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CO_2 emissions from land-use change affected more by nitrogen cycle, than by the choice of land-cover data

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Abstract

The high uncertainty in land-based CO_2 fluxes estimates is thought to be mainly due to uncertainty in not only quantifying historical changes among forests, croplands, and grassland, but also due to different processes included in calculation methods. Inclusion of a nitrogen (N) cycle in models is fairly recent and strongly affects carbon (C) fluxes. In this study, for the first time, we use a model with C and N dynamics with three distinct historical reconstructions of land-use and land-use change (LULUC) to quantify LULUC emissions and uncertainty that includes the integrated effects of not only climate and CO_2 but also N. The modeled global average emissions including N dynamics for the 1980s, 1990s, and 2000–2005 were 1.8 ± 0.2, 1.7 ± 0.2, and 1.4 ± 0.2 GtC yr^{-1}, respectively, (mean and range across LULUC data sets). The emissions from tropics were 0.8 ± 0.2, 0.8 ± 0.2, and 0.7 ± 0.3 GtC yr^{-1}, and the non tropics were 1.1 ± 0.5, 0.9 ± 0.2, and 0.7 ± 0.1 GtC yr^{-1}. Compared to previous studies that did not include N dynamics, modeled net LULUC emissions were higher, particularly in the non tropics. In the model, N limitation reduces regrowth rates of vegetation in temperate areas resulting in higher net emissions. Our results indicate that exclusion of N dynamics leads to an underestimation of LULUC emissions by around 70% in the non tropics, 10% in the tropics, and 40% globally in the 1990s. The differences due to inclusion/exclusion of the N cycle of 0.1 GtC yr^{-1} in the tropics, 0.6 GtC yr^{-1} in the non tropics, and 0.7 GtC yr^{-1} globally (mean across land-cover data sets) in the 1990s were greater than differences due to the land-cover data in the non tropics and globally (0.2 GtC yr^{-1}). While land-cover information is improving with satellite and inventory data, this study indicates the importance of accounting for different processes, in particular the N cycle.

Keywords: carbon cycle, carbon emissions, land-use change, model, nitrogen cycle

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Introduction

Land-use and land-use change (LULUC) refers to carbon (C) fluxes from the land due to human activity: that resulting from the use or management of land within one type of land cover (e.g., forest management for wood harvest) and changes in land-cover type (e.g., deforestation, afforestation, conversion of grasslands to pastureland). In total, LULUC was responsible for approximately 11% of all anthropogenic CO_2 emissions (7.8 ± 0.4 GtC yr^{-1} fossil fuel; 1.0 ± 0.5 GtC yr^{-1} LULUC) in the decade 2000–2009 (Le Quéré *et al.*, 2012).

The land and the ocean each take up about 30% of all anthropogenic C emissions (Denman *et al.*, 2007; Le Quéré *et al.*, 2009, 2012). The land takes up C from the atmosphere due to natural processes, affected by environmental change such as CO_2 and N fertilization effects, and climate change (e.g., longer growing seasons in northern extratropical forests) (Denman *et al.*, 2007). The atmospheric measurements of $[CO_2]$ combined with O_2: N ratios suggest that the land is currently acting as a net sink of CO_2 despite large-scale tropical deforestation (Denman *et al.*, 2007; Raupach, 2011). Both the IPCC (Denman *et al.*, 2007) and the Global Carbon Project (Le Quéré *et al.*, 2012) calculate land sink due to the natural response of ecosystems to environmental change as the residual from other better constrained flux terms and LULUC emissions calculated by models (2.5 ± 0.8 GtC yr^{-1}, Le Quéré *et al.*, 2012). Thus, this term is often known as the 'residual terrestrial flux'. Uncertainties in LULUC emissions propagate into uncertainties in the residual terrestrial uptake calculations, making these two terms the most uncertain in the C budget (Denman *et al.*, 2007; Le Quéré *et al.*, 2012).

Estimates of the flux of C from LULUC vary widely among different model estimates (Houghton *et al.*, 2012). According to the most recent IPCC assessment (Denman *et al.*, 2007), C emissions due to LULUC for the 1990s had a range of 0.5–2.7 GtC yr^{-1}, with a median value of 1.6 GtC yr^{-1} based on two results: the Houghton (2003) book-keeping model and data based on the 2005 global Forest Resources Assessment (FRA)

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of the Food and Agricultural Organization (FAO, 2006), and the tropical satellite study of DeFries *et al.* (2002) also using the Houghton book-keeping model. With improvements in data on land-cover change and biomass, and better understanding, information and modeling of different land processes, the mean estimate has been revised downwards and the range across results is reduced despite the much larger number of modeled estimates now published. A recent intercomparison study of many published estimates reported a mean, standard deviation, and range across 13 process-based vegetation models and book-keeping models of 1.1 ± 0.2 GtC yr^{-1} (full range 0.75–1.50 GtC yr^{-1}) for the 1990s (Houghton *et al.*, 2012). The authors of the intercomparison used the limited amount of literature assessing uncertainty in LULUC emission estimates, along with expert judgment to suggest an uncertainty of $\pm$ 0.5 GtC yr^{-1}.

It is widely acknowledged that a key uncertainty in LULUC emissions stems from uncertainties in estimating historical changes in areal coverage among forests, croplands, and grassland, though the uncertainties have significantly narrowed with time mainly due to improved data from satellites and inventories (Goldewijk & Ramankutty, 2004; Lepers *et al.*, 2005; Ramankutty *et al.*, 2007; Houghton, 2010; Hurtt *et al.*, 2011; Verburg *et al.*, 2011). Further uncertainty stems from incomplete understanding of all the processes affecting the net flux of C from LULUC, different approaches adopted to calculate emissions, and data-related uncertainties. Several previous intercomparison studies (e.g., Ramankutty *et al.*, 2007; Ito *et al.*, 2008; Houghton *et al.*, 2012) have evaluated the overall range of uncertainty associated with estimates of net flux of C resulting from LULUC. However, complex linkages among the various contributing factors have made it difficult to quantify and attribute the resulting uncertainties to each of its sources.

In an earlier study, Jain & Yang (2005) quantified the uncertainties resulting from using two different, but commonly used land-use change data sets (Ramankutty & Foley, 1999; and Houghton & Hackler, 2001) to drive the C cycle component of a land-surface model, the Integrated Science Assessment Model (ISAM) for the time period 1765–1990. Differences in the rates of changes in cropland area between the two data sets contributed significantly to uncertainty in estimated C fluxes, and it was argued that further refinement of land-use data sets using ground and satellite-based measurements was required. The Jain & Yang (2005) study was useful in explaining and quantifying the uncertainty due to LULUC on C flux as a part of wider studies on estimating LULUC-related uncertainties (Ramankutty *et al.*, 2007; Piao *et al.*, 2008; Ricciuto *et al.*, 2008).

In recent years, several LULUC data sets have been updated. Improvements have primarily taken place on three aspects: using historical inventory data with higher level of spatial detail; integrating multiple and advanced high-resolution satellite estimates; an improved methodology to downscale inventory data to grid cell level. Three of the most commonly used data sets were harmonized using a globally consistent methodology by Meiyappan & Jain (2012): (i) The HYDE (Historical Database of the Global Environment) spatially explicit data set (Klein Goldewijk *et al.*, 2010, 2011), which is the basis of the Hurtt *et al.* (2011) data set supplied for Earth System Models being used in the upcoming IPCC Fifth Assessment Report; (ii) The spatially explicit RF data set (Ramankutty & Foley, 1999), updated to include pasture conversions and revised cropland estimates (Ramankutty *et al.*, 2008); and (iii) The Houghton data set (Houghton & Hackler, 2001) updated with FAO (2006) forest area data (Houghton, 2008; the version that was used by Meiyappan & Jain, 2012) and more recently with FAO (2010) data which substantially revised down deforestation rates for the 1990s.

The effects of inclusion of different processes in calculating LULUC fluxes have been explored with various process-based global vegetation models. Several studies have shown that emissions from LULUC activities are different when considering the fertilization effects of changing [CO_2] on ecosystem C balance (Churkina *et al.*, 2007; Pongratz *et al.*, 2009; Arora & Boer, 2010). Most process models now include the effects of climate and CO_2 on vegetation, but few include the effects of nitrogen (N).

N is a limiting nutrient for plant growth in mid- and high-latitude regions (Vitousek & Howarth, 1991). In tropical regions, N is not considered a limiting nutrient, because the warmer and wetter tropical climate enhances N mineralization in soils (Vitousek & Howarth, 1991; Cleveland & Townsend, 2006) and biological N fixation is high (Yang *et al.*, 2009). The N cycle is rapidly changing due to human activity (Galloway *et al.*, 2004, 2008; Canfield *et al.*, 2010). Enhanced N in the atmosphere can act as a pollutant or have a fertilization effect on plants (Reay *et al.*, 2008). Climate, CO_2, and N all interact to alter plant growth (Jain *et al.*, 2009) and decomposition, thus affecting both the C lost when vegetation is removed, and the rate of C accumulation in regrowing vegetation and soils (Mathers *et al.*, 2006).

A recent modeling study by Zaehle *et al.* (2011) indicates that anthropogenic N inputs account for about a fifth of the C sequestered by terrestrial ecosystem between 1996 and 2005. Churkina *et al.* (2007) estimated a C uptake of 0.75–2.21 GtC yr^{-1} during the 1990s by regrowing forest in response to enhanced N deposition.

The wide ranges in their study arise from assumptions made about proportions and age of regrowing forests. However, neither study included the effects of LULUC.

Yang *et al.* (2010) modeled for the first time the effect of including a fully coupled N cycle (in ISAM) on global LULUC. ISAM results indicated that the contribution of N deposition to C uptake was about 0.13 GtC yr^{-1} in regrowing secondary forests, and 0.31 GtC yr^{-1} in all ecosystem types. Consideration of full N dynamics limited C uptake due to N limitation in regrowing forests in northern temperate regions in particular. The study was very sensitive to land transitions in tropical regions. While N is not a limiting nutrient in primary tropical forests, the results suggested strong N limitation in the secondary forests of tropical regions, because land-use change activities (harvesting, burning) remove large amounts of N from the system. N removal due to LULUC constrained the fertilizing effects of N deposition and atmospheric CO_2 in some regions, but less in others depending on climatic conditions emphasizing the need to consider the interactive effects of all three drivers (climate, CO_2, N) on net LULUC flux.

In this article, we build upon our previous studies to provide revised estimates of C emissions from historical LULUC looking for the first time at the effects of N under different LULUC scenarios. This study presents several crucial updates on multiple fronts, in particular: (i) We use a fully coupled Carbon-Nitrogen (C–N) cycle component of the ISAM (Yang *et al.*, 2009), very few of the current generation of global vegetation models include a N cycle component, and only ISAM has been applied specifically to estimate LULUC emissions; (ii) The study incorporates the impact of N limitation and N deposition on the C sink associated with secondary forest regrowth including the effects of wood harvest activities (Yang *et al.*, 2010); (iii) The estimates have been extended until the year 2010 where possible; and (iv) We use three historical reconstructions of LULUC (Meiyappan & Jain, 2012) based on new and updated data sets (Klein Goldewijk *et al.*, 2011; updated estimates based on Ramankutty & Foley (1999) and Ramankutty *et al.* (2008); and, Houghton, 2008). In addition, all the three reconstructed data sets include the effects of urban land expansion (Klein Goldewijk *et al.*, 2010) and wood harvest (Hurtt *et al.*, 2011).

Materials and methods

Overview of the ISAM C–N model

The C–N cycle component of the ISAM is used to assess the C emissions from LULUC. The structure, parameterization, and performance of ISAM has been previously discussed in detail (Jain & Yang, 2005; Jain *et al.*, 2009; Yang *et al.*, 2009). Here, we provide an overview. The model calculates C and N fluxes between vegetation and the atmosphere, above and below ground litter, and soil organic matter compartments of the terrestrial biosphere at 0.5° x 0.5° spatial resolution. The modeled C cycle accounts for important feedback processes, including impact of increasing atmospheric [CO_2] on Net Primary Productivity (NPP); impact of temperature and precipitation changes on photosynthesis, autotrophic and heterotrophic respiration; and the effect of N deposition on C uptake by plants. The modeled N cycle accounts for major processes as described in Yang *et al.* (2009). In addition, the model accounts for both symbiotic and non symbiotic biological N fixation. The performance of ISAM and its N cycle has been extensively calibrated and evaluated using field measurements (Jain *et al.*, 2009; Yang *et al.*, 2009).

Each 0.5° x 0.5° grid cell contains at least one of the 18 land-cover types (Yang *et al.*, 2010), of which 10 are forest land-cover types, five are herbaceous land-cover types and the other three being cropland, pastureland, and urban land. ISAM accounts for five climatic types of primary forest (tropical evergreen, tropical deciduous, temperate evergreen, temperate deciduous, and boreal) and their corresponding 'secondary forests'. The model accounts separately for forest regrowth following agricultural abandonment and wood harvest, and this is what we refer to as a 'secondary forest' (Yang *et al.*, 2010).

The land conversions in the model are carried out based on the method described in Meiyappan & Jain (2012). We start with a map of potential natural vegetation at 0.5° x 0.5° resolution, which is indicative of the land cover that would have existed if human activities were absent. We then advance in time (starting from 1765 to 2010), by superimposing the year-to-year cropland, pastureland, wood harvest, and urban land maps, respectively. We define rules, specific to each land-disturbance activity (cropland, pastureland, wood harvest, and urban land), for replacing natural vegetation. In general, following cropland and pastureland expansion, the natural vegetations present in a grid cell are removed proportional to its area and demand for cropland/pastureland. Upon abandonment (reduction in cropland/pastureland area between two consecutive years), the land recovers back to the dominant potential natural vegetation in the grid cell. Wood is preferentially harvested from primary forest, and secondary (regrowing) forest is used when the extent of primary forest is less than the demand. Urban land expansion usually occurs at the expense of cropland abandonment and in other cases from natural vegetations. The resulting land-cover maps for the period 2000–2005 are compared with remote sensing-based land-cover maps (500 m resolution MODIS data – Friedl *et al.*, 2010) spanning the same period. Discrepancies in forest area between satellite data and model estimates are used to accordingly adjust the land-disturbance activity specific rules (for each grid cell) to increase (or decrease) the proportions at which forest was cleared (or regrown) historically following expansion (or abandonment) of agricultural activity, such that rerunning the model with adjusted rules results in land-cover maps whose forest distribution closely agrees with remote sensing observations for recent years. This calibration implicitly accounts for uncertainty in potential vegetation map, rule-based assumptions, and spatial heterogeneity in land-use dynamics. Thus, the three reconstructions start with a common potential natural vegetation map and end with a map whose forest distribution are consistent with satellite estimates, but the pathway they follow between the starting and ending point is constrained by the land-use data sets used.

Emissions of C due to LULUC are calculated as described in Jain & Yang (2005). In brief, upon removal of natural vegetation from a grid cell, a specified fraction of vegetation biomass is transferred to litter reservoirs, effectively representing plant material left on the ground following deforestation activities (Yang *et al.*, 2009). The remaining vegetation materials are either burned to clear the land for agriculture, which releases C and N (in gaseous and/or mineral form) contained in the burned plant material; or are transferred as C and N to wood and/or fuel product reservoirs and subsequently released at three different rates depending on the assigned product categories.

LULUC data

The three historical LULUC reconstructions (ISAM-HYDE, ISAM-RF, and ISAM-HH) were based on cropland and pastureland area change in the three updated historical land-use change data sets: (i) HYDE 3.1 (Klein Goldewijk *et al.*, 2011); (ii) RF (Ramankutty & Foley, 1999) including new pastureland estimates and updated cropland estimates based on and Ramankutty *et al.* (2008); and (iii) Houghton & Hackler (2001) deforestation estimates updated in Houghton (2008) with revised deforestation rates from FAO (2006), respectively. The HYDE and RF data sets are both based on FAOSTAT agricultural statistics including data on change in agricultural land area (FAO, 2009), which is available from 1960, making assumptions on the change in other land cover (e.g., forest) to meet agricultural demand. The Houghton (2008) data set is based primarily on FAO FRA area change and biomass data (FAO, 2006) making assumptions about change in other land cover (e.g., croplands, pasture) to account for forest area change, supported by FAOSTAT data. A variety of other historical information is used to estimate land-use transitions prior to the availability of FAO data in each data set. A common spatially explicit data set for wood harvest based on FAO data (Hurtt *et al.*, 2011) and urban land extent (Klein Goldewijk *et al.*, 2010) was applied to all three reconstructions. ISAM-HYDE, ISAM-RF, and ISAM-HH estimates start from the year 1765 and extend until 2010, 2007, and 2005, respectively. All three reconstructions start with a common land-cover map during 1765 and follow different pathways as determined by the land-use change data sets to attain forest area distributions close to satellite estimates of forests for recent years. The sum of non forested land-cover types (herbaceous vegetation, cropland, pastureland, and urban land) matches satellite estimates. However, there are discrepancies between the land-use data sets and satellite estimates in the extent of individual herbaceous land-cover types.

Model simulations performed

The ISAM was initialized with an atmospheric [CO_2] of 278 ppmv, representative of approximate conditions in the starting year (1765 AD) of the model simulation, to allow vegetation and soil C pools to reach an initial steady state. During the time period of 1765–2010, net C exchanges between atmosphere and terrestrial ecosystems are calculated based on observed changes in climate (updated estimates based on Mitchell & Jones, 2005), atmospheric [CO_2] (Meinshausen *et al.*, 2011), wet and dry atmospheric N deposition rates (Galloway *et al.*, 2004), and three distinct historical reconstructions of LULUC as harmonized in Meiyappan & Jain (2012).

Two separate model runs are carried out to calculate the contribution of LULUC to the terrestrial C fluxes (Table 1). In the first model run (A1), atmospheric [CO_2], climate, and N deposition rates are varied with time based on prescribed values and the LULUC is assumed to be zero over time. In the second model run (A2), atmospheric [CO_2], climate, N deposition rates, and LULUC are varied with time. The second model run (A2) was performed for each of the three historical LULUC reconstruction used in this study. The emissions due to LULUC are estimated by subtracting C fluxes calculated in first model run (A1) from those in the second model run (A2). With this approach we captured the interactive effects of CO_2, climate, and N limitation on LULUC emissions.

We carried out two additional model runs (B1 and B2) to study the impact of excluding the interactive effects of N limitation on LULUC emissions (Table 1). Both experiments B1 and B2 are similar to A1 and A2, respectively, but they did not include the effects of N limitation. Land is always assumed to have sufficient N for plant growth. Subtracting C fluxes calculated in experiment B1 from that of B2 provides an estimate of LULUC emissions that only includes the interactive effects of

Table 1 Design of the simulation experiments. Tick mark (✓) indicates the environmental factor was varied with time. Cross mark (✗) indicates that the environmental factor was held constant at initial value. Inclusion of N deposition is irrelevant (denoted by '–') when N dynamics is inactive in the model

Experiment	CO_2	Climate	N deposition	Land-use and land-use change (LULUC)	N dynamics
A1	✓	✓	✓	✗	Active
A2	✓	✓	✓	✓	Active
B1	✓	✓	–	✗	Inactive
B2	✓	✓	–	✓	Inactive

CO_2 and climate. This (B2-B1) model experiment is analogous to the majority of other model approaches to calculating the LULUC flux in models that include only climate and CO_2 effects (e.g., McGuire *et al.*, 2001; Pongratz *et al.*, 2009; Piao *et al.*, 2009; Van Minnen *et al.*, 2009; Arora & Boer, 2010 noninteractive runs; Stocker *et al.*, 2011). The difference between the two sets of experiments (A2–A1) and (B2–B1) is an indicator of the effect of additionally considering N cycle effects and its interactions with CO_2 and climate on LULUC fluxes. We did not look at the effects of N on LULUC alone (i.e., excluding climate and CO_2 effects) as the study attempts the best quantification of LULUC including all possible drivers and processes, and to assess the possible uncertainty in LULUC estimates by failing to account for N effects.

To summarize, the following three estimates are calculated based on the four experiments (Table 1):

1. LULUC flux including N effect = A2 (Δ climate, CO_2, N, LULUC)−A1 (Δ climate, CO_2, N).
2. LULUC flux excluding N effect = B2 (Δ climate, CO_2, LULUC)−B1 (Δ climate, CO_2).
3. Effect of N on LULUC flux = (A2−A1)−(B2−B1).

Results

Global net LULUC emissions based on different land-cover reconstructions

Large interannual variations in global net C emissions from LULUC are observed in the model runs based on each of the three data sets, for the period 1900–2010 (Fig. 1). These variations are mainly induced by the effects of interannual variations in climate on LULUC fluxes. In particular, soil respiration, decomposition of slash and litter, and NPP in growing vegetation are affected by changes in temperature and precipitation in both the runs subject to LULUC (A2 and B2) and those not subject to LULUC (A1 and B1) (e.g., McGuire *et al.*, 2001; Jain & Yang, 2005). Because the natural vegetation responds to climate drivers the same way in A1 and A2, the flux shown here (A2–A1) reflects the combined effect of LULUC and climate variability (in addition to CO_2 and N) on the land affected by LULUC only.

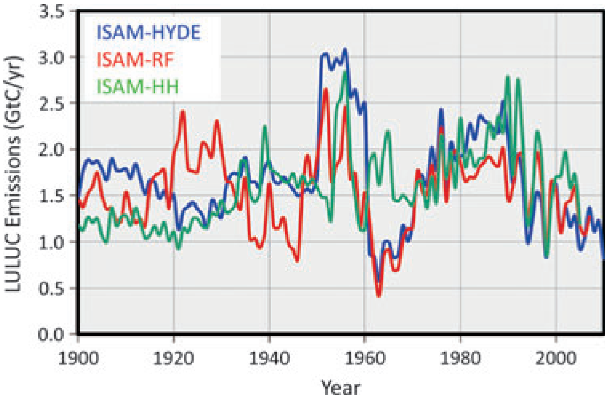

Fig. 1 ISAM-estimated global land-use and land-use change (LULUC) emissions for the period 1900–2010 (GtC yr^{-1}) based on Integrated Science Assessment Model-Historical Database of the Global Environment (ISAM-HYDE), ISAM-RF and ISAM-HH data sets. Estimates based on ISAM-RF and ISAM-HH estimates extend until year 2007 and 2005, respectively.

From 1900 to 2005, the global cumulative net emissions from LULUC were 178, 160, and 163 GtC for ISAM-HYDE, ISAM-RF, and ISAM-HH, respectively. The ISAM-HYDE estimated global total C emissions for the time period 1900–2010 were 180 GtC. *(All data in this section are from model runs including the N dynamics unless otherwise stated)*. All three estimated emission trajectories show substantially different trends over the period 1900–1960, although they all have a mean value of approximately 1.5 GtC yr^{-1} (Fig. 1). The net emissions based on all three data sets peaked in the 1950s, with ISAM-HH reaching its peak slightly later than the other two data sets. This result from rapid deforestation due to expansion of agriculture in the tropics around the early 1950s followed by a rapid reduction in the rates of deforestation around the late 1950s and early 1960s, with less of a reduction based on ISAM-HH data. Emissions estimates based on ISAM-HH data are very different from those based on ISAM-RF and ISAM-HYDE in the 1960s. Emissions over the last three decades then follow similar trends based on all three data sets; an increase from 1970 to 1990 and a decline since 1990.

The mean decadal net emissions based on ISAM-HYDE data are higher during the 1980s and lower during the 1990s and 2000s compared to other two data sets, which show similar emissions during the 1980s and 1990s (Table 2). Thus, the decline in emissions from the 1980s to the 2000s is much more pronounced in ISAM-HYDE. The reasons can be found looking at the rate of conversion of land types in the underlying harmonized data sets (Fig. 2). ISAM-HYDE shows a sharp decrease in the expansion rates of both cropland and pastureland between 1980 and 2005 (Fig. 2a–d), and a sharp decrease in deforested area (Fig. 2e) which is offset to a lesser extent each decade by a declining expansion of the area of secondary forest regrowth (Fig. 2f) (partly reforestation on abandoned agricultural land and partly conversion of 'natural' forests to secondary regrowth forests after wood harvest). In contrast, ISAM-RF and ISAM-HH data show an increase in conversion into cropland (Fig. 2a and b) and a decrease in conversion of forests to pastures (Fig. 2c). Both ISAM-RF and ISAM-HH show an increase in the expansion rate of secondary forest regrowth from the 1980s to the 2000s partly offsetting the loss of primary forest area (Fig. 2e and f).

Table 2 Regional breakdown of decadal mean net land-use and land-use change (LULUC) emissions (GtC yr^{-1}) for the 1980s, 1990s and 2000s based on Integrated Science Assessment Model-Historical Database of the Global Environment (ISAM-HYDE), ISAM-RF, and ISAM-HH data sets

	1980s				1990s				2000s			
Region/global	ISAM-HYDE	ISAM-RF	ISAM-HH	Mean & range	ISAM-HYDE	ISAM-RF	ISAM-HH	Mean & range	ISAM-HYDE*	ISAM-RF†	ISAM-HH‡	Mean & range
Tropical America	0.26	0.33	0.59	*0.39 ± 0.17*	0.20	0.34	0.64	*0.39 ± 0.22*	0.14	0.24	0.46	*0.28 ± 0.16*
Tropical Africa	0.01	−0.03	0.11	*0.04 ± 0.07*	0.04	−0.03	0.11	*0.04 ± 0.07*	0.03	−0.04	0.09	*0.03 ± 0.06*
Tropical Asia	0.34	0.35	0.40	*0.37 ± 0.03*	0.31	0.34	0.38	*0.34 ± 0.03*	0.25	0.43	0.53	*0.41 ± 0.14*
Tropics total	*0.61*	*0.65*	*1.11*	*0.79 ± 0.25*	*0.56*	*0.65*	*1.13*	*0.78 ± 0.29*	*0.43*	*0.63*	*1.08*	*0.71 ± 0.33*
North America	0.30	0.28	0.19	*0.25 ± 0.06*	0.27	0.28	0.21	*0.25 ± 0.03*	0.25	0.23	0.28	*0.25 ± 0.03*
Eurasia	0.71	0.60	0.29	*0.53 ± 0.21*	0.47	0.62	0.34	*0.48 ± 0.14*	0.39	0.46	0.22	*0.36 ± 0.12*
China	0.59	0.15	0.08	*0.27 ± 0.26*	0.19	0.14	0.07	*0.13 ± 0.06*	0.12	0.09	0.06	*0.09 ± 0.03*
Oceania	0.00	0.03	0.02	*0.02 ± 0.01*	0.00	0.05	0.08	*0.04 ± 0.04*	0.02	−0.08	0.01	*−0.02 ± 0.5*
Non tropics total	*1.61*	*1.06*	*0.56*	*1.08 ± 0.52*	*0.92*	*1.09*	*0.70*	*0.90 ± 0.19*	*0.80*	*0.69*	*0.57*	*0.69 ± 0.12*
Global	*2.21*	*1.70*	*1.72*	*1.88 ± 0.26*	*1.48*	*1.74*	*1.83*	*1.68 ± 0.18*	*1.22*	*1.33*	*1.65*	*1.40 ± 0.21*

*Average for the period 2000–2009.

†Average for the period 2000–2007.

‡Average for the period 2000–2005.

Emissions based on ISAM-HH data become higher than the other two estimates from 2000 to 2005 (Fig. 1 and Table 2) because the conversion of forests to croplands and pastures (Fig. 2a and c), and hence the overall area of deforestation (Fig. 2e) is higher.

Regional differences in LULUC emissions

There are substantial differences in regional estimates of LULUC emissions between the model results based on the different data sets (Table 2). Except for Tropical America, Eurasia, and China, there is no consistent trend exhibited among the three estimates. These three regions show a generally decreasing trend from between the 1980s to the end of the data set for all three data sets, with the decline being much more pronounced in ISAM-HYDE than that in ISAM-RF and ISAM-HH.

LULUC emissions based on ISAM-HYDE have decreased substantially over the last three decades for the tropics (30% decline) and non tropics (50%). In contrast, the estimated emissions based on ISAM-RF show very little change in the tropics and a smaller decrease in the non tropics (30%) between 2000 and 2005 compared to both the 1980s and 1990s, which were very similar. ISAM-HH shows very little change in the tropics, and a small increase from the 1980s to the 1990s then a similar decline again to the 2000s (2000–2005 average) in the non tropics.

Over the last three decades, net emission estimates based on ISAM-HH data are higher for tropical regions and lower for nontropical regions compared to net emission estimates based on other two data sets (Table 2). This is because ISAM-HH data shows much higher deforestation rates for agricultural land in tropical regions (especially in Tropical America) (Fig. 2a, c and e). In nontropical regions, the ISAM-HH data set (based on forest statistics) has lower conversion of forests to croplands than the other two data sets, and assumes no clearing of forests for pastureland (forest clearing would have been assumed converted to cropland or secondary forests). The other two data sets (based on agricultural statistics), derived based on a rule-based approach to clear vegetation, have a fraction of pastureland expansion at the expense of forests (Meiyappan & Jain, 2012) (Fig. 2c). Houghton (2008) (which forms the basis for ISAM-HH) assumes that the expansion of pasture area in North America, China and Pacific Developed regions occurred in the 1950s, and therefore has negligible impact on C emissions for recent years. On the other hand, ISAM-HYDE and ISAM-RF indicate that in the non tropics, forest area was converted to pastures over the last three decades (Fig. 2c).

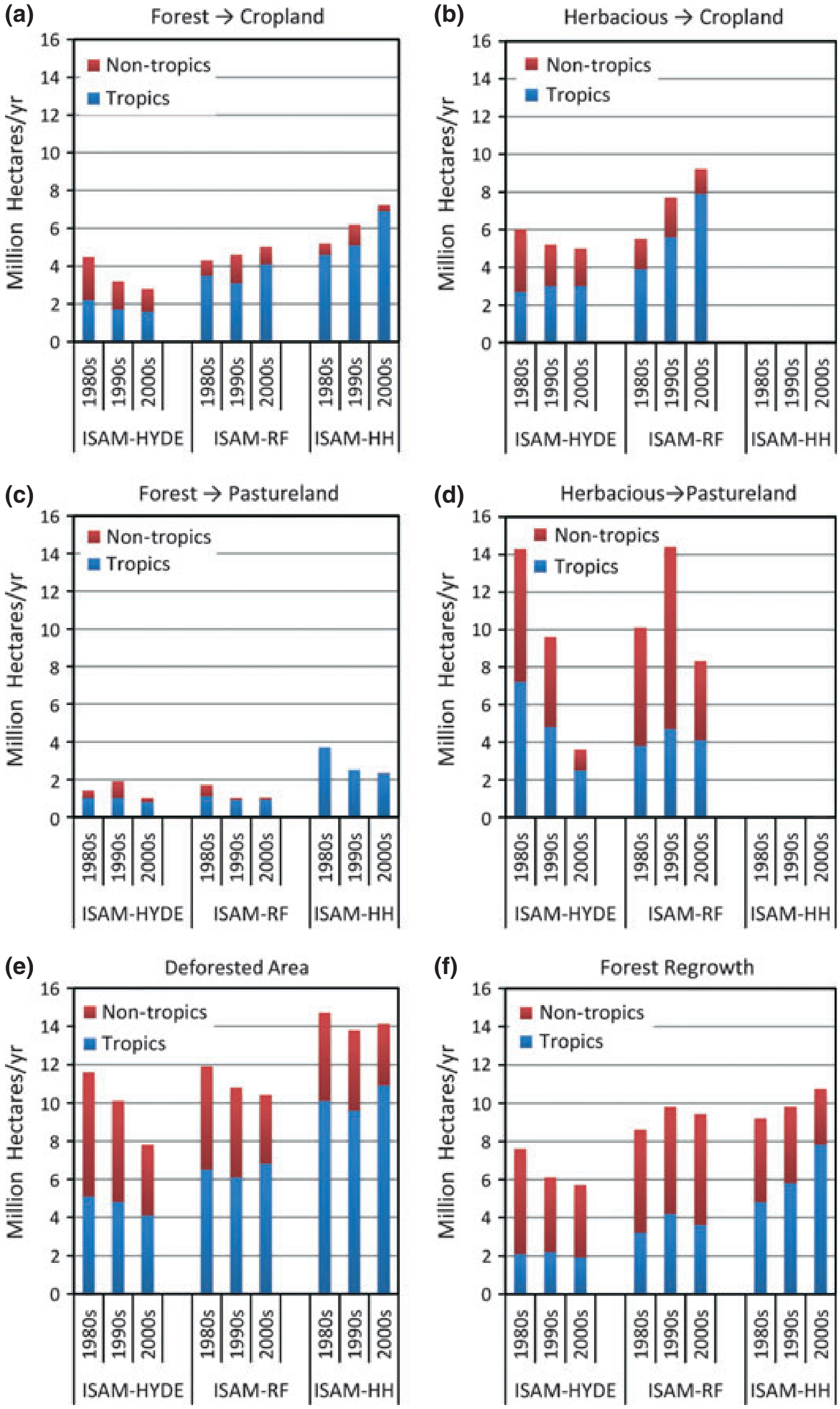

Fig. 2 Decadal (1980–2009) average rate of conversions of land in the tropics and non tropics from (a) forest to cropland, (b) herbaceous to cropland, (c) forest to pastureland, (d) herbaceous to pastureland, and (e) deforested area (includes forest area loss due to wood harvest), and (f) reforested area due to expansion and abandonment of cropland, pastureland, and wood harvest.

In the non tropics, forest regrowth area is generally higher in ISAM-HYDE and ISAM-RF than that in ISAM-HH across all three periods (Fig. 2f). Forest regrowth would be expected to have increased the C stocks in secondary forest ecosystems (Churkina *et al.*, 2007; Reay *et al.*, 2008; Jain *et al.*, 2009; Shevliakova *et al.*, 2009; Yang *et al.*, 2010) partially offsetting the higher emissions from forest to pasture/cropland conversion we see in ISAM-HYDE and ISAM-RF than that in ISAM-HH in the non tropics. However, the net nontropical emissions of ISAM-HYDE and ISAM-RF remain higher than those in ISAM-HH. Part of the reason for this is that the regrowth is limited in the model due to N availability, and therefore the CO_2 fertilization effect is constrained.

Effects of including the N cycle

Including the N cycle in the model resulted in higher net emissions compared to the model runs without the interactive N cycle (Table 3, numbers in brackets are runs without the N-cycle). These results indicate that failing to account for the effects of N dynamics may lead to an underestimate in LULUC emissions by around 40% globally across all three data sets. The effects were more pronounced in nontropical regions, where simulations without the N cycle were lower by 61–76% across all three data sets, while in the tropics emissions were lower only by 7–9%.

Discussion

Comparison with other studies

Our mean estimate of global net LULUC emission with N dynamics and wood harvest of 1.68 GtC yr^{-1} (range across results 1.48–1.83 GtC yr^{-1}) for the 1990s is the highest compared to the other published estimates as shown in Table 3 (excluding Denman *et al.*, 2007 which is a synthesis based on old estimates). Breaking it down regionally, where other published estimates were available for comparison, our net emissions are similar in the tropics (mean 0.78 GtC yr^{-1}), but much higher in the non tropics (0.90 GtC yr^{-1}). While other published results find that tropical emissions are higher than nontropical emissions, our estimates based on two data sets (ISAM-RF and ISAM-HYDE) with N dynamics show the opposite trend, that is, higher LULUC net emissions for non tropics than tropics. Our modeling results indicate that without considering the N dynamics effect, the estimated nontropical LULUC emissions for ISAM-RF, ISAM-HYDE, and ISAM-HH cases are underestimated by 0.66, 0.58, and 0.53 GtC yr^{-1}, respectively, for the 1990s, emphasizing the importance of including N dynamics in estimating LULUC emissions. The ranges of nontropical emission estimates when N dynamics is excluded in this study (0.17–0.43 GtC yr^{-1}) are not only well within the range of values of other published studies, but also lower than estimates for the tropics.

N is usually not considered as a limiting nutrient in the tropical regions, because warmer and wetter tropical climate enhance N mineralization in soils, and biological N fixation is high. Therefore, it is not surprising that ISAM-estimated tropical emission with (0.56–1.13 GtC yr^{-1}) and without (0.51–1.04 GtC yr^{-1}) N dynamics are approximately the same as each other (Table 3), and are well within other model estimated range of values (0.50–1.44 Gt/C).

It is interesting to note that Houghton's own book-keeping model estimates (Houghton, 2010) are the highest for the tropics and the lowest for the non tropics as compared to other model estimates (Table 3). This is, unsurprisingly, similar to the results we found using the ISAM-HH data set compared to the other data sets within our modeling study, as it is driven by the underlying data assumptions in the Houghton data set based on FAO FRA forest data (FAO, 2006). The FAO data indicate a net loss of total forest area in the tropics, and vice versa in the non tropics (Houghton, 2010) for the last three decades. In contrast, other data sets (HYDE or RF) used by other modeling studies indicate a decrease in forest area for both tropics and non tropics (This cannot be directly interpreted from the data in Fig. 2 as some of the area of primary deforestation goes to secondary forests after harvesting and some does not. Likewise only a portion of secondary forest regrowth occurs on deforested land and the rest on abandoned agricultural land. Therefore, the numbers cannot be directly summed to get net change in forest area). Note that the latest FAO FRA (FAO, 2010) substantially revised down deforestation rates in the tropics.

The land-cover data may not be the full reasons for discrepancies. Houghton (2010) results are even higher than our ISAM-HH results in the tropics and even lower in the non tropics. Thus, differences in the modeling framework used by Houghton (2010) and other studies shown in Table 3 may explain a part of the discrepancies. Houghton (2010) estimates are based on book-keeping model that tracks areas of land conversions and calculates subsequent changes in C pools using standard growth and decay curves derived from actual field inventory data from the literature that are unchanging over the calculation period (representing either recent or historic climate and environmental conditions) and averaged over a large region or vegetation type. Most other modeling studies, with the exceptions of satellite-based tropical region estimates of DeFries *et al.* (2002) and Achard *et al.* (2004), model soil and vegetation processes and how they are affected by climate, atmospheric CO_2, and, in this study, N drivers that vary spatially and possibly temporally. A sensitivity analysis based on process-based model and book-keeping model approaches suggests that book-keeping model estimated LULUC emissions were about 40% higher than the process-based modeling approach, due

Table 3 Comparison of Integrated Science Assessment Model (ISAM) estimated LULUC emissions for 1990s with other model and data studies. The decade 1990–1999 was chosen for comparison, as most of the estimates in literature covered this time period. Estimates that do not account for N dynamics are provided in brackets

Study	LULUC data	Tropics	Non tropics	Global
This study	ISAM-RF	0.65 (0.59)	1.09 (0.43)	1.74 (1.02)
	ISAM-HYDE	0.56 (0.51)	0.92 (0.34)	1.48 (0.85)
	ISAM-HH	1.13 (1.04)	0.70 (0.17)	1.83 (1.21)
	Range	0.56–1.13 (0.51–1.04)	0.70–1.09 (0.17–0.43)	1.48–1.83 (0.85–1.21)
Other studies				
Strassmann *et al.* (2008)	HYDE	(1.02)		(1.08)
Van Minnen *et al.* (2009)	HYDE	(0.70)	(0.60)	(1.30)
Arora & Boer (2010)*	RF			1.06
Piao *et al.* (2011)	HYDE	(0.74)	(0.48)	(1.22)
Yang *et al.* (2010)	HYDE/RF			1.44 (1.03)
Houghton (2010)	Houghton	(1.44)	(0.06)	(1.50)
Pongratz *et al.* (2009)†	Pongratz			(1.30)
Shevliakova *et al.* (2009)	RF cropland + HYDE pastures			(1.31)
Shevliakova *et al.* (2009)	HYDE			(1.07)
Kato *et al.* (2011)	Hurtt (HYDE)			(1.00–1.28)
Stocker *et al.* (2011)				(0.93)
DeFries *et al.* (2002)‡	AVHRR	(0.50–1.40)		
Achard *et al.* (2004)§	Landsat	0.80–1.40		
Denman *et al.* (2007) range¶				(0.50–2.70)
Houghton *et al.* (2012) range‖				(0.75–1.50)
Poulter *et al.* (2010)**	HYDE			(0.88)
Other Studies Range††		(0.50–1.44)	(0.06–0.60)	(0.88–1.50)

*This result is based on the data underlying the thick orange line in fig. 10a of Arora & Boer (2010), data supplied by (V. Arora, personal communication). Their study represents the approach most similar to ours for calculating the land-use and land-use change (LULUC) flux (see text for details).

†Underlying data set described in Pongratz *et al.* (2008) is based on RF cropland and RF pastureland with rates of pasture changes from Historical Database of the Global Environment (HYDE). Pastureland was preferential allocation on natural grassland.

‡Calculated using the Houghton & Hackler (2001) book-keeping model in combination of AVHHR satellite data for land-cover change.

§Calculated using the biomass and biomass change in tropical forest estimates of Food and Agricultural Organization (FAO, 1997) and Landsat data for land-cover change. These estimates may have implicitly accounted for the N dynamics effect.

¶Denman *et al.* (2007) is not an estimate in itself, but is a synthesis range across two estimates including uncertainty: DeFries *et al.* (2002) and Houghton (2003). The Houghton (2003) estimates has since been updated and revised downwards (Houghton, 2010).

‖Houghton *et al.* (2012) give the mean and standard deviation across thirteen different model estimates of LULUC as 1.12 ± 0.25 GtC yr^{-1}, full range as 0.75–1.50 GtC yr^{-1}. Their estimate of uncertainty in mean LULUC emissions is about ±0.5 GtC yr^{-1}.

**As reported in Le Quéré *et al.* (2012).

††The range values given here are based on the published studies included in this table and do not account for the ranges in Denman *et al.* (2007) and Houghton *et al.* (2012) as these are themselves ranges across other published estimates. The estimates of Denman *et al.* (2007) are now out of date for the reasons discussed in ¶.

primarily to higher soil C emissions assumed to be 25% soil C loss following land-use change (Reick *et al.*, 2010).

Most process-based studies, including this study, use historical transient CO$_2$ and climate as an external driving force and run the model with and without changes in land use and derive the LULUC emissions as the difference (e.g., McGuire *et al.*, 2001; Pongratz *et al.*, 2009 'LULUC+CO$_2$'; Van Minnen *et al.*, 2009; Piao *et al.*, 2009; Stocker *et al.*, 2011). The study by Shevliakova *et al.* (2009) ran with present climate and CO$_2$ in both the with- and without-LULUC simulations.

The LULUC past emissions not only affect the 'managed' vegetation that is subject to LULUC but also the 'natural' or 'primary' vegetation. This has been referred to as the 'feedback flux' (Strassmann *et al.*, 2008) or the 'coupling flux' (Pongratz *et al*., 2009). The feedback flux on natural vegetation is typically to be considered part of the 'residual terrestrial flux' as it is an indirect effect of human activity and not considered as part of net LULUC emissions. In the case above, where LULUC emission are derived by the difference between the without-LULUC case and with-LULUC cases, the effects of past LULUC emissions on the natural vegetation are factored out, only the past LULUC effects on the vegetation that is subject to LULUC are included. However, some coupled climate-carbon cycle model studies, for example, Arora & Boer (2010), include the effects of LULUC emissions on natural vegetation which is why their flux of 0.25–0.84 GtC yr^{-1} in the 1990s based on different data sets are much lower than other estimates, including our own. When they apply the same approach as we use here, their estimated emissions based on RF data increase from 0.71 GtC yr^{-1} (their fig. 10a, thin orange line) to 1.06 GtC yr^{-1} (their fig. 10a, thick orange line) (personal communication data supplied by V. Arora for analysis). The interactive effects of LULUC on atmospheric [CO_2] merit further investigation, but are beyond the scope of this study.

Our modeled LULUC emissions for the 2000's vary between 1.2 and 1.7 GtC yr^{-1} (Table 2), consistent with, but at the high end of most recent estimated range across a number of published studies of 0.4–1.8 GtC yr^{-1} (Houghton *et al*., 2012).

Uncertainty in LULUC Emissions Estimates

Our modeled estimates give an indication of uncertainty in LULUC emissions due to the choice of data set. Estimated ranges across the three data sets for 1980s, 1990s, and 2000s, respectively, were ±0.26 GtC yr^{-1}, ±0.18 GtC yr^{-1}, and ±0.21 GtC yr^{-1}. The estimated uncertainty due to data set variability is much lower than other uncertainty estimates (see below) partly reflecting more accurate and revised land-use change data sets applied in a globally consistent methodology to produce historical LULUC estimates (Meiyappan & Jain, 2012), but also as it does not account for uncertainty in other data, the model approach or implementation.

Our results further indicate a large uncertainty due to the missing process of the N cycle in other estimates. Failure to account for the N cycle may underestimate net C flux due to LULUC by 0.1 GtC yr^{-1} in the tropics, 0.6 GtC yr^{-1} in the non tropics and 0.7 GtC yr^{-1} globally (mean across land-cover data sets).

A recent meta-analysis study by a range of experts for the Global Carbon Project (Houghton *et al*., 2012), estimates the total errors resulting from data-related uncertainty and incomplete understanding of all the process to be in the order of about ±0.5 GtC yr^{-1} based on expert judgment, drawing on the range across many published model studies, and studies that specifically looked at uncertainty due to data or modeling approaches. Previous publications for the Houghton book-keeping model approach gave an uncertainty estimate of ±0.7 GtC yr^{-1} (Houghton, 2010), that have since been revised down to ±0.5 GtC yr^{-1} (R. A. Houghton, personal communication). The most recent IPCC estimated uncertainty of ±1.1 GtC yr^{-1} for 1990s (Denman *et al*., 2007) can now be considered too high. The higher end based on Houghton (2003) was revised downwards due to the reduction in the deforestation estimates for tropical regions in subsequent FAO FRA (FAO, 2006, 2010) brought about by integration of satellite-based estimates (e.g., Hansen *et al*., 2009; Nepstad *et al*., 2009). The lower end of the range was based on DeFries *et al*. (2002) is an underestimate, as it is based on satellite measurements for three tropical regions, and does not account for legacy emissions deforestation rates prior to the period of analysis (1980s and 1990s) (Ramankutty *et al*., 2007).

Differences in land processes included

In this study, secondary forest regrowth only occurs as a result of wood harvest and agricultural abandonment on land that was originally covered by forests (i.e., a reduction in agricultural area in a grid cell will regrow forest). In some countries or regions, for example North America, Europe, Japan, China, and India, there are active programs of afforestation and reforestation (Kenji, 2000; Merker *et al*., 2004; FAO, 2006, 2010). These may not be captured by the data sets of change in agricultural and pasture areas, particularly if the forests are established on previously grassland areas, or if they shift agriculture to grassland areas so that the agricultural area does not decline. Hence, this study may be underestimating the forest area in some regions and hence the C uptake by the afforested land.

This study does not include the effects of fire suppression and woody encroachment, which are suggested to contribute to regional C sink (e.g., in the United States, see Pacala *et al*., 2001). This is because the effects of these processes have not yet been well defined due to lack of comprehensive data (Denman *et al*., 2007).

C emissions due to the common practice of shifting cultivation in the tropics (clearing forest often by fire for agriculture then abandoning to regrowth after a number of years) are estimated to have a significant impact on historical LULUC emissions (Hurtt *et al*., 2006, 2011). This creates a mosaic of cropped fields often with trees and fallows intermixed with secondary and mature forests and cause some loss of ecosystem C (Houghton & Hackler, 2001). We did not specifically model the effects of shifting cultivation due to huge uncertainties in magnitude and spatial distribution, and as some of these effects would be captured in the data sets of changing forest or agricultural area we already used (Hurtt *et al*., 2006, 2011).

Natural disturbances such as fire, pests, disease, drought, wind, snow, ice, and floods affect 104 Mha of forest on average each year (FAO, 2006), with local- to national-scale ecological significance (e.g., Giglio *et al*., 2010; Van der Werf *et al*., 2010; also see Lambin *et al*., 2003 and Foley *et al*., 2003). This study has not considered emissions due to natural disturbances because it is not human-induced LULUC, and in any case it is typically assumed that disturbance is followed by regrowth and the net effects are minimal (unless the land is subsequently converted to agricultural land).

A key missing process is the decomposition of soil C following drainage of tropical peatlands (Ballhorn *et al*., 2009). According to Hooijer *et al*. (2010), draining and burning of peatlands in southeast Asia are thought to add another 0.3 GtC yr^{-1} to LULUC emissions.

Summary and implications of results for climate modeling and climate policy

Emissions of CO_2 from LULUC constitute a significant portion of global emissions, and therefore strongly affect global climate. Modeling them correctly has implications for global climate policy. The estimated cumulative LULUC emissions over the period 1900–2010 based on ISAM-HYDE data are approximately 180 GtC, which are approximately 33% of total C emissions (345 GtC from burning fossil fuels-Friedlingstein *et al*., 2010). The contribution of LULUC to global anthropogenic C emissions (land-use plus fossil fuel) in 1990s and 2000s were approximately 18–22% and 14–17%, respectively, (using fossil fuel emissions as in Le Quéré *et al*., 2012) for our modeled results across three underlying data sets and including the N cycle.

Our estimated net global emissions from LULUC (mean and range) across three data sets are 1.88 (1.7–2.21) GtC yr^{-1} for the 1980s, 1.66 (1.48–1.83) GtC yr^{-1} for the 1990s, and 1.44 (1.22–1.65) for the 2000s (Table 2). Our estimates are higher than other published estimates that range from 0.88 to 1.5 GtC yr^{-1} for the 1990s (Table 3: Achard *et al*., 2004; Arora & Boer, 2010; DeFries *et al*., 2002; Houghton, 2010; Piao *et al*., 2009; Pongratz *et al*., 2009; Stocker *et al*., 2011; Strassmann *et al*., 2008; Shevliakova *et al*., 2009; Van Minnen *et al*., 2009; Yang *et al*., 2010; Kato *et al*., 2011; Zaehle *et al*., 2011; Poulter *et al*., 2010) and 1.1 GtC yr^{-1} for the 2000s (Friedlingstein *et al*., 2010; Houghton *et al*., 2012). If LULUC emissions are higher than assessed, it means fossil fuel emissions would have to be even lower to meet the same mitigation target.

Our results are higher than other published estimates because they include the effects of N limitation on regrowth of forests following wood harvest and agricultural abandonment. This effect is particularly noticeable in the cooler non tropics where N removal through harvest or burning is not compensated by N deposition or N mineralization. The estimated LULUC emissions for the tropics are 0.79 ± 0.25 for the 1980s, 0.78 ± 0.29 for the 1990s, and 0.71 ± 0.33 GtC yr^{-1} for the 2000s, and for the nontropical regions are 1.08 ± 0.52, 0.90 ± 0.19, and 0.69 ± 0.12 GtC yr^{-1} for the three decades (Table 2). Not only are our results much higher in the non tropics than other results (Table 3) but also for two of the data sets they are higher in the non tropics than in the tropics. This is because the estimated nontropical LULUC emissions with N dynamics considered are 0.53–0.66 GtC yr^{-1} higher than those without N dynamics for the 1990s in the non tropics and 0.62–0.72 GtC yr^{-1} higher globally. Without considering the N cycle, our model results of 0.85–1.2 GtC yr^{-1} globally, 0.51–1.04 GtC yr^{-1} in the tropics, and 0.17–0.43 GtC yr^{-1} in the non tropics in the 1990s across the three data sets are similar to other published studies (Table 3). Our model results indicate that failing to account for the N cycle underestimates by about 40% globally (0.66 GtC yr^{-1}), 10% in the tropics (0.07 GtC yr^{-1}) and 70% in the non tropics (0.59 GtC yr^{-1}).

Many inventory studies in both managed and natural forests find higher sinks than in the past and attribute this to the effects of changing climate and [CO_2] (Luyssaert *et al*., 2008; Phillips *et al*., 2008; Lewis *et al*., 2009; Pan *et al*., 2011). Our results are not in conflict with this. Climate and CO_2 still enhance uptake in northern regrowth forests, but the effects are limited when N removal due to LULUC is considered. As the total net flux of CO_2 between the land and atmosphere is known from atmospheric measