reported a global forest loss rate of  $12.5 \text{ Mha yr}^{-1}$  between 2000 and 2012 (Hansen et al., 2013), suggesting the census-reported rates for 2000 to 2010 (FAO, 2010) may be estimating less deforestation than is really occurring. If recent rates of observed forest area change persist, the global forest area projected in all four RCP scenarios by Hurtt et al. (2011) will become over-estimates in the near future, especially in RCP4.5 and RCP6.0. More extreme land use scenarios are plausible, and would have a larger effect on climate. We introduce

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the worst case scenario to place an upper bound on the potential LULCC RF for this century. The worst case scenario, in which all arable land is converted to agricultural land and all remaining land that is pasturable is converted to grasses by the year 2100, does not take some important agricultural factors, such as changes in crop yields and per capita caloric intake, into account, but was created as a plausible limit to cropland expansion on Earth. Since we designate arable land using a measure of climate suitability (Sect. 2), following Ramankutty et al. (2002), crop area could conceivably expand beyond this limit with the use of irrigation. In fact, areas of South Asia currently support more agriculture than estimates of climate suitability suggest they should (Ramankutty et al., 2002).

In the worst case scenario, crop area roughly doubles by the year 2050, and continues to increase at the same rate to 2100. The rate of deforestation required to accommodate the expanded agriculture is three times greater than upper estimates from the RCPs for year 2000–2030 forest loss (Fig. 7), resulting in the near complete removal of tropical forests by the year 2100 (Fig. 4), and a global release of  $\sim 500$  PgC from vegetation to the atmosphere. Loss of soil C often accompanies forest conversion to crops or grasses (Lal, 2004) but this process is not well simulated in this generation of terrestrial models. House et al. (2002) estimate terrestrial C loss from a complete deforestation to be between 450 to 820 PgC, with much of the uncertainty in the range due to different estimates of C loss from soils. Our CLM3 experiment resulted in negligible soil C change globally, even after applying the drastic forest and crop area changes of the worst case scenario. Still, loss of C from vegetation alone in the worst case scenario corresponds to roughly two-thirds of the value of the proven reserves of fossil fuels (760 PgC) (Meinshausen et al., 2009). The substantial loss of terrestrial C to the atmosphere in the worst case scenario leads to a RF of  $1.6 \text{ W m}^{-2}$  for  $\text{CO}_2$  (Fig. 6). The magnitudes of all other forcing agents are enhanced in this scenario, leading to a sum RF of  $4.3 \pm 1.0 \text{ W m}^{-2}$  at the year 2100.

### 4.3 Total radiative forcing compared with CO<sub>2</sub>-derived radiative forcing

On average over all converted land types and land management histories, CO<sub>2</sub> RF from LULCC is enhanced by the accompanying (although not necessarily concurrent) emissions of non-CO<sub>2</sub> greenhouse gases and aerosols, such that the total RF is 2 to 3 times that of the CO<sub>2</sub> alone. For example, we estimate the direct carbon release from LULCC between 1850–2010 to be 140 PgC, leading to a RF from CO<sub>2</sub> of  $\sim 0.4 \text{ W m}^{-2}$  in 2010, or about half of the total LULCC RF. In contrast, for other anthropogenic activities the RF from CO<sub>2</sub> and the total RF are roughly equal (Figs. 5 and 6). Therefore, while LULCC accounted for about 20 % of anthropogenic CO<sub>2</sub>-equivalent emissions in 2010 (Tubiello et al., 2013), its contribution to the anthropogenic RF is 45 % (+30 %, –20 %). We can express this enhancement factor as the ratio of the sum RF to the CO<sub>2</sub> RF for LULCC, divided by the same ratio for other anthropogenic activities (FF+), or  $E = (\text{RF}_{\text{sum}}/\text{RF}_{\text{CO}_2})_{\text{LULCC}}/(\text{RF}_{\text{sum}}/\text{RF}_{\text{CO}_2})_{\text{FF+}}$ . For all future LULCC scenarios the enhancement factor is between 2.1 to 3.1 (Table 6). We compute the maximum enhancement of the CO<sub>2</sub> RF for the RCP4.5 scenario ( $E = 3.1$ ). In the development of the RCP4.5 scenario, international carbon trading incentivizes preservation of forests and reforestation, which reduces CO<sub>2</sub> emissions and the resulting CO<sub>2</sub> RF from LULCC, increasing the enhancement factor.

## 5 Conclusions

Effective strategies for mitigation of human impacts on global climate require an understanding of the major sources of those impacts (Unger et al., 2010). Anthropogenic land use and changes to land cover have long been recognized as important contributors to global climate forcing (Feddema et al., 2005), and yet most studies on this topic focus on either land use (e.g. Unger et al., 2010) or land cover change (e.g. Davin et al., 2007; Pongratz et al., 2009), but not both. In this study we compute the fraction of

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anthropogenic RF that results from LULCC activities including a more comprehensive range of forcing agents.

Current estimates of the LULCC C flux between 1850 and 2000 are between 108 PgC and 188 PgC (Houghton, 2010), while here we estimate 131 PgC. Estimates from this study using the future scenarios analyzed in the IPCC (the representative concentration scenarios or RCPs) suggest between 20 and 210 C will be released, consistent with Strassmann et al. (2008), and at the higher end of the model range reported by Brovkin et al. (2013). Our model underpredicts the uptake of land carbon relative to other models (e.g Arora et al., 2013), and unlike other estimates includes the explicit interplay between changes in land use and fires (e.g. Marlon et al., 2008; Kloster et al., 2010). The RCP scenarios were designed to cover a diverse set of pathways and create a broad range in possible outcomes for the next century (Moss et al., 2010). Given that the RCP scenarios all project decreases in global forest area loss rates in the 21st century relative to current rates, these scenarios are likely to be lower bounds on deforestation rates in the future (Fig. 7). To explore higher rates of global forest loss and crop and pasture expansions, we introduce a worst case scenario, in which all the land which is likely to be arable is converted to agriculture and pasture usage by 2100. Since the rates of deforestation in this scenario are higher than current rates, this scenario is an upper bound on what could occur. We calculate that with the intense pressures on land inherent to this scenario, between 590 and 700 PgC would be released from LULCC in this century.

We find that the total RF from LULCC is 2 to 3 times the RF from CO<sub>2</sub> alone when additional positive forcings from non-CO<sub>2</sub> greenhouse gases and relatively small forcings from aerosols and surface albedo are considered. The RF of other anthropogenic activities (largely fossil fuels) in 2010 and in 2100 (RCP4.5), relative to 1850, includes a large magnitude negative aerosol forcing that offsets enough of the warming contribution from greenhouse gases that the total RF matches closely with the RF from CO<sub>2</sub>. The result of this enhancement of the LULCC RF with respect to its CO<sub>2</sub> emissions, and lack of enhancement of the other anthropogenic activities RF, is a 45 % LULCC

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contribution to present day anthropogenic RF, a substantially larger percentage that is deduced from greenhouse gas emissions alone (Tubiello et al., 2013). The percentage of anthropogenic RF attributable to LULCC activities is likely to decrease in the future, but the magnitude of the LULCC RF is likely to increase by between 0.1 to 1.2 Wm<sup>-2</sup> from 2010 to 2100. The lifetime and distribution of short-lived species makes simplification difficult in terms of equating CO<sub>2</sub> RF to other constituents (Shine et al., 2007), but simple approaches of controlling cumulative carbon (Allen et al., 2009) should account for the two to three times enhancement of the LULCC RF over long time periods per unit CO<sub>2</sub> emitted relative to other sources of CO<sub>2</sub>.

Including forcings from aerosols in our assessment, while only slightly affecting the mean estimate of the total LULCC RF, greatly increases the uncertainty in the estimate. Much of the uncertainty arises from the simulation of aerosol/cloud interactions and the indirect effect for which very little model consensus exists on a global scale (Forster et al., 2007). In addition to these uncertainties, the perturbations of natural aerosol emissions by LULCC activities (mineral dust, SOA, wildfire smoke) are only beginning to be better understood on a global scale (Ginoux et al., 2012; Ganzeveld et al., 2010). Further research into the sources and lifetimes of natural aerosols, and anthropogenic impacts on their emissions, could efficiently reduce our uncertainty in the contribution of LULCC to global RF. Since most of the calculations presented here are within uncertainty estimates across many models and estimates of present day anthropogenic RF (Fig. 5), we expect that other models or approaches would obtain similar results.

While it is likely that advances in, and proliferation of, agricultural technologies will be sufficient to meet global food demand without such an extreme increase in crop and pasture area, investment in foreign lands for agriculture, as a cost-effective alternative to intensification of existing agriculture, may be hastening the conversion of unprotected natural lands (Rulli et al., 2013). Given the huge potential for climate impacts from LULCC in this century, estimated here to be  $4.3 \pm 1.0 \text{ Wm}^{-2}$  at the maximum, similar to some estimates of future climate impacts from fossil fuels (e.g. Van Vuuren

et al., 2011), our study substantiates that not only energy usage but land use and land cover change needs to remain a focus of climate change mitigation.

## Appendix A

### Computing uncertainties

5 The uncertainties in RF estimations are substantial (Forster et al., 2007) and include uncertainties in the model representation of physical and chemical processes, model internal variability and imperfect knowledge of processes. Here we describe the calculation of uncertainties for the RFs reported in this paper and we assume the uncertainty has three sources: model and RF computations, partitioning of emissions  
10 between LULCC and non-LULCC, and uncertainty in the emissions from future fires (values given in Table A1).

#### A1 Anthropogenic RF calculation uncertainties

For the uncertainty in the total anthropogenic RF calculations, we take the 90 % confidence intervals generated by the IPCC (Forster et al., 2007) for each forcing agent and assume these represent a Gaussian probability density function around the central  
15 estimate (Table A1, “Model” column). This assumption may not be appropriate for all forcing agents if the goal were to compute uncertainties that could be interpreted probabilistically. Therefore we stress that the calculated uncertainties are rough estimates and should not be interpreted as probabilistic. We propagate this uncertainty to LULCC and non-LULCC by multiplying by the corresponding fraction of the RF from LULCC or  
20 non-LULCC, or in the case of the aerosol forcings, by the fraction of AOD from LULCC or non-LULCC. Since we use the IPCC aerosol forcings in our total LULCC RF estimates, we do not include uncertainty introduced by the secondary aerosol effects.

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## A2 Partitioning uncertainty

The partitioning uncertainty is determined from previous estimates of the error in sector-specific trace gas and aerosol emissions. We define this uncertainty as the maximum range in the ratio of LULCC to non-LULCC emissions that could result from the two sources varying from plus to minus one standard deviation of their own source-specific uncertainty (Table A1, “Partitioning” column).

The source uncertainties for trace gases CO<sub>2</sub>, CH<sub>4</sub>, NH<sub>3</sub>, NO<sub>x</sub>, and N<sub>2</sub>O are taken from the IPCC AR4 (Forster et al., 2007). The source uncertainties in emissions of N species (that is, the range in the ratio of LULCC N emissions to non-LULCC N emissions varying within the uncertainties from each source reported by Forster et al., 2007) are combined to produce the partitioning uncertainty of the aerosol biogeochemical feedback onto CO<sub>2</sub> concentrations. The feedback of RF from non-LULCC and LULCC separately onto the carbon cycle (Sect. 3.3.3) is also included here as part of the CO<sub>2</sub> partitioning uncertainty. The partitioning uncertainty for CH<sub>4</sub> is combined with uncertainty in global sinks of CH<sub>4</sub> (from Forster et al., 2007) that affect our understanding of the CH<sub>4</sub> atmospheric lifetime. For emissions of CO (used in O<sub>3</sub> partitioning uncertainty) we estimate a two times uncertainty in all emissions (Unger et al., 2010). Similarly, we begin with a two times uncertainty in aerosol emissions, as this has been estimated for carbonaceous aerosols (Unger et al., 2010), but noting that the emissions of dust and SOA are more uncertain than emissions of carbonaceous aerosols, we double this uncertainty for aerosol emissions (4 times uncertainty). The partitioning uncertainties for halocarbon emissions and land surface albedo changes are zero since we only consider one source, LULCC or non-LULCC, for these forcing agents.

## A3 Summing the uncertainties

Using the Monte Carlo method with  $N = 100000$  iterations, and assuming that the different forcing agents vary independently of one another, we produce Gaussian probability density functions for the combined RF (all agents, and LULCC and other an-

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thropogenic sources) and for the LULCC RF (all agents, only LULCC sources). Adding these uncertainties together (root of the sum of squares) gives the uncertainty in the fraction of anthropogenic RF attributable to LULCC (Table 3). The assumption of independence among forcing agents is not perfect. For example,  $\text{NO}_x$  concentrations are used to predict changes in  $\text{O}_3$ ,  $\text{CH}_4$ , and total N, and the same aerosol emissions are used to estimate several different forcings. However, given that there are large uncertainties specific to the calculation of each forcing agent, and apart from those associated with emissions, we retain the assumption of independence for approximating the sum of the uncertainties.

We apply the same uncertainties to the future RFs for LULCC and add additional uncertainty due to variability in global fire activity between 2010–2100 that is due to the different atmospheric forcing used in these simulations. We define this uncertainty as the total range in RF caused by using the different atmospheric forcing datasets to drive global fires in CLM (Table A1, “Fire” columns). The different forcing datasets were chosen to represent a large spread in projected temperature and precipitation by the year 2100 (Kloster et al., 2012). The uncertainties of the different forcing agents with regard to fire emissions are not independent of each other and, therefore, are added directly to the sum uncertainties after the Monte Carlo simulations have determined the sum of the other, more independent, uncertainties.

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**Table 1.** Summary outline of Sect. 3.

Section	Topic	Summary
3.1	<b>LULCC Activities</b>	–
3.1.1	LCC and wood harvesting	These processes simulated in CLM3 (LCC: land cover change)
3.1.2	Fires	Changes in global fires from LULCC simulated by CLM3
3.1.3	Agricultural activities	Fertilizer, soil modification, livestock, rice cultivation and waste burning
3.2	<b>Emissions</b>	Non-LULCC emissions from ACCMIP and van Vuuren et al. (2011)
3.2.1	Agricultural emissions	Historical emissions from ACCMIP, RCPs from van Vuuren et al. (2011)
3.2.2	Fire emissions	Emissions factors applied to changes in fire activity from CLM3
3.2.3	Dust emissions	Cultivated area used to modify soil erodibility and resulting dust emissions
3.2.4	SOA emissions	Computed offline with MEGAN using LULCC leaf area changes from CLM3
3.2.5	CO <sub>2</sub> emissions	Difference in terrestrial C storage in CLM3 with and without LULCC
3.2.6	N <sub>2</sub> O emissions	Emissions scaled by changes in crop and pasture area
3.3	<b>Concentration changes</b>	–
3.3.1	Tropospheric O <sub>3</sub> conc.	Concentration changes simulated by CAM4 with year 2000 climate
3.3.2	CH <sub>4</sub> concentration	Direct and indirect changes computed using methods of Ward et al. (2012)
3.3.3	CO <sub>2</sub> concentration	Pulse response function with approximated fertilization feedback included
3.3.4	N <sub>2</sub> O concentration	Box model approach from Kroeze et al. (1999)
3.3.5	Aerosols concentrations	Simulated by CAM5 with MAM3, four year simulations (post-spinup)
3.4	<b>RF calculations</b>	Future LULCC RFs are computed against a RCP4.5 background atmosphere
3.4.1	Tropospheric O <sub>3</sub> RF	Computed offline with the Parallel Offline Radiative Transfer (PORT) tool
3.4.2	CO <sub>2</sub> , CH <sub>4</sub> , N <sub>2</sub> O RFs	Computed with simple expressions from Ramaswamy et al. (2001)
3.4.3	Aerosol effects	Simulated by CAM5 and scaled to the estimates of Forster et al. (2007)
3.4.4	Land surface albedo	Computed from albedo change simulated by CLM3 for LULCC
3.4.5	Aerosol bgc feedbacks	Changes to CO <sub>2</sub> conc. from biogeochemical feedbacks (Mahowald, 2011)
3.5	<b>Uncertainty</b>	See Appendix A for details of uncertainty calculations

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**Table 2.** Changes in emissions of important aerosol and trace gases due to LULCC activities for year 2010 and year 2100 for the listed future scenarios (worst case scenario is abbreviated to WCS). Values are given in  $\text{Tg}(\text{species})\text{yr}^{-1}$  except where noted otherwise. Values in parentheses are the percent change in global emissions due to LULCC for the time period and scenario listed. Biogenic SOA precursors are considered the sum emissions of biogenic CO, isoprene, monoterpenes, and methanol.

	$\text{N}_2\text{O}$ [ $\text{TgN}(\text{N}_2\text{O})\text{yr}^{-1}$ ]	Dust	Biogenic SOA Precursors [ $\text{TgCyr}^{-1}$ ]	Fire (BC + OC)
2010	4.3	+619 (18)	+7 (1)	-2.2 (13)
RCP2.6	5.4	+1003 (28)	-141 (16)	-6.0 (25)
RCP4.5	2.9	+806 (23)	-54 (6)	+1.8 (8)
RCP6.0	3.8	+1008 (28)	-105 (12)	-4.0 (17)
RCP8.5	5.3	+866 (24)	-149 (16)	-8.1 (34)
WCS	11.7	+4330 (222)	-656 (74)	-15.4 (65)





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**Table 4.** RFs for the year 2010 and the year 2100 compared to van Vuuren et al. (2011). For year 2100 we show the RF from RCP4.5 scenario emissions (referenced to year 1850) estimated from the modeling results in this study and from van Vuuren et al. (2011) given in  $Wm^{-2}$ . Note, as stated in the main text, the total aerosol direct and indirect RFs for the year 2010 are from the IPCC model consensus with only the partitioning between LULCC and other anthropogenic activities (FF+) determined by the modeling results of this study and the same scaling is applied to the year 2100 aerosol RFs.

	LULCC	FF+	Total	Van Vuuren et al. (2011)
<b>2010</b>				
Total RF	0.88	1.05	1.93	1.95
CO <sub>2</sub> RF	0.43	1.35	1.78	1.69
CH <sub>4</sub> RF	0.3	0.14	0.44	0.44
N <sub>2</sub> O RF	0.14	0.03	0.17	0.16
Halocarbons	0	0.34	0.34	0.34
Aerosols/O <sub>3</sub> /alb*	0.01	-0.81	-0.8	-0.68
<b>2100-RCP4.5</b>				
Total RF	0.95	3.34	4.29	4.14
CO <sub>2</sub> RF	0.31	3.16	3.47	3.47
CH <sub>4</sub> RF	0.31	0.12	0.43	0.37
N <sub>2</sub> O RF	0.18	0.12	0.3	0.31
Halocarbons	0	0.18	0.18	0.18
Aerosols/O <sub>3</sub> /alb*	0.15	-0.24	-0.09	-0.19

\* This sum RF includes aerosols (direct effects, indirect effects on clouds, and deposition onto snow/ice surfaces), tropospheric O<sub>3</sub> and forcing from surface albedo changes.

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**Table 5.** Quantiles of the spatial distribution of the different forcings from historical LULCC (assessed in 2010) when represented as a probability density function. The grid spacing is 1.9° latitude by 2.5° longitude. Note that we show AOD in place of the aerosol forcings since the distribution of these forcings includes variability in cloud properties that are not directly attributable to changes in aerosols at this grid spacing.

Forcing	Mean	Quantiles						
		Min.	$q_{0.1}$	$q_{0.25}$	Median	$q_{0.75}$	$q_{0.9}$	Max.
CO <sub>2</sub>	0.43 [±0.27]	0.43	0.43	0.43	0.43	0.43	0.43	0.43
N <sub>2</sub> O	0.14 [±0.04]	0.14	0.14	0.14	0.14	0.14	0.14	0.14
CH <sub>4</sub>	0.30 [±0.07]	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Ozone	0.12 [±0.18]	−0.10	0.06	0.08	0.11	0.15	0.19	0.37
Albedo*	−0.05 [±0.12]	−5.6	−0.45	−0.09	0	0	0.08	2.5
Ice alb.*	0.01 [±0.02]	−1.52	−0.01	0	0	0.01	0.06	2.6
AOD	0.005	−0.18	−0.02	0	0.03	0.07	0.11	0.29

\* The spatial distribution of the RF from albedo changes is computed only for land points.

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**Table 6.** Enhancement of CO<sub>2</sub> RF by other forcing agents for LULCC and other anthropogenic activities (FF+). RFs are given in units of W m<sup>-2</sup>.

Scenario	LULCC		FF+ <sup>a</sup>		Enhancement <sup>b</sup>
	CO <sub>2</sub> RF	TOTAL RF	CO <sub>2</sub> RF	TOTAL RF	
2010	0.43	0.88	1.35	1.05	2.6
RCP2.6	0.51	1.08	3.14	3.14	2.1
RCP4.5	0.31	0.96	3.14	3.14	3.1
RCP6.0	0.54	1.21	3.14	3.14	2.2
RCP8.5	0.81	2.25	3.14	3.14	2.8
WCS <sup>c</sup>	1.58	4.58	3.14	3.14	2.9

<sup>a</sup> Other anthropogenic activities, dominated by fossil fuel burning, and including the aerosol effects RFs from the IPCC AR4 (Forster et al., 2007).

<sup>b</sup> Enhancement is defined as the ratio of total RF to CO<sub>2</sub> RF for LULCC divided by the ratio of total RF to CO<sub>2</sub> RF for FF+.

<sup>c</sup> Worst case scenario.

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**Table A1.** Values for the three types of uncertainty calculated in this study. Uncertainty due to fires is specific to each future LULCC scenario and for other future anthropogenic activities (FF+).

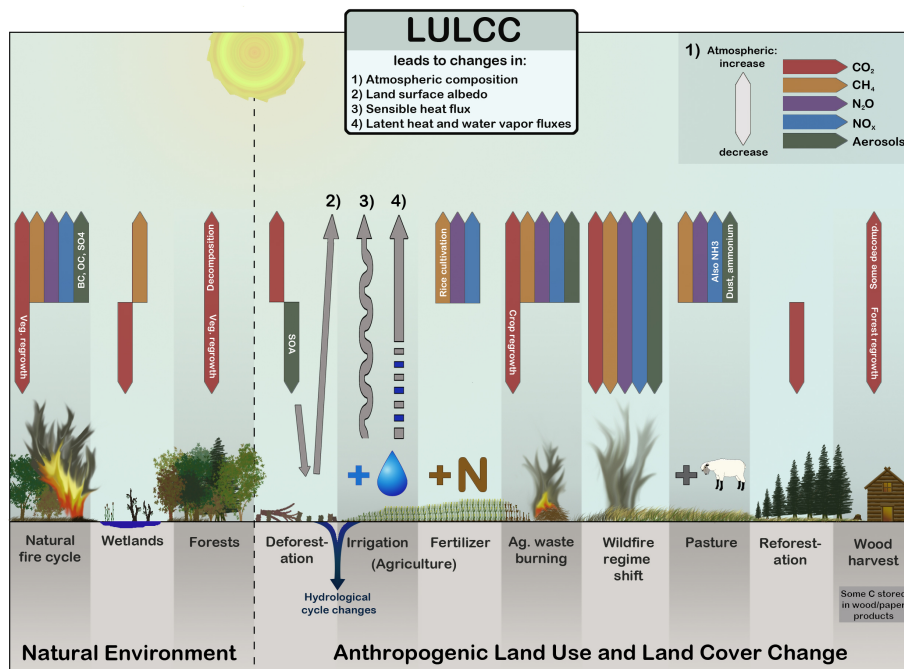
Forcing	Model [Wm <sup>-2</sup> ]	Partitioning [%]	Fire [Wm <sup>-2</sup> ]					
			RCP2.6	RCP4.5	RCP6.0	RCP8.5	WCS*	FF+
CO <sub>2</sub>	±0.10	±15	±0.04	±0.02	±0.04	±0.05	±0.15	0
N <sub>2</sub> O	±0.01	±25	0	0	0	0	0	0
CH <sub>4</sub>	±0.03	±15	±0.01	±0.01	±0.01	±0.01	±0.02	±0.02
Ozone	+0.18, -0.06	±40	0	0	0	0	±0.01	±0.01
Aero DE	±0.24	±40	0	±0.02	±0.02	±0.02	±0.1	±0.1
Aero IE	+0.24, -0.67	±40	±0.05	±0.02	0	±0.14	±0.23	±0.28
Albedo	±0.12	0	±0.01	±0.01	0	0	±0.01	0
Ice alb.	±0.06	±40	0	±0.01	0	0	0	0
HaloCs	±0.02	0	0	0	0	0	0	0

\* Worst case scenario.

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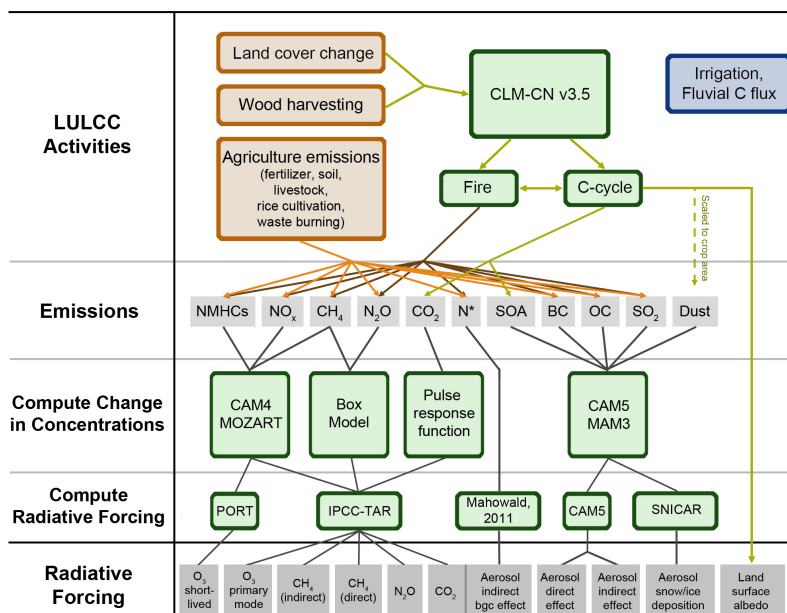
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**Fig. 1.** A schematic illustration of the climate impacts of land use and land cover change. See Fig. 2 for a representation of the processes and emissions included in this study.

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**Fig. 2.** A flow chart summarizing the methodology used in this study to compute the RF of the various forcing agents of LULCC. The colors of the boxes indicate processes that are independent of this study (orange), processes and computational steps that were completed as part of this study (green), and processes that were not included in this study, but are likely important for climate (blue). Acronyms are defined as follows: CLM-CN (Community Land Model with Carbon/Nitrogen cycles) (Oleson et al., 2008; Stockli et al., 2008), CAM (Community Atmosphere Model) (Gent et al., 2011), MOZART (Model for Ozone and Related Chemical Tracers) (Emmons et al., 2010), PORT (Parallel Offline Radiative Transfer) (Conley et al., 2013), TAR (Third Assessment Report) (Ramaswamy et al., 2001), and SNICAR (Snow Ice and Radiative Aerosol Model) (Flanner and Zender, 2006). \* Total nitrogen (N) includes contributions from NH<sub>3</sub>, N<sub>2</sub>O and NO<sub>x</sub> emissions.

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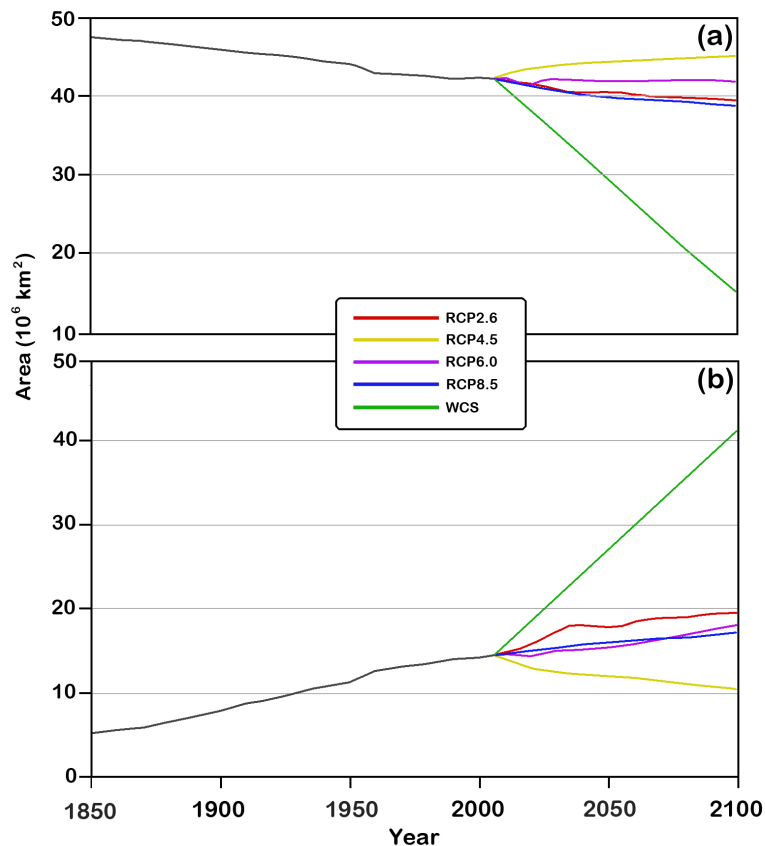
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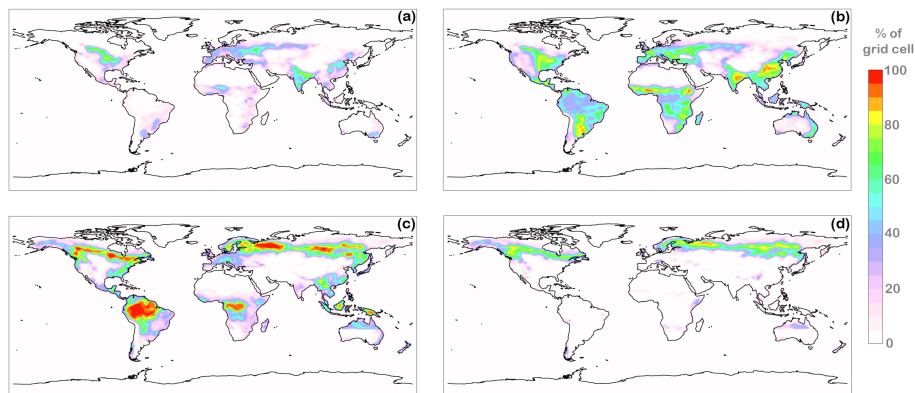
**Fig. 3.** Change in global total (a) forest and (b) crop areal coverage with time for historical and Representative Concentration Pathway scenarios (Lawrence et al., 2012), and the worst case scenario (WCS; green).

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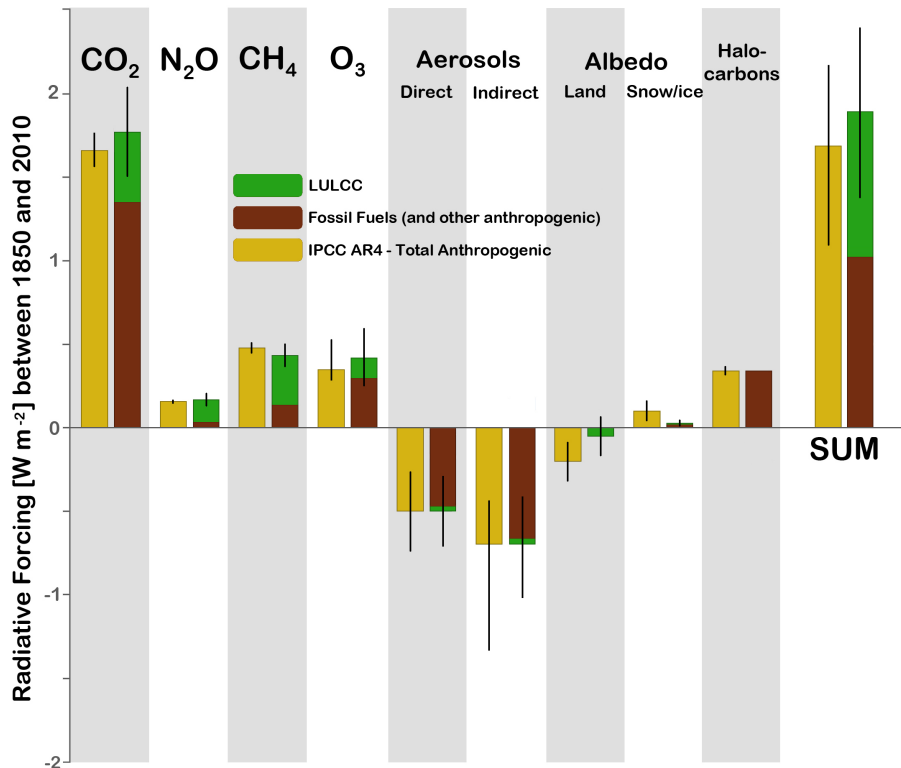
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**Fig. 4.** Percent of gridbox area consisting of **(a)** year 2010 crops, **(b)** potential crops based on climate and soil suitability, **(c)** year 2010 forests, and **(d)** year 2100 forests in the worst case scenario.

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**Fig. 5.** RFs for LULCC and other anthropogenic impacts estimated by this study for the year 2010 referenced to the year 1850. Total anthropogenic RF from the IPCC AR4 (Forster et al., 2007) are shown for comparison (yellow). Error lines represent one sigma uncertainties in total anthropogenic RF for the IPCC bars and one sigma uncertainties in LULCC RFs as computed in this study (green bars, data given in Table 3). The “SUM” bars show the total RF when all forcing agents are combined. Note that aerosol RFs are scaled to IPCC AR4 values, as explained in the main text.

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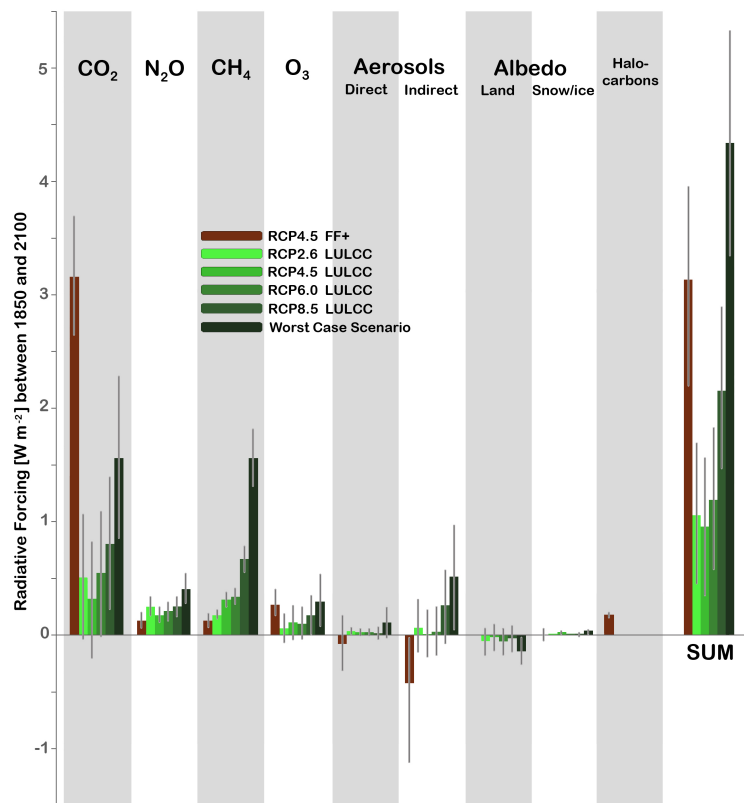
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**Fig. 6.** RF for all LULCC and other anthropogenic impacts (RCP4.5 FF+) estimated by this study for the year 2100, referenced to the year 1850. Error bars show one sigma uncertainties as computed in this study (Table 3). The “SUM” bars show the total RF when all forcing agents are considered.

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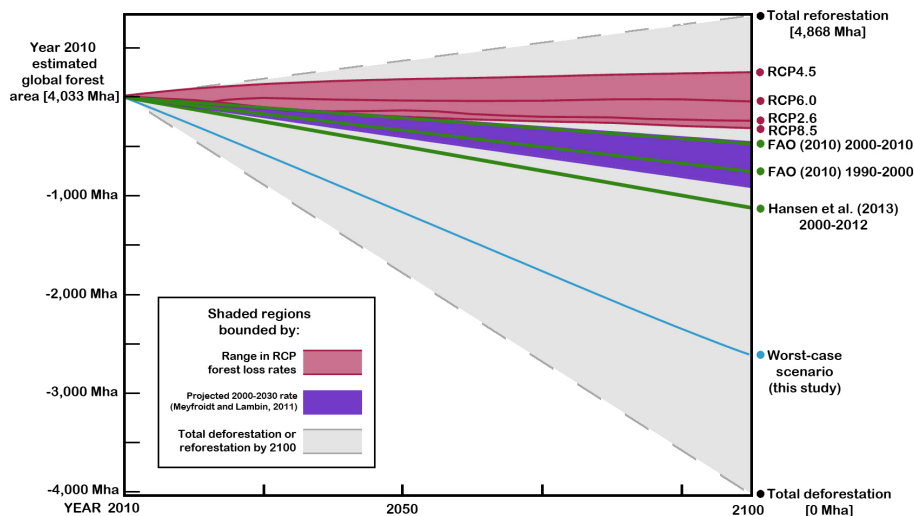
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**Fig. 7.** Comparison of projected annual rates of forest area change. Color lines and shading represent the change in global forest area between 2010 and 2100 for the Representative Concentration Pathways (red) and the worst case scenario (light blue). The grey shaded region is bounded by the annual rate of forest area change required to completely reforest to the estimated prehistoric forest area (Pongratz et al., 2008), or remove all forests by year 2100. Reported and projected forest area change from Meyfroidt and Lambin (2011) (purple), and FAO (2010) and Hansen et al. (2013) (green) are depicted as constant rates through year 2100 to show the result if these rates were sustained.

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