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Carbon density and anthropogenic land use influences on net land-use change emissions

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Abstract

We examine historical and future land-use emissions using a simple mechanistic carbon-cycle model with regional and ecosystem specific parameterizations. Our central estimate of net terrestrial land-use change emissions, exclusive of climate feedbacks, is 250 Gt C over the last three hundred years. This estimate is most sensitive to assumptions for pre-industrial forest and soil carbon densities. We also find that estimates are sensitive to the treatment of crop and pasture lands. These sensitivities also translate into differences in future terrestrial uptake in the RCP4.5 land-use scenario. This estimate of future uptake is lower than the native values from the GCAM integrated assessment model result due to lower net reforestation in the RCP4.5 gridded land-use data product.

1 Introduction

Over the past 500 yr of human-induced changes to the terrestrial environment, substantial changes in atmospheric CO_2 concentration have been driven in part by land-use change (LUC), and substantial changes will continue to occur in the next century. A key indicator of terrestrial changes is net land-use change (LUC) emissions, that is the net change in terrestrial carbon stocks not accounting for climate feedbacks. If net LUC emissions could be accurately quantified, this would provide constraints on the nature and magnitude of climate feedbacks on the terrestrial system.

Previous studies of LUC emissions, which include bookkeeping, GIS-based, and process-based ecosystem models, have estimated widely varying values over the historical period as discussed further below. Differences are caused by a variety of factors, including assumptions for ecosystem parameters, such as carbon densities, and historical and current land-use patterns (Ramankutty and Foley, 1999; Klein Goldewijk, 2001; Hurtt et al., 2011), particularly forest cover.

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Analyses of these uncertainties, for example Houghton (2010), generally rely on comparing results from different studies. This can make firm conclusions difficult because methodologies and assumptions differ in multiple ways between studies. We examine here the sensitivity of past and future LUC emissions to a wide suite of assumptions by using a flexible carbon-cycle model parameterized using spatially explicit data sets with regional detail. We consistently treat LUC, vegetation growth and the associated carbon flows, forest succession, and wood harvest, in a model complex enough to capture relevant detail, but simple enough that assumptions can be easily and transparently changed. This model also allows analysis of the quantitative implications of land-use and carbon-cycle assumptions in more complex Earth Systems Models (ESMs).

We will approach this issue by posing the following question: given a set of spatially-detailed LUC scenarios, how do different assumptions for ecosystem properties and the representation of anthropogenic land-uses impact estimates of the resulting net release in terrestrial CO_2 over time? We consider land-use changes over the pre-industrial period through to 2100 under the RCP4.5 scenario for future land-use changes (Thomson et al., 2011). The RCP4.5 scenario was chosen because this scenario represents a future with net reforestation, which offers a useful test of model dynamics over this period in contrast to net deforestation historically.

The terrestrial carbon model will be described below, followed by the input data sets and the parameter values used, concluding with a discussion of results.

2 G-CARBON model structure

The G-Carbon model consists of a hierarchy of box models, organized by region and ecosystem. The version of the model used here is implemented for 14 regions and 12 ecosystem/land-use types (Table 1). The ecosystem/land-use types were chosen as a minimal set that resolves major LUC over time and will, for simplicity, be referred to collectively in the text as ecosystem types. The G-CARBON model is built on the same

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code base as the GCAM integrated assessment model, and is set up, in this work, with the same regional and similar ecosystem structure in order to facilitate comparisons with GCAM.

The same set of carbon box models is implemented in each region, with region-specific parameters as described below. Each box model is driven by exogenously determined land-use changes and simulates the growth and decay of a specific type of vegetation, represented as carbon stocks and flows. We have implemented here the simplest model that is capable of describing vegetation dynamics, with each box model consisting of net primary productivity (NPP) and vegetation, litter, and soil pools. Exclusive of LUC, which will be described below, the amount of carbon in each pool is simulated with a simple first order equation, as used in many simple carbon models (Harvey, 1989; Wigley, 1993) where each carbon pool (C_i) is characterized by a turnover timescale specific to each ecosystem type and region (τ_i). The equations describing carbon flow are as follows, with vegetation, litter, and soil carbon pools denoted by v, l, and s, respectively.

$$\frac{\mathrm{d}C_v}{\mathrm{d}t} = a^v_{\mathrm{npp}}\mathrm{NPP} - \frac{C_v}{\tau_v} - f_v(\mathrm{LUC}) \tag{1}$$

$$\frac{\mathrm{d}C_l}{\mathrm{d}t} = a^l_{\mathrm{npp}}\mathrm{NPP} + a^l_v\frac{C_v}{\tau_v} - \frac{C_l}{\tau_l} - f_l(\mathrm{LUC}) \tag{2}$$

$$\frac{\mathrm{d}C_s}{\mathrm{d}t} = a^s_{\mathrm{npp}}\mathrm{NPP} + a^s_l\frac{C_l}{\tau_l} + a^s_v\frac{C_v}{\tau_v} - \frac{C_s}{\tau_s} - f_s(\mathrm{LUC}) \tag{3}$$

The model is operated on an annual timestep, and the partition of annual net carbon flow out of each carbon pool, and from NPP, into other pools or the atmosphere is specified by a set of coefficients that are set according to ecosystem type (a^j_i) (Supplement,

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SM). Atmospheric accumulation is the balance of carbon removed through NPP and carbon released into the atmosphere from each carbon pool.

Each of these carbon box models represents total carbon in one ecosystem in one region. Land-use changes alter the amount of land in a given ecosystem, which results in carbon flows, represented by f_i(LUC) in Eq. (1). A separate set of transfer coefficients determine the disposition of carbon under LUC at each time step (see SM). Carbon in parcels of land that transition from one ecosystem type to another can be specified to stay in its current carbon pool (in the new ecosystem), transfer to another carbon pool, or be immediately transferred to the atmosphere.

3 Input data

The input data for the model are described in the sections below, detailing NPP and carbon density values, potential vegetation classification, land-use and LUC, and wood products for our central case.

3.1 Model carbon calibration

To set the quantities of carbon in the terrestrial system, we specify regionally-specific average NPP rates for each ecosystem along with an average equilibrium carbon density for each carbon box in each ecosystem. Average pre-industrial NPP and carbon densities for each ecosystem type were set using pre-industrial equilibrium carbon data from more detailed ESMs. For most quantities, values are aggregated from global gridded data, so the inputs capture regional heterogeneity. Central case values were based on terrestrial carbon data from the Integrated Science Assessment Model (ISAM) (Jain and Yang, 2005); with exceptions described in the SM. Except for wetland ecosystems (see SM) initial carbon stocks of each carbon box were set at equilibrium values at the start of the model run in 1500.

Following Van Minnen et al. (2009) and Yang et al. (2010), forest NPP in the Northern Hemisphere is exogenously increased by 4 % from 1950 to 2000, and held constant thereafter, to account for nitrogen fertilization and management improvements. This value is uncertain, and its impact will be examined in a later section.

3.2 Cropland and pasture

The aggregate properties of crops have changed over time as agricultural practices improved. In order to represent these trends, cropland is modeled in the same manner as other ecosystems, however with an exogenous trend in an effective NPP derived from historical data, as described in the SM. All carbon in the harvested crop is assumed to be transported from the cropland area and, in net, consumed and returned to the atmosphere. Effective NPP is defined as crop NPP minus the carbon content of harvested products. We also account for the increase in the harvest index for grains over the period from 1940 to 1980 drawing from Hay and Porter (2006) and Sinclair (1998).

Harvested cropland areas are from the Food and Agriculture Organization (FAO) of the United Nations ("FAOSTAT Production," 2012). All FAO estimates are smaller than the estimates of total cropland used in this study, which is originally from the HYDE3 dataset (Klein Goldewijk, 2001). The excess is land left fallow, temporarily used as pasture, or not planted for other reasons. This "Other Arable Land" was estimated as described in the SM, and is assumed to have the same NPP as grassland of the same region; final NPP values were calculated as an average, weighted by area, of the crop and Other Arable Land NPP values.

As we will demonstrate below, the treatment of pasture land also has a significant impact on results. Because pasture is a land-use potentially comprised of multiple ecosystem types, pasture NPP and carbon density values were set as a regional average of grassland, shrubland, tundra, and rock, ice, and desert values, weighed by the areas of each of these vegetation types for the year 2000 pasture distribution. This captures

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the average productivity of pasture land in 2000 so that spurious carbon flows do not take place due to transfers of land to pasture use.

3.3 Land-use data

The amount of land in each ecosystem type over time is a central input to the model. To calculate this, two datasets were needed: a map of potential vegetation (in the absence of human influence), and maps of land-use transitions over time.

3.3.1 Potential vegetation data

The primary data source for land-cover before anthropogenic disturbances is the SAGE global potential vegetation dataset of Ramankutty and Foley (1999). This dataset describes the potential vegetation that would most likely exist in the absence of human activities using 15 vegetation types specified at 5-min resolution. These vegetation types were aggregated into the ecosystems types given in Table 1, with their six forest categories reclassified into Boreal Forest or Non-boreal Forest (see SM).

Wetlands, especially at high latitudes, are sites of high carbon sequestration, and play a significant role in the global carbon cycle. Because global wetlands are not represented in the SAGE potential vegetation dataset, the SAGE data was supplemented with gridded data from the Global Lakes and Wetlands Database (GLWD) (Lehner and Doll, 2004) as described in the SM.

A significant amount of area, mostly at high latitudes, is classified in the SAGE data as "Evergreen/Deciduous Mixed Forest." Because this classification is vague, Mixed Forest areas that were not already reclassified as wetlands were reclassified, particularly at high latitudes, by substituting land cover categories from the MOD12C1 Moderate Resolution Imaging Spectroradiometer (MODIS) 0.05° Land Cover Type data product (LP DAAC, 2001), recognizing that this may overestimate the pre-industrial extent of shrublands (Lantz et al., 2012; Strum et al., 2005). MODIS data was also used to fill in for island areas missing in the SAGE dataset.

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3.3.2 Land-use change over time

Land-use change information is needed to specify transitions from one land-use or ecosystem to another, including forest harvest. The RCP historical dataset developed by Hurtt et al. (2011) was used to specify land-use changes over time. These estimates use the SAGE and HYDE 3 historical datasets for crop, pasture, and urban area, as well as data from Houghton (1999) for wood harvest and areas of shifting cultivation. This dataset gives estimates of the fraction of each 0.5° grid as primary land, secondary land, cropland, pasture, and urban land, and specifies the amount of area that transitions between land uses for each year from 1500 to 2100. The potential vegetation dataset was applied equally through each 0.5° cell to allocate ecosystem types to the unmanaged land areas, and to characterize transitions between potential ecosystem types and land uses. All accounting of LUC was done at a 0.5° resolution to capture fine scale changes, and the areas were then aggregated into the ecosystem and regions specified in Table 1.

For most ecosystems, no distinction was made between primary and secondary land types; grassland area, for example, is the sum of both primary and secondary land. The age structure of forests, however, is essential in modeling the carbon cycle, as re-growing forests represent a substantial carbon sink, while mature forests represent large carbon stocks. For non-boreal forest a set of discrete cohorts of secondary forest, 50 yr in length, were used to capture the effects of forest age structure (we found little impact on the results if 25 or 75 yr cohorts were used). The Hurtt et al. transition data was used to specify for each year, the area of zero-age secondary forest. In each year, land is both gained and lost from the current cohort, but can only be lost from previous cohort areas, thus capturing the general changes in forest age structure over time. For the most recent forest vintage, we track both net and gross land gain in order to approximate rapid turnover of forestland in some regions due to either short-rotation forestry or shifting cultivation. The resulting changes in land area of each ecosystem are shown in the SM.

