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

S. J. Smith and A. Rothwell

Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park, MD, USA

Correspondence to: S. J. Smith (ssmith@pnnl.gov)

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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. We use the latest gridded data for historical and future land-use changes, which includes estimates for the impact of forest harvesting and secondary forest regrowth. Our central estimate of net terrestrial land-use change emissions, exclusive of climate–carbon feedbacks, is 250 GtC over the last 300 yr. This estimate is most sensitive to assumptions for preindustrial forest and soil carbon densities. We also find that land-use change emissions estimates are sensitive to the treatment of crop and pasture lands. These sensitivities also translate into differences in future terrestrial uptake in the RCP (representative concentration pathway) 4.5 land-use scenario. The estimate of future uptake obtained here is smaller than the native values from the GCAM (Global Change Assessment Model) 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. Changes in the net terrestrial carbon balance can conceptually be considered as two terms. The first is net LUC emissions, which are defined as the net change in terrestrial carbon stocks not accounting for climate-carbon feedbacks (see below), e.g., carbon releases minus uptake due to regrowth. Net LUC emissions can be considered as the flux of carbon to the atmosphere from land-use changes. The second term is the residual terrestrial sink, which is the net effect of changes in climate, carbon dioxide concentrations, and deposition of sulfur and nitrogen compounds. While LUC emissions are thought to be a net source historically, the terrestrial system is currently estimated to be a net carbon sink. The strength of the terrestrial sink is commonly estimated as the residual between net LUC emissions and other terms, such as ocean uptake and fossil emissions, in the global carbon balance (Houghton, 2013), although it can also be estimated directly through use of dynamic vegetation models (Le Quéré et al., 2012). For either methodology, the uncertainty in this sink is large.

We focus in this work on net LUC emissions in order to isolate the impact of human-caused changes in terrestrial carbon fluxes, as discussed further by Houghton (2013). If net LUC emissions could be accurately quantified, this would provide constraints on the nature and magnitude of climate–carbon feedbacks on the terrestrial system. LUC emissions also are a key indicator of terrestrial changes. 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.

Analyses of the uncertainties in LUC emissions (e.g., Houghton, 2010; Houghton et al., 2012), 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

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Table 1. Regions used in this study.

Regions
USA
Canada
Western Europe
Japan
Australia and New Zealand
Former Soviet Union
China
Middle East
Africa
Latin America
Southeast Asia
Eastern Europe
Korea
India

Table 2. Ecosystem types used in this study (as 50 yr age classes).

Ecosystem Types
Boreal forest
Primary non-boreal forest
Secondary non-boreal forest (as 50 yr age classes)
Grassland
Shrubland
Cropland
Pasture
Rock, ice, and desert
Urban land
Tundra
High latitude wetland/peatland
Mid and low latitude wetland

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 (Hurtt et al., 2011), 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 preindustrial period through to 2100 under the RCP4.5 scenario for future land-use changes (Thomson et al., 2011). The RCP (representative concentration pathway)4.5 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.

Analysis of the carbon-cycle is conducted with a range of model structures. The most sophisticated analyses are produced from spatially resolved process oriented models that aim to produce estimates based on fundamental biological and physical principles. There is, however, still significant uncertainty in such results. On the other end of the spectrum more parameterized, although often still physically based, carbon-cycle representations are used in integrated assessment models (van Vuuren et al., 2009; Wigley, 1993). Such models can be used to explore, for example, the implications of uncertainty in the carbon cycle for climate policy costs (Smith and Edmonds, 2006). The model used here is still highly parameterized, but incorporates greater spatial and process-level detail than most integrated assessment models, including integration of carbon-cycle and land-use dynamics. We note that land-use dynamics is rarely integrated into simple models. In addition to the type of sensitivity analysis conducted here, this analysis is also useful as a bridge between more complex models and integrated assessment.

In addition to the type of sensitivity analysis conducted here, this analysis is also useful as a bridge between more complex models and those used in integrated assessment. The G-Carbon model is designed to be calibrated to spatially detailed ecosystem models so that analysis consistent with these models can be conducted in a more flexible and fast framework (although, as we note later, the data available from more detailed models is generally not provided in an ideal form for this calibration).

The analysis here focuses on the net change in terrestrial carbon stocks, e.g., land-use change emissions, without considering the influence of changing climate and carbon dioxide concentrations. We refer to these influences here generically as climate–carbon feedbacks (Davidson et al., 2006; Friedlingstein et al., 2006; Thornton et al., 2006).

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 (Tables 1 and 2). 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 code base as the GCAM (Global Change Assessment Model) 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 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 time step, 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) (see Supplement (SM) Sect. 1.1). 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 $f_i(\mathrm{LUC})$ in Equation 1. Our conceptual representation separates the impacts of land-use change into two components: short-term and long-term. Over the long-term, the carbon content of land that transitions from one land-use category to another is represented by a relaxation toward the equilibrium state of the ecosystem type that gains land as represented in Eqs. (1–3). The shorter timescale changes associated more directly with the land-use change process itself, for example tree removal and soil disturbance, are represented by explicit land-use change flows noted as $f_i(\mathrm{LUC})$ in Eqs. (1–3). 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. A separate set of transfer coefficients specified by ecosystem determine the disposition of carbon under LUC at each annual time step (see SM Sect. 1.1).

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 preindustrial NPP and carbon densities for each ecosystem type were calculated using preindustrial 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 Sect. 1.2. Except for wetland ecosystems (see SM Sect. 1.2), 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 Sect. 1.3. 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). The harvest index is the ratio of gain yield to total plant biomass. A portion of the growth in productivity over the 20th century is an increase in allocation of plant biomass to grains, which means that agricultural productivity increases did not translate directly into an increased amount of plant biomass.

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 data set (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 by subtracting harvested area from total cropland area, 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.

Note that, because we use actual reported productivity values for harvested crops over time, these values would include all climate and carbon dioxide influences on crop productivity. While this is inconsistent with our exclusion of such feedbacks for other ecosystems, given the uncertainty in the magnitude of these effects, we did not attempt to estimate historical trends in crop productivity without climate–carbon feedbacks.

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, rock, ice, and desert values, weighed by the areas of each of these vegetation types for the year 2000 pasture distribution. This captures 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.

While we assume that some fraction of above- and below-ground carbon is immediately lost upon conversion to cropland or pasture, we assume that no carbon in cropland or pasture litter and soil is lost upon reversion to its native ecosystem (SM Sect. 1.1).

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 data sets 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 data set of Ramankutty and Foley (1999). This data set 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 ecosystem types given in Table 2, with their six forest categories reclassified into boreal forest or non-boreal forest (see SM Sect. 1.4).

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 data set, 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 Sect. 1.5.

A significant 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 preindustrial 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 data set.

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 data set developed by Hurtt et al. (2011) was used to specify land-use changes over time. These estimates use the SAGE and HYDE 3 historical data sets for crop, pasture, and urban area, as well as data from Houghton (1999) for wood harvest and areas of shifting cultivation. This data set 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 data set 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 Tables 1 and 2.

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 regrowing 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. (2011) transition data was used to specify, for each year, the area of zero-age secondary forest. In each year, land can be both gained and lost from the youngest cohort, which represents stands with ages up to 50 yr. Older cohorts represent stands that have regrown in previous years, and land can only be lost from these cohorts. This structure captures the general changes in forest age structure over time. Each forest cohort, therefore, consists all stands of roughly equal age (within 50 yr) within a region. For the most recent forest vintage, we track both net and gross land gain in order to approximate rapid turnover of forest land in some regions due to either short-rotation

Table 3. Net land-use change emissions by ecosystem type (negative values indicate net uptake).

Land Use	Total 1700–2000 GtC	Total 1850–2000 GtC	Total 2000–2100 GtC	Average 1980–1989 $GtC\,yr^{-1}$	Average 1990–1999 $GtC\,yr^{-1}$
Primary non-boreal forest	219.4	160.7	71.7	1.18	0.97
Secondary non-boreal forest	−29.9	−9.5	−97.2	−0.06	−0.20
Grassland	25.8	22.5	−10.0	0.08	0.05
Shrubland	8.9	7.7	0.6	0.04	0.02
Cropland	53.0	42.8	−6.6	0.18	0.13
Pasture	−11.7	−9.8	−3.5	−0.06	−0.07
High latitude wetland/peatland	−8.3	−3.3	−3.2	−0.03	−0.02
Mid and low latitude wetland	−1.5	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
Urban land	0.5	0.4	0.1	0.00	0.00
Wood products	−10.5	−8.1	−10.8	−0.09	−0.09
Total	251.4	210.4	−65.2	1.29	0.80

forestry or shifting cultivation. The resulting changes in land area of each ecosystem are shown in Fig. SM-1.

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 harvesting was incorporated into the model by dividing the 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 data are from Hurtt et al. (2006) for 1700–1899 (drawn in large part from Houghton, 1999) and from the FAO for 1961–2005, with intermediate years interpolated between the two data sets. Wood harvest data beyond 2005 are from the RCP4.5 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 to 200 yr, pulpwood from 10 to 200 yr, other round wood from 13 to 50 yr, and short-term wood products 2 yr (see SM Sect. 1.6).

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, except for three illustrative sensitivity cases discussed below. The impact of feedbacks will be examined in more detail 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 type that loses land. Emissions or uptake that occurs after land conversion, for example due to forest regrowth or to soil equilibrium to a new turnover timescale, are attributed to the ecosystem type that gained land.

LUC emission estimates from the G-Carbon model, by ecosystem for the years 1800–2100, are shown in Fig. 1 and Table 3. Land-use changes drive an increase 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.

Note that wetlands are presented as net sink. Because of loss of wetlands, relative to preindustrial conditions, there is a net loss of wetlands as an ongoing carbon sink. This loss is, in effect, an additional anthropogenic emission that we estimate as 10 GtC over 1700–2000 that is not included in the LUC totals (SM Sect. 3.6).

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

Figure 2 and Table 4 show LUC emissions by geographic region. The rapid rise in emissions between 1800 and 1850

Table 4. Net land-use change emissions and uptake (GtC) by region.

Region	Total 1700–2000 GtC	Total 1850–2000 GtC	Total 2000–2100 GtC	Average 1980–1989 GtC yr^{-1}	Average 1990–1999 GtC yr^{-1}
North America	44.2	39.1	−11.8	−0.05	−0.04
South and Central America	50.7	48.3	−15.1	0.44	0.31
Eastern and Western Europe	16.3	11.0	−3.9	−0.01	−0.04
Former Soviet Union	36.3	28.4	−16.5	0.02	0.00
East Asia	26.1	19.9	7.7	0.47	0.24
South Asia	40.8	28.0	−14.7	0.20	0.07
Africa	28.0	26.2	−10.2	0.15	0.22
Australia and Middle East	9.1	9.4	−0.8	0.07	0.04
Tropical Regions*	145.6	122.5	−32.3	1.3	0.8
Exa-Tropical Regions	105.8	87.9	−32.9	0.0	0.0

* Tropical Regions taken to be South and Central America, East and South Asia, and Africa.

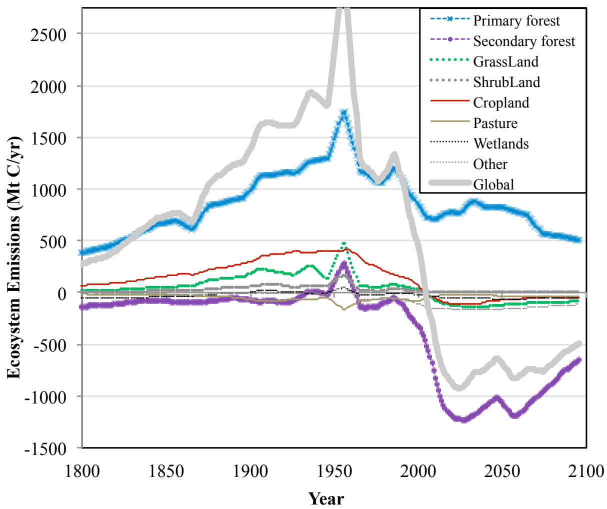

Fig. 1. Annual land-use change emissions (MtC yr^{-1}) by ecosystem from the G-Carbon model (smoothed by 9 yr averaging).

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 regrowth 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 and Central America also begin to increase by the end of the 19th century; largely from deforestation. By the middle of the 20th century, Africa, 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.

Regrowing 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 17 GtC, in South and Central America 9 GtC, and in the Former Soviet Union 6 GtC. Due to the assumption of ongoing shifting cultivation, there are significant areas of secondary forests in Africa and South and 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 and 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. Where 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., 2012). Total excess LUC emissions over 1950–1960 are 10 GtC, or 5 % of total 1850–2000 emissions. It is, therefore, difficult to draw

Table 5. Estimates of net land-use change emissions from other studies.

Data source	Total 1700–2000 GtC	Total 1850–2000 GtC	Average 1980–1989 $GtC\,yr^{-1}$	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 and HYDE	140	110	0.7	1.1	Pongratz et al. (2009)
HYDE–Hurtt	240	160		1.1	Shevliakova et al. (2009)
SAGE–Hurtt	290	190		1.3	Shevliakova et al. (2009)
IMAGE 2	140	–	–	–	Van Minnen et al. (2009)
Houghton (2003)	–	160	2.0	2.2	Houghton (2003)
2005FRA	–	–	1.5	1.6	Houghton (2010)
Predisturbance maps	160	–	–	–	DeFries et al. (1999)
Satellite (AVHRR)[b]	–	–	0.57	0.91	DeFries et al. (2002)
Satellite (Landsat)[b]	–	–	–	1.1	Achard et al. (2004)
GFED	–	–	–	1.5	van der Werf et al. (2009)
ISAM-HH	110[a]	–	1.3	–	Jain and Yang (2005)
ISAM-RF	113[a]	–	0.70	–	Jain and Yang (2005)

[a] Total 1765–1990, [b] tropical regions only.

firm conclusions about the impact of pasture conversion on LUC emissions. It seems likely that this data artifact results in a slight overestimate of historical 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 53 GtC, mainly in North America (21 GtC) and the Former Soviet Union (16 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 radiative forcing stabilization scenario, based on the assumption that carbon on land is valued, globally, at the same rate as carbon emitted from fossil fuel consumption (Thomson et al., 2011). 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 and 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 $\sim 1\,GtC\,yr^{-1}$ in 2000 to $\sim 0.5\,GtC\,yr^{-1}$ in 2100; this final rate is comparable to the emissions $\sim$ 1820. Most of this reduction occurs in South and 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 $\sim 0.3\,GtC\,yr^{-1}$ in 2000 to $\sim 1.3\,GtC\,yr^{-1}$ in 2030, surpassing primary forest emissions by $\sim$ 2009.[1] This rate is reduced to $\sim 0.6\,GtC\,yr^{-1}$ by 2100. The cumulative uptake by secondary forests over the 21st century is 97 GtC.

As cropland and pastureland are abandoned and grassland expands over the 21st century in this scenario, there is significant net carbon uptake in grassland. Grasslands take up 10 GtC, the majority of which occurs in Africa and the Former Soviet Union. Cropland also becomes a net sink, taking up 7 GtC, largely because of the assumed continued increases in cropland productivity. Pastureland is also a carbon sink, taking up 4 GtC, largely as a dynamic effect of recovering from earlier conversion losses, although a pasture data artifact may have had an impact on this result (Chini et al., 2012). Note that, consistent with the assumptions in the RCP4.5 scenario, this cropland uptake is solely due to regional shifts in production 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 (and will be examined in separate work).

[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 in which global policies are put into place to enhance terrestrial carbon storage.

Total carbon stocks are often also used to characterized terrestrial models. Total carbon stocks in the G-Carbon model are 2200 GtC in 1700 and 1900 GtC in 2000 (vegetation: 420; litter: 170; soil: 1300 GtC). The largest changes over this time period are in vegetation (−160 GtC) and soil (−100 GtC) carbon stocks, with a smaller change in litter (−30 GtC). The year 2000 soil carbon stock is nearly identical to the value from Todd-Brown et al. (2013) of 1260 GtC (range 890–1660 GtC), derived from the Harmonized World Soil Database ((FAO/IIASA/ISRIC/ISSCAS/JRC, 2012). Note that, as we discuss later, soil carbon emissions under land-use change are uncertain, but there are considerable uncertainties in soil carbon stocks as well.

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. We focus here on studies that examined LUC emissions without climate or carbon feedbacks. 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 data set most similar to the one used here, including shifting cultivation and wood harvesting. The land-use data set 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.

Incorporation of wood harvesting and shifting cultivation lower the average carbon content of forests and, therefore, increase net emissions. While a portion of historical wood demand is supplied through land conversion, a large portion, particularly in the present day, is supplied through forest management. Shevliakova et al. (2009) find that the inclusion of these two effects increases emissions over 1700–2000 by 40 and 50 %, under the Hyde and Sage historical cropland data sets, respectively. Most of the estimates in Table 4 do not include these two effects (Houghton et al., 2012), which means that the lower land-use change emission estimates are to be expected.

Van Minnen et al. (2009) also find a significant impact from the inclusion of timber harvest using 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. The Van Minnen et al. (2009) estimate of net LUC emissions of 140 GtC between 1700–2000 may be lower than that found in the present work because of climate–carbon-cycle feedbacks.

Over the more recent period 1850–2000, our estimate of 210 GtC is higher than the estimate of Houghton (2003). Our inclusion of cropland productivity changes over time may account for some of this difference.

Houghton et al. (2012) compared the average emissions rate from 1920 to 1999 from a number of estimates (including most of those in Table 5), with the average emission rage over this period ranging from 0.9 to 1.4 GtC yr^{-1}. This compares with a value over this period of 1.6 GtC yr^{-1} in this work. This difference may be due to the lack of wood harvest and shifting cultivation in many of the estimates quoted in Houghton et al. (2012).

Estimates of average annual rates of change over the last two decades of the 20th century from other studies are also shown in Table 5. The values here are 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 (see SM Sect. 2.1). Results from this work are similar for US cropland soils, with a somewhat smaller uptake in G-Carbon, with a difference in sign for Canadian cropland soils likely due to slower equilibrium timescales for cropland soils in G-Carbon. The Hayes et al. results for other ecosystems consistently show a larger uptake, with the largest difference for forest lands, where the uptake value estimated in Hayes et al. is much larger than the net LUC uptake value estimated here. This is consistent with the Hayes et al. results estimating actual uptake rates, which would include any climate–carbon feedbacks, while the G-Carbon results are for net LUC emissions without such effects. The G-Carbon results for croplands also do not include the impact of no-till adoption. CO_2 fertilization, which is not included in the central G-Carbon results, could increase forest uptake substantially.

5 Sensitivity tests

The sensitivity of the LUC emission results to alternative input data and parameter values is examined in this section. 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. Absolute differences with our central scenario are shown in Table 6 with percentage changes shown in Table SM-11.

5.1 Ecosystem carbon content

The preindustrial 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

Table 6. Global land-use change emissions from sensitivity tests.

Scenario	1700–2000 Total GtC	1850–2000 Total	2000–2100 Total	1980–1989 Average $GtC\,yr^{-1}$	1990–1999 Average
Central Scenario	250	210	−66	1.3	0.8
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 and NPP Assumptions					
All forest C densities based on CASA model	88	75	−22	0.7	0.5
Non-boreal forest C densities based on VEGAS model	−46	−34	6	−0.2	−0.1
Non-boreal forest C densities based on CESM model	−15	−7	11	0.3	0.2
CESM soil C densities for all available ecosystems	−39	−40	−8	−0.3	−0.3
CESM soil C densities for organic soils	−16	−21	−7	−0.2	−0.2
Tropical forest C densities from Harris et al. (2012)	−28	−24	7	−0.2	−0.2
Cropland and Pasture					
Cropland with grassland C values	−58	−47	17	−0.2	−0.2
Pasture with grassland C values	−27	−25	−5	−0.2	−0.2
Climate and CO_2 Sensitivity					
CO_2 concentration (Beta) feedback	−108	−95	−215	−1.4	−1.6
Respiration (Q10) feedback	18	18	73	0.3	0.6

impact of these assumptions by calibrating to carbon density values from several sources, as described in more detail in the SM Sect. 3.2.

A key determinant of LUC emissions are the assumed forest carbon densities. We compared results calibrated to forest vegetation and litter (which includes deadwood) carbon density estimates from the CASA (van der Werf et al., 2010), CESM (Lawrence et al. 2011, , 2012), and VEGAS models (Zeng et al., 2005a, b). LUC emissions from 1700 to 2000 increase by 88 GtC (35%) for CASA, and decrease by 15 (6 %) and 46 GtC (18 %) with CESM and VEGAS inputs (Table 5). These models were chosen as a sample of convenience: these modeling groups provided equilibrium spin-up carbon pool and NPP data in a gridded format.

The values used in the above tests 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 values estimated by Harris et al. (2012) for tropical regions, total LUC emissions are 28 GtC (11 %) lower than our central estimate. If forest carbon values were also lower in temperate regions, then the global impact of calibrating to inventory data, instead of data from ecosystem models, would 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" to produce endogenous estimates of soil carbon have organic soil carbon pools that are smaller than observed values due to a spin up period that is short relative to the age of some of these ecosystems. If we use, for example, the low organic carbon levels in the CESM model, global emissions are 6 % lower, since conversion of organic soils to, for example, cropland results in large carbon releases. This results in a low bias in such models. 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 potentially be as important as forest carbon density assumptions. Note, however, that CESM soil carbon values are lower than the central values from a global database (Todd-Brown et al., 2013).

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 in our simulations. This may be due to lower levels of land-use change in general, including a closer balance between regrowth 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 equilibrium forest carbon densities, for example, are assumed to be higher, then historical LUC emissions will be higher, but future uptake (negative in the above table) under net reforestation will also be larger. The reverse is

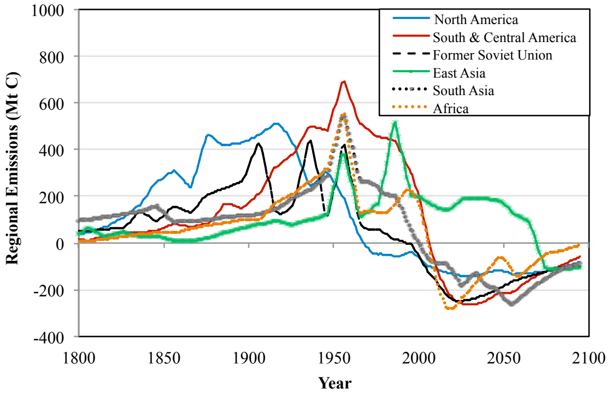

Fig. 2. Annual land-use change emissions ($MtC\,yr^{-1}$) by region from the G-Carbon model (smoothed by 9 yr averaging).

true if equilibrium forest carbon densities are assumed to be 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 3). If regional grassland NPP and carbon densities are used for cropland instead of regionally-specific cropland carbon densities and historical crop productivity changes, then historical global emissions are 23 % lower than in our central case. This may be one reason our estimates are larger than many of the previous literature estimates (Table 5). 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 in 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 in our study.

5.3 Alternative land-use history scenarios

In addition to the RCP4.5 scenario data set used here as our central case, Hurtt et al. (2011) examined a number of variants with different assumptions for land-use practices. 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. The Hurtt et al. (2011) focal case used as the core scenario in this work has parameters set between the extremes of these alternative scenarios; with secondary land prioritized in Eurasia and primary land prioritized elsewhere.

The impact of alternative land-use practices on total forest area varies. If shifting cultivation does not occur, prioritizing primary land conversion in all regions has little effect on forest area from 1700 to 2000 relative to the focal case; prioritizing secondary land leaves another 28.4 million km^2 of primary forest intact over this period. With shifting cultivation, if primary land is prioritized, another 23.3 million km^2 of primary forest are lost from 1700 to 2000; if secondary land is prioritized 27.0 million km^2 of primary forest are saved.

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 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 67 GtC over this period (1700–2000), 27 % more than the central case. Instead of sequestering carbon, pasture releases 8.9 GtC over this period.

These rather small total 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 larger than their impact on past uptake. With no shifting cultivation and primary land priority, net LUC carbon uptake is 9 % larger; with secondary land priority, uptake is 8 % lower. With shifting cultivation and primary land priority, net uptake is 17 % higher; with secondary land priority it is 14 % 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 Sect. 3.

The short-term fate of carbon, particularly soil carbon, under land-use changes is not well-constrained (SM Sect. 1.1). LUC results are moderately 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 preindustrial carbon stocks were used as a calibration value in these sensitivity tests. Larger, but still modest (4–15 %) impacts on 21st century total carbon uptake, were seen for changes in these parameters. This larger impact is likely due to the greater importance of reforestation in the 21st century in the RCP4.5 scenario.

If wetlands are eliminated from the model, historical LUC emissions decrease slightly, 7 % over 1850–2000, while uptake over the 21st century increases by 11 %. 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 %.

While the focus of this paper is on land-use change emissions without climate–carbon feedbacks, we also performed additional sensitivity tests to temperature and CO_2 concentrations using two commonly considered feedback formulations. The first is carbon dioxide "fertilization", which increases NPP, taken to be the commonly used beta formulation (SM Sect. 3.7). The second is temperature feedbacks, which increase heterotrophic respiration, incorporated using a Q10 formalism (SM Sect. 3.7). Temperature and carbon dioxide concentrations over time were taken from historical estimates as noted in the SM.

Increased productivity due to increased carbon dioxide concentrations could have a substantial impact throughout the historical period, larger than the largest sensitivity to any other parameter for the $\beta = 0.6$ case used here. Temperature feedbacks are smaller over the historical period, but comparable to sensitivity of a number of other parameters. Both feedbacks are potentially more important into the future, although it is even more likely that the simple functional forms used here may not be applicable over the climate regime considered for the 21st century.

We stress that these are illustrative feedback calculations that do not explicitly consider many important factors such as nutrient and water limitations. The strength and nature of these feedbacks are still quite uncertain, and would ultimately need to be constrained to be consistent with observations.

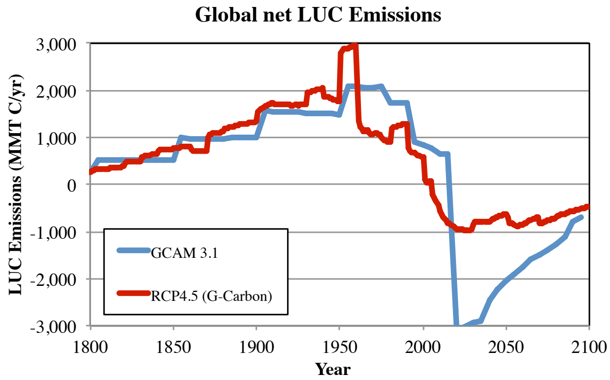

Fig. 3. Global LUC emissions from the G-Carbon model and from the latest GCAM release version 3.1.

6 Comparison to GCAM

The gridded land-use change results for the RCP4.5 scenario used in this paper (Hurtt et al., 2011) were also used in the CMIP5 model comparison exercise (Taylor et al., 2012). 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. One of the goals of the overall RCP and CMIP exercise was to enable comparison between integrated assessment and earth system models (Moss et al., 2010). It is useful, therefore, 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 the 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 7 shows global areas for several ecosystems as simulated by GCAM in the RCP4.5 scenario as compared to the areas used in this work, as derived from data from the Global Land-use Model (GLM) (Hurtt et al., 2011). 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 reforestation present in the GCAM policy scenario. This is because the GLM processing was not constrained using forest area information from GCAM,

Table 7. Land areas (in million ha) 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
	GCAM	1631	1466	1385	1360	1328	1262	1214
Pasture	G-Carbon	3341	3143	2962	2863	2850	2854	2868
	GCAM	3277	3079	2878	2799	2782	2791	2804
Grassland and Shrubland	G-Carbon	2413	2579	2713	2784	2805	2828	2842
	GCAM	1856	1737	1659	1642	1642	1651	1657
Forests	G-Carbon	3340	3512	3605	3651	3677	3709	3731
	GCAM	4108	4590	4950	5071	5120	5169	5197
Other Land	G-Carbon	2346	2372	2398	2414	2417	2418	2417
	GCAM	1959	1959	1959	1959	1959	1959	1959

only 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 areas 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 subgrid-scale 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 reforestation seen in GCAM RCP4.5 scenario is, therefore, not reflected in the GLM results. This difference will also be seen in global climate model scenarios using the GLM data (Taylor et al., 2012).

7 Conclusions and discussion

Using spatially resolved data on land-use change in an aggregate model that resolves 12 ecosystem types in 14 global regions, we find net land-use change (LUC) emissions over 1700–2000 of 250 GtC and over 1850–2000 of 210 GtC. 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 data set that also includes the impact of wood harvesting on carbon stocks. As found by Shevliakova et al. (2009), inclusion of wood product harvest and shifting cultivation, not included in most of the literature estimates to date, can substantially increase the estimates of historical land-use change. Our sensitivity tests (Table 6) indicate that a more realistic treatment of cropland productivity over time, also increases historical LUC estimates. These changes could increase historical LUC estimates in the literature to the values seen in our central case. We note, however, that our land-use estimates are likely biased slightly high (perhaps by 5–10 %) due to what appears to be an artifact in the land-use data arising from the transition to different data sources for pasture data through the 20th century (Chini et al., 2012).

Not included in the estimates produced in this paper are the impacts of woody encroachment, conservation tillage, and fire suppression, all of which would reduce emission estimates.

Over the 21st century, in the RCP4.5 scenario used here, all cases have a net carbon uptake ranging from 50 to 90 GtC, with an uptake of 70 GtC in our central scenario.

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 190 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 about 10 % lower than our central case 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 using reported crop productivity over time. In most cases, conversion to cropland, particularly prior to the mid-20th century "green revolution", resulted in a net loss of soil carbon. Treating cropland as grassland is 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 grassland also produces unrealistically low LUC emissions since many areas classified as pasture are relatively low productivity, often semi-arid, ecosystems.

This raises the issue of how cropland and pasture, which are land-use categories, are treated in spatially explicit ecosystem models, including those embedded in global earth systems models, which are designed to represent different ecosystems. While specific crops can be represented in ecosystem models, we emphasize here the importance of including, perhaps exogenously, the net productivity and physiological changes (e.g., harvest index) that occurred over time due to changes in management practices and changes in crop phenotypes through improved cultivars.

Spatially detailed models seem less likely to contain biases in representing conversion of land to pasture given that these models explicitly represent spatially varying productivity. Some ambiguities are still present, however, such as how, from an ecosystem perspective, the conversion of, for example, forested land to pasture should be represented. Representation of pasture can be a larger issue in simpler land-use models.

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 data sets for cropland and pasture extent and forest harvesting. Different assumptions for these data would likely have a larger impact on results.

Only modest sensitivity was found for 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, in large part, to a larger amount of reforestation in the GCAM integrated assessment model that was not carried forward into the GLM land-use data used here (and also used 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 substantial uncertainty in LUC emissions has long been known, we highlight here through sensitivity tests that a substantial uncertainty in historical and future estimates exists due to uncertainty in preindustrial carbon stocks. A large portion of this uncertainty stems from assumptions used for preindustrial 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 forest 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.

The G-Carbon model was designed to be calibrated using information from more spatially detailed ecosystem models. In this exercise the primary calibration variable was equilibrium carbon stocks. While we did not attempt to calibrate transient carbon dynamics to different models, we find that land-use change emissions are not as sensitive to the relevant parameters (such as growth timescale or partition coefficient). This indicates that the approach taken here could provide a mechanism for further research that is consistent with the results of more detailed models. We recommend, therefore, that future carbon-cycle comparisons report carbon densities at an ecosystem level, so as to enable offline analysis and also so that these values can be more directly compared between models.

We have focused in this work on LUC emissions without consideration of carbon dioxide or climate-related feedbacks. This is consistent with the literature on land use and land-use change (LULUC) emissions, as discussed by Houghton (2013). As also noted by Houghton (2013), environmental changes, for example climate and carbon-cycle feedbacks, interact with LULUC, which means that an unambiguous and unique identification of anthropogenic influence is likely not possible. It is possible that these environmental interactions may dominate anthropogenic influences in the future, but this depends both on the background scenario for land-use changes, the magnitude of anthropogenic climate change, and the magnitude of specific environmental impacts on the carbon cycle. Finally, these environmental interactions may well alter the sensitivity relationships explored here, making past or future terrestrial fluxes more or less sensitive to the uncertainties examined herein.

Supplementary material related to this article is available online at http://www.biogeosciences.net/10/6323/2013/bg-10-6323-2013-supplement.pdf.

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