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3.4 Wood products

Wood products act as short- to long-term carbon sinks as they are used to produce wood and paper products and then decay and release carbon into the atmosphere after use. The impact of wood harvest was incorporated into the model by dividing wood harvest within each region into four product pools: sawn wood, paper and pulpwood, other roundwood products, and short-term wood products. Historical wood harvest are from Hurtt et al. (2006) for 1700–1899 (drawn in large part from Houghton, 1999) and from FAO for 1961–2005, with intermediate years interpolated between the two datasets. Wood harvest data beyond 2005 are from the RCP 4.5 scenario. A global average value was estimated for the fraction of each commodity assigned to each product pool using global annual wood flow values from Buchanan and Levine (1999). The turnover timescale depends on the region and product pool. Annual oxidation fractions from Winjum et al. (1998) are converted to lifetimes. The sawn wood lifetime ranges from 50–200 yr, pulpwood from 10–200 yr, other round wood from 13–50 yr, and short-term wood products 2 yr (see SM).

4 Results

4.1 Central case LUC emissions

We now examine the results for net land-use change emissions, which are defined as net emissions from the terrestrial biosphere accounting for land-use changes and regrowth, but not climate or CO_2 feedbacks (which will be examined in separate work). Note that, in the accounting system in this carbon model, land-use change emissions that occur at the time of land conversion are attributed to the ecosystem that loses land.

LUC emissions estimates from the G-CARBON model, by ecosystem for the years 1800–2100, are shown in Fig. 1 and Table 2. Land-use changes drive an increase

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in global emissions between 1800 and 1960. Global net emissions generally fall over recent years, and become negative by 2010. Emissions remain negative over the 21st century in the RCP4.5 land-use scenario considered here, due to a stabilization in the rate of primary forest loss and an overall net global reforestation, as reflected in the secondary forest sink seen in Fig. 1.

Over the period 1700–2000, there is a net LUC release of 250 GtC, again not accounting for carbon feedbacks. Loss of primary non-boreal forest is the primary contributor, with forest loss net re-growth accounting for 70–75 % of total emissions over the historical period. The sum of grassland, shrubland, cropland and pasture accounts for most of the remaining emissions.

Figure 3 shows LUC emissions by geographic region. The rapid rise in emissions between 1800 and 1850 occurs primarily in North America. Most of this carbon is released as forest is lost and land is converted to cropland, with primary forest loss and cropland the major sources, and secondary forest re-growth as the major sink. After 1850, significant carbon is released from the Former Soviet Union; where grassland conversion is also a major source. Emissions from South & Central America also begin to increase by the end of the 19th century; largely from deforestation. By the middle of the 20th century, Africa and South Asia and East Asia are also contributing to global net LUC emissions. Deforestation of primary forest is the principal source in South Asia and East Asia. In Africa, land conversions in grasslands and secondary forest, which include the impact of shifting cultivation, are also significant.

North American LUC emissions begin to decline in the early 20th century, and are net negative by the 1960s. Emissions from other regions are net negative by 2010 except for East Asia (again, exclusive of climate feedbacks).

Re-growing forest takes up a net total of 30 GtC between 1700 and 2000. Because of shifting cultivation and management for timber production, secondary forests have lower aggregate carbon densities than primary forests. Significant regrowth occurs in three regions before 2000; North America uptake was 18 GtC, in South & Central America 9 GtC, and in the Former Soviet Union 6 GtC. Due to the assumption of

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ongoing shifting cultivation, there are significant areas of secondary forests in Africa and South & Central America by 1700 which result in small net carbon changes. Secondary forest is estimated to be a significant carbon source in Africa between 1850 and 2000 (releasing 11 GtC), and a small source in Central & South America in the middle of the 20th century.

From 1700–2000, 1.8 million kha of global grasslands are converted, largely, to pasture and cropland, releasing 26 GtC. This is offset, in part, by an expansion of pasture by 3 million kha, which results in a net uptake of 12 GtC. 9 GtC of this occurred in African pastureland, and East Asia and the Former Soviet Union captured a significant amount of carbon as well. Loss of shrubland area was a small carbon source in many regions, most significantly Australia/New Zealand.

There is significant uncertainty in carbon loss and gain from grassland and pasture, due to uncertainty in the impact of pasture conversion on carbon stocks and flows and in the relative properties of land used as pasture as compared to native ecosystems. There is also substantial uncertainty in the land-use data for pasture in general, and potential issues with data continuity over time. All the results here exhibit a large spike in LUC emissions in 1950. A portion of this emission feature is likely to be an artifact of discontinuous pasture data over this time period (Chini et al., 2013). Total excess LUC emissions over 1950–1960 are 10 GtC, or 5 % of total 1850–2000 emissions. It is, therefore, difficult to draw firm conclusions about the impact of pasture conversion on LUC emissions.

Land converted to cropland remained a major emissions source after conversion, as croplands have, historically, low average soil C densities relative to the ecosystems from which they are converted, and carbon was slowly released until soils equilibrated at lower densities. Global croplands over 1700–2000 released 55 GtC, mainly in North America (22 GtC) and the Former Soviet Union (17 GtC)

Over the 21st century, shifts in global land-use occur in the RCP4.5 scenario that result in a net increase in terrestrial carbon storage. The RCP4.5 scenario is a forcing stabilization scenario, based on the assumption that carbon on land is valued, globally,

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at the same rate as carbon emitted from fossil fuel consumption. As a result, the scenario exhibits reforestation globally over the 21st century. The amount of reforestation in the land-use data used here is smaller, however, compared to the GCAM model and this difference will be examined later.

In the early 21st century LUC emissions decline rapidly in South & Central America, Africa, and South Asia. In the Americas and South Asia, this is mainly due to reduced emissions from primary forest and increased secondary forest uptake; in Africa, grassland uptake is significant. Emissions remain high in East Asia until 2050, and decline rapidly over the following 25 yr; the high emissions are mainly due to primary forest loss, which persists until 2065. Globally, emissions from primary forests continue to be the main net source of LUC carbon to the atmosphere. These emissions slow from a release rate of $\sim 1.0\ \mathrm{GtC\,yr^{-1}}$ in 2000 to $\sim 0.48\ \mathrm{GtC\,yr^{-1}}$ in 2100; this final rate is comparable to the emissions in ~1820. Most of this reduction occurs in South & Central America and East Asia, while primary forest conversion rates increase in the Former Soviet Union and North America over the 21st century. The global secondary forest uptake intensifies rapidly in the beginning of the 21st century in all regions; uptake increases from $\sim 0.33\ \mathrm{GtC\,yr^{-1}}$ in 2000 to $\sim 12\ \mathrm{GtC\,yr^{-1}}$ in 2028, surpassing primary forest emissions by ~2009.[1] This rate is reduced to $\sim 0.65\ \mathrm{GtC\,yr^{-1}}$ by 2100. The cumulative uptake by secondary forests over the 21st century is 98 GtC.

As cropland and pastureland are abandoned and grassland expands over the 21st century in this scenario, there is signifant net carbon uptake in grassland. Grasslands take up 10 GtC, the majority of which in Africa and the Former Soviet Union. Cropland also becomes a net sink, and both cropland and pastureland take up carbon as the total areas of each decrease, but cropland productivity is assumed to continue to increase.

[1] We note that this, of course, does not imply that this is actually what occurred in 2009. The land-use scenario used here transitions from estimated historical data in 2000 to the modeled future scenario by 2010. The year 2010, in the RCP4.5 scenario, is a hypothetical year where the world has begun a transition to a regime were global policies are put into place to enhance terrestrial carbon storage.

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Cropland takes up 9 GtC and pastureland captures 4 GtC, mainly in East Asia. Note that, consistent with the assumptions in the RCP4.5 scenario, this cropland uptake is solely due to regional shifts and the assumed increases in crop productivity. Changes in production practices, such as low or no-till, that could further increase cropland carbon content were not included.

4.2 Comparisons with other studies

The cumulative global land-use change emission over the period 1700–2000, 250 GtC, is compared to values for other recent studies in Table 5. The G-Carbon estimate is at the high end of other recent estimates, although similar to the HYDE-Hurtt estimate of Shevliakova et al. (2009), which is the study that uses a dataset most similar to the one used here, including shifting cultivation and wood harvest. The land-use dataset used can make a significant difference, for example, the SAGE-Hurtt results from Shevliakova et al. (2009), result in higher emission estimates due to a higher rate of conversion from primary vegetation than the HYDE-Hurtt reconstruction.

The lower land-use change emissions estimates of Pongratz et al. (2009) and Strassman et al. (2008) are expected to some extent, as these studies did not calculate the effect of wood harvesting on primary and secondary lands on emissions. Pongratz et al. (2009) also does not include shifting cultivation, with cropland expansion preferentially allocated to pasture areas. Reasons for the lower estimate DeFries et al. (1999) are not clear.

The estimate of Van Minnen et al. (2009) uses the IMAGE 2 model coupled to the HYDE database, which implies the use of similar historical cropland and pasture estimates. Their timber demand is estimated on the basis of a linear increase between 1700 and 1970, followed by FAO statistical information up to 2000. In one of their experiments, they kept cropland and pasture constant, and only changed land-use involving wood harvest; LUC emissions between 1700 and 2000 were 44 GtC, giving an indication of the magnitude of the impact of wood harvest.

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Over the more recent period 1850–2000, our estimate of 210.7 GtC is higher than the estimates of Houghton (2010).

Estimates of average annual rates of change over the last two decades of the 20th century of many studies are shown in Table 5. The values here within the range of other studies, but as we note below these values are sensitive to multiple assumptions.

Hayes et al. (2011) give estimates of the North American average annual net ecosystem exchange (NEE) for the period 2000–2006. Results from this work are similar (see SM), with a larger uptake in Hayes et al., perhaps due to climate feedbacks.

5 Sensitivity tests

The sensitivity of the LUC emissions results to alternative input data and parameter values was examined. Changes in the assumed productivity and equilibrium carbon values, alternative land-use histories, variations in the assumed carbon released during LUC disturbance, the treatment of cropland and pasture, and different timescales for forest carbon were examined.

5.1 Ecosystem carbon content

The pre-industrial carbon densities, and NPP values, that are used to calibrate this model are uncertain. Also, as has been described by Houghton (2010), carbon stocks can vary greatly within a single ecosystem type as a result of heterogeneity in the environment. We investigate the potential impact of these assumptions by calibrating to carbon density values from several sources, as described in more detail in the SM.

A key determinant of LUC emissions are the assumed forest carbon densities. We compared results using vegetation and litter (which includes deadwood) carbon density estimates from the CASA, CESM, and VEGAS models. LUC emissions from 1700–2000 increase by 35 % for CASA, and decrease by 6 % and 18 % with CESM and VEGAS inputs (Table 5).

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The values used in the tests above were derived from ecosystem models. Forest carbon density values from inventory data are often lower than the values used here. If tropical forest carbon densities are scaled to match the estimated Harris et al. (2012) for tropical regions, total LUC emissions are 28 Gt C (11 %) lower than our central estimate If forest carbon estimates were also lower in temperate regions, then the global impact of calibrating to inventory data might be even larger.

The amount of carbon in soils is also uncertain, particularly for organic soils, such as peatlands. Some ecosystem models that are "spun up" with endogenous estimates of soil carbon do not have large organic soil carbon pools. If we use, for example, the low organic carbon levels in the CESM model, global emissions are 8 % lower, since conversion of organic soils to, for example, cropland results in large carbon releases. The CESM also has lower mineral soil carbon values as compared to our central case, and using these values results in emissions that are 8 % lower still. We find, therefore, that soil carbon assumptions can be as important as forest carbon density assumptions.

Sensitivity to carbon assumptions in absolute terms is larger over the last few decades of the 20th century as compared to, for example, the first three decades of the 21st century. This may be due to lower levels of land-use change in general, including a closer balance between re-growth and deforestation.

Here, and with some other sensitivities, the sign of the sensitivity changes in the 21st century as compared to the historical period. If forest carbon densitieis, for example, are assumed to be higher (lower), then historical LUC emissions will be higher (lower), but future uptake (negative in the above table) under net reforestation will also be larger (smaller).

5.2 Cropland and pasture representation

Conversion of land to cropland results in a substantial net carbon release over the historical period, and a net uptake over the 21st century (Table 2). If regional grassland NPP and carbon densities are used for cropland instead of regionally-specific crop productivity changes over time, then historical global emissions are 30 % lower than

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in our central case. This may be one reason our estimates are larger than many of the previous estimates in the literature (Table 4). The much lower productivity of crops prior to the agricultural revolution results in much lower soil carbon contents in tilled soils, which results in a larger net carbon release over time. The use of fertilizer, improved management techniques, and improved crop varieties over the 20th century has resulted in a net global uptake by cropland soils by the present day (Fig. 1). The assumed continued increases in productivity into the 21st century in the RCP4.5 scenario results in a continued global net uptake by cropland in the future.

The representation of pasture also has an impact on model results. If pasture is represented as grassland, then global emissions are about 10 % lower due to a spurious uptake of carbon when land is converted to pasture. Much of global pasture lands are arid or semi-arid lands with relatively low productivity and lower soil carbon content as compared to grasslands. While there may be, in addition, carbon-cycle consequences of grazing, these are not understood sufficiently to be modeled on a global basis in our study.

5.3 Alternative LUH scenarios

In addition to the RCP 4.5 scenario dataset used here as our central case, Hurtt et al. (2011) examined a number of variations different assumptions about land-use practices on the frequency and magnitude of land-use transitions. We examined here two dimensions that were particularly important in their analysis: the inclusion/exclusion of shifting cultivation in tropical areas, and the priority given to primary or secondary land for land conversion.

Overall, we find that these assumptions have little impact on global historical emissions, with emissions changing only by up to ± 3 %. This small net difference masks larger changes in the fluxes of carbon by ecosystem. For instance, in the scenario with primary land priority and no shifting cultivation, net secondary forest area is nearly the same as in the central case. With fewer gross transitions between this forest and agricultural land, however, this forest area takes up twice as much carbon. The lower

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number of gross transitions also causes cropland and pasture to inherit soil with higher carbon levels, and these areas stay in agricultural land-use for longer periods of time. As a result, cropland releases 26 % more carbon; instead of sequestering carbon, pasture releases 8.9 GtC over the period.

These rather small changes are perhaps not surprising since the underlying driver data, e.g. cropland and pasture areas, and wood harvest levels, are unchanged. Variations in these data will have a larger impact on results (e.g., Jain and Yang, 2005; Shevliakova et al., 2009).

The effects of these scenarios on 2000–2100 net global emissions are noticeably larger than their impact on past uptake. With no shifting cultivation and primary land priority, net LUC carbon uptake is 9.4 % larger; with secondary land priority, uptake is 8.6 % lower. With shifting cultivation and primary land priority, net uptake is 16.8 % higher; with secondary land priority it is 13.9 % lower.

5.4 Other sensitivities

A series of other sensitivity tests were conducted. A summary is provided here, with further information provided in the SM.

The fate of carbon, particularly soil carbon, under land-use changes is not well-constrained. LUC results are most sensitive to assumptions about the fate of soil carbon under land-use disturbance. If 10 % higher soil carbon loss is assumed, then global LUC emissions increase by 9 % in the historical period, while LUC uptake increases by 6 % over the 21st century. If no soil loss was assumed under land-use change, LUC fluxes decrease by 4 % relative to our reference case assumptions.

Historical LUC results are fairly insensitive to parameters that influence the growth and flow of carbon, given that pre-industrial carbon stocks were used as a calibration value in these sensitivity tests (See SM). Modest, 4–15 %, impacts on 21st century total carbon uptake, were seen for changes in these parameters.

If wetlands are eliminated from the model, historical LUC emissions decrease slightly, 7 % over 1850–2000, while uptake over the 21st century increases by 10 %.

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The assumed increase in forest growth due to nitrogen deposition and management practices decreases historical emissions by 4–5 %, and increases 21st century uptake by 14 %.

6 Comparison to GCAM

Gridded land-use change results for the RCP4.5 scenario were used for the results in this paper. The RCP4.5 scenario was produced by the GCAM integrated assessment model (Thomson et al., 2011), which produces its own estimate of LUC emissions, derived from a simple accounting model. It is useful to compare the results here with the GCAM results.

Figure 3 shows global LUC emissions from the G-Carbon model and from the latest release version of the GCAM model, both for a RCP4.5 scenario. Total net LUC emissions are similar for the historical period, however this similarity is somewhat coincidental due to offsetting differences of opposite sign. The GCAM historical values have a substantial uptake due to pasture, and larger net emissions from forested lands. The former is because GCAM assumes higher carbon values for pasture than for the equivalent native ecosystems. The latter is due, at least in part, due to the lack of secondary forests in GCAM land-use model.

The two results diverge substantially in the future. While the G-Carbon model results have a net uptake in the 21st century, this is, overall, much smaller than the GCAM result.

To examine the reason for this difference, Table 6 shows global areas for several eco-systems as simulated by GCAM in the RCP4.5 scenario as compared to areas as used in this work, as derived from the GLM data. The GLM data was processed so that cropland and pasture areas were identical to the GCAM outputs (to the extent practical) and this is, indeed, the case. We find, however, that the GLM data does not capture the full extent of the re-forestation present in the GCAM policy scenario. This is because the GLM processing was not constrained using forest area information from GCAM, only

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wood harvest data was used (Hurtt et al., 2010). In the GCAM scenario, pasture and cropland shift, in net, to grassland and shrubland areas, while forest area increases. The opposite behavior is seen in the GLM data, where grassland and shrubland area actually increase, whereas these areas decrease in the GCAM scenario Note that our interpretation of the GLM results could depend, at least somewhat, on the assumptions for sub-gridscale allocations between ecosystem types.

As a result of this difference in land-use change assumptions, the G-Carbon scenario has a much smaller increase in carbon storage in forests over the 21st century. The much larger carbon uptake due to re-forestation seen in GCAM RCP4.5 scenario is, therefore, not reflected in the GLM results. This difference will also be seen in GCM scenarios (Taylor et al., 2012) using the GLM data.

7 Conclusions

Using spatially resolved data on land-use change in an aggregate model that resolves 12 ecosystem types in 14 global regions, we find that net land-use change (LUC) emissions over 1700–2000 of 250 GtC and over 1850–2000 of 210 GtC. These are emissions without consideration of climate or temperature-related feedbacks. These values are somewhat higher than many estimates in the literature, but comparable to recent estimates (e.g. Shevliakova et al., 2009) that use a similar land-use change dataset that also includes the impact of wood harvest on carbon stocks. Not included in these estimates are the impacts of woody encroachment, conservation tillage, and fire suppression, all of which would reduce emission estimates.

We find that the carbon cycle is most sensitive to different estimates of the amount of carbon in the terrestrial system and to the way that pasture and cropland are represented. For the period of 1700–2000, cumulative global LUC emissions range from 180 GtC to 340 GtC in our sensitivity tests, with the highest estimates from a scenario calibrated to the higher forest carbon densities from the CASA model. Emissions were

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about 10 % lower if the model is calibrated to the lower tropical forest carbon densities from Harris et al. (2012).

The lowest value for LUC emissions was found in a scenario where croplands are represented as grasslands, instead of reported crop productivity over time. This is, however, an unrealistic assumption because the productivity of cropland is different than natural grasslands, and dramatically so in the past. We also note that treating pasture as a grassland also produces an unrealistically low LUC emissions since many areas classified as pasture are relatively low productivity, often semi-arid, ecosystems.

In the RCP4.5 scenario used here, all scenarios have a net carbon uptake over the 21st century, with an uptake of 70 GtC in our central scenario and a range of 60 GtC to 90 GtC.

We found relatively low sensitivity to alternative historical land-use change assumptions (Hurtt et al., 2011), although all the land-use change data used here were based on the same foundational datasets for cropland and pasture extent and forest harvest. Different assumptions for these data would likely have a larger impact on results.

Only modest sensitivity was found to changes in turnover timescales and assumptions about carbon disposition under land-use change. This is, in part, due to our approach whereby equilibrium carbon contents were calibrated to reference values.

The uptake over the 21st century in this scenario is much smaller than the uptake from the GCAM integrated assessment model that produced the RCP4.5 scenarios. We find that the difference is due to a larger amount of re-forestation in the GCAM integrated assessment model that was not carried forward into the GLM land-use data used here (and also in CMIP5 global model experiments).

We find that use of values derived from the CESM global model results in lower LUC emissions, with the largest impact due to lower carbon in soils, particularly organic soils, but also somewhat lower forest carbon values.

While the substantial uncertainty in LUC emissions were about 10 % lower than in our central case, we highlight here through sensitivity tests that a substantial uncertainty in historical and future estimates exists due to uncertainty in pre-industrial carbon stocks.

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A large portion of this uncertainty stems from assumptions used for pre-industrial primary forest carbon stocks. Ecosystem models have a variety of implicit assumptions for the equilibrium value of forest carbon stocks. Better constraints on forest carbon are needed, including a better characterization of forest heterogeneity. For example, if ecosystem models are using forest density assumptions based on dense forests patches, while actual forest areas contain large amounts of low-density forest (due to slope, patches of rocky or poor soil, etc) then forest carbon contents would be overestimated. Methods that explicitly measure forest heterogeneity (e.g. Baccini et al., 2012) may help to better quantify these issues. More explicit documentation of the amount of standing and fallen deadwood would also be useful, as these form a non-trivial component of forest carbon stock. In areas with little primary forest these characteristics would need to be extrapolated form the properties of the current secondary forest.

In order to facilitate model comparisons, explicit output of forest carbon density parameters from ecosystem and land-use models, instead of grid-cell averages available at present, would also facilitate analysis and comparison.

We also find that the treatment of anthropogenic changes, particularly pasture and cropland, also have a significant impact on results. Overly simplified treatment of these land-uses results in biased results. Cropland productivity and management changes over time are an important contributor to historical LUC emissions and need to be included in models. The impact of assumptions for productivity and amount of non-harvested cropland and management changes such as agricultural waste burning and low-till agriculture should be further investigated.

Supplementary material related to this article is available online at: http://www.biogeosciences-discuss.net/10/4157/2013/ bgd-10-4157-2013-supplement.pdf.

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Table 1. Regions Ecosystem Types used in this study.

Regions	Ecosystem Types
USA	Boreal forest
Canada	Primary non-boreal forest
Western Europe Japan	Secondary non-boreal forest (as 50-year age classes)
Australia_NZ	Grassland
Former Soviet	Union Shrubland
China	Cropland
Middle East	Pasture
Africa	Rock, ice, and desert
Latin America	Urban land
Southeast Asia	Tundra
Eastern Europe	High latitude wetland/peatland
Korea	Mid and low latitude wetland
India	

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Table 2. Net land-use change emissions and uptake by ecosystem type.

Region	Land-Use Total 1700–2000 Gt C	Total 1850–2000 Gt C	Total 2000–2100 Gt C	Average 1980–1989 Gt C yr^{-1}	Average 1990–1999 Gt C yr^{-1}
Primary non-boreal forest	219.3	160.7	71.7	1.18	0.97
Secondary non-boreal forest	−29.9	−9.6	−97.5	−0.06	−0.20
Grassland	25.7	22.5	−10.1	0.08	0.05
Shrubland	8.9	7.7	0.6	0.04	0.02
Cropland	55.0	43.2	−8.7	0.10	0.07
Pasture	−11.7	−9.9	−3.6	−0.06	−0.07
High latitude wetland/peatland	−8.3	−3.3	−3.2	−0.02	−0.02
Mid and low latitude wetland	−1.4	2.3	−2.2	0.02	0.01
Boreal forest	1.2	0.8	−3.8	−0.04	−0.02
Tundra	3.1	2.5	−0.4	0.05	0.01
Rock, Ice and Desert	1.5	1.3	0.1	0.02	0.01
Urbanland	0.5	0.4	0.1	0.00	0.00
WoodProducts	−10.5	−8.1	−10.8	−0.09	−0.09
Total	253.4	210.7	−67.8	1.21	0.73

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Table 3. Net land-use change emissions and uptake (Gt C) by region.

Region	Total 1700–2000 Gt C	Total 1850–2000 Gt C	Total 2000–2100 Gt C	Average 1980–1989 Gt C yr^{-1}	Average 1990–1999 Gt C yr^{-1}
North America	45.4	40.2	−12.6	−0.076	−0.060
South & Central America	50.7	48.3	−15.2	0.437	0.309
East & West Europe	16.5	11.3	−4.0	−0.019	−0.045
Former Soviet Union	37.1	28.8	−17.1	0.007	−0.016
East Asia	25.9	19.4	7.4	0.458	0.231
South Asia	40.7	27.2	−15.0	0.189	0.061
Africa	28.0	26.1	−10.4	0.147	0.216
Australia & Middle East	9.1	9.4	−0.8	0.070	0.037

Table 4. Estimates of net land-use change emissions from other studies. Data source.

Data Source	Total 1700–2000 GtC	Total 1800–2000 GtC	Average 1980–1999 $GtC\,yr^{-1}$	Average 1990–1999 $GtC\,yr^{-1}$	Reference
G-CARBON	250	210	1.2	0.7	this study
HYDE3.0	190	–	1.5	1.1	Strassman et al. (2008)
SAGE & HYDE	140	110	0.7	1.1	Pongratz et al. (2009)
HYDE-Hurtt	240	160	1	1.1	Shevliakova et al. (2009)
SAGE-Hurtt	290	190	1.4	1.3	Shevliakova et al. (2009)
IMAGE 2	140	–	–	–	Van Minnen et al. (2009)
Houghton (2003)	–	160	2	2.2	Houghton (2003)
2005FRA	–	–	1.5	1.6	Houghton (2010)
Pre-disturbance maps	160	–	–	–	DeFries et al. (1999)
Satellite (AVHRR)	–	–	0.6	0.9	DeFries et al. (2002)
Satellite (Landsat)	–	–	–	1.1	Achard et al. (2004)
GFED	–	–	–	1.5	van der Werf et al. (2009)
ISAM-HH	109*	–	1.3	–	Jain and Yang (2005)
ISAM-RF	113*	–	0.7	–	Jain and Yang (2006)

* Total 1765–1990

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Table 5. Land-use change emissions from sensitivity tests.

Scenario	Total 1700–2000	Total 1850–2000	Total 2000–2100	Average 1980–1989	Average 1990–1999
	Gt C			Gt C yr^{-1}	
Central Scenario	253	211	−68	1.2	0.7
		Difference with Central Scenario			
Land-Use History					
No Shifting Cultivation, Primary Land Priority	2	0	−6	0.0	−0.1
No Shifting Cultivation, Secondary Land Priority	−6	−6	6	0.0	0.0
Shifting Cultivation, Primary Land Priority	7	6	−11	0.1	0.1
Shifting Cultivation, Secondary Land Priority	−3	−4	9	0.0	0.0
Carbon Density & NPP Assumptions					
All forest C densities based on CASA model	89	75	−22	0.7	0.5
Non-boreal forest C densities based on VEGAS	−20	−12	4	0.0	0.0
Non-boreal forest C densities based on CESM	32	37	7	0.7	0.6
CESM soil C densities for all ecosystems	−40	−41	−8	−0.3	−0.3
CESM soil C densities for organic soils	−16	−22	−7	−0.2	−0.2
Tropical forest C densities from Harris et al.	−28	−24	7	−0.2	−0.2
Cropland And Pasture					
Cropland with grassland C values	−76	−65	−19	−0.6	−0.6
Pasture with grassland C values	−27	−25	−5	−0.2	−0.2

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Table 6. Land-Areas (MHa) in GCAM RCP4.5 and G-Carbon RCP4.5 Scenarios.

		2005	2020	2035	2050	2065	2080	2095
Cropland	G-Carbon	1559	1394	1323	1288	1250	1190	1142
	RCP4.5	1631	1466	1385	1360	1328	1262	1214
Pasture	G-Carbon	3341	3143	2962	2863	2850	2854	2868
	RCP4.5	3277	3079	2878	2799	2782	2791	2804
Grassland & Shrubland	G-Carbon	2412	2579	2713	2784	2805	2828	2842
	RCP4.5	2374	2256	2177	2161	2161	2169	2176
Forests	G-Carbon	2519	2679	2767	2813	2838	2869	2890
	RCP4.5	4108	4590	4950	5071	5120	5169	5197

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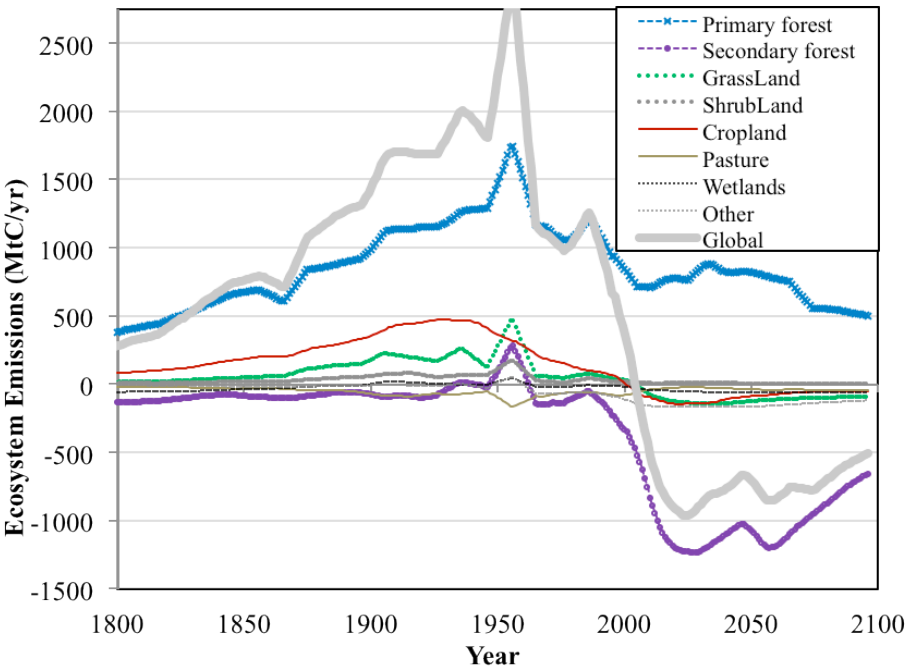

Fig. 1. Annual land-use change emissions ($MtC\,yr^{-1}$) by ecosystem from the G-CARBON model (smoothed by 9 yr averaging).

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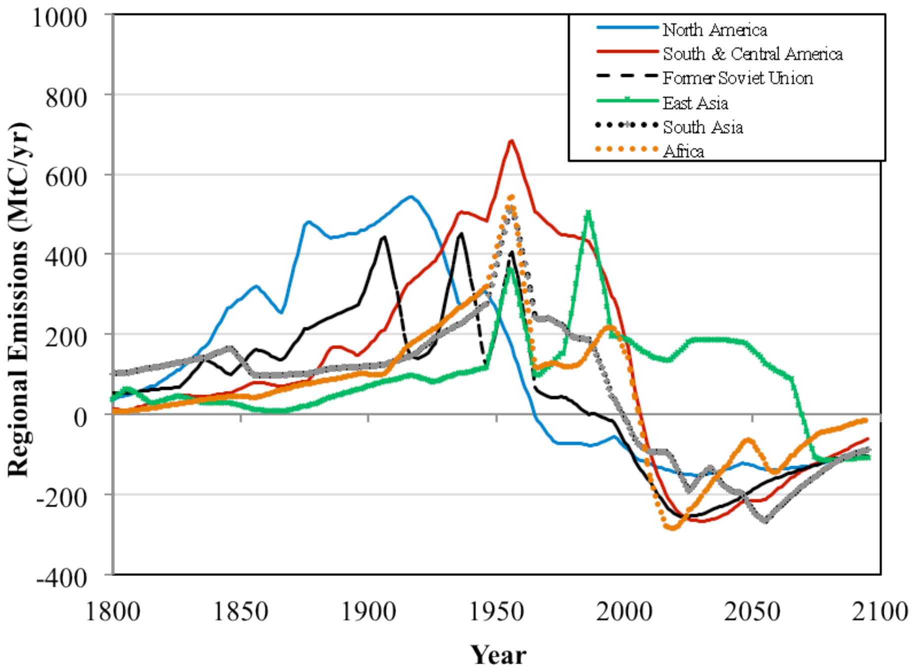

Fig. 2. Annual land-use change emissions ($MtC\,yr^{-1}$) by region from the G-CARBON model (smoothed by 9 yr averaging).

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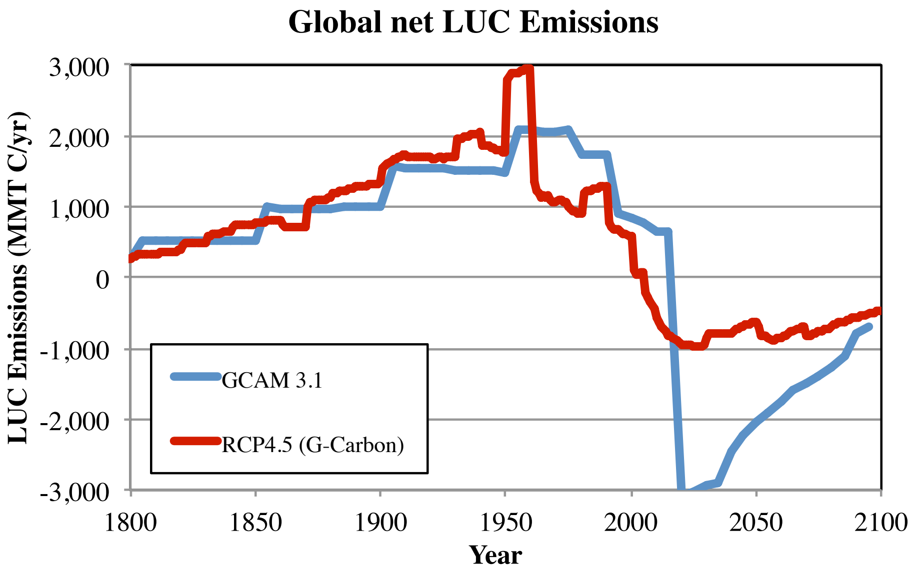

Fig. 3. Global LUC emissions from the G-Carbon model and from the latest GCAM release version 3.1.

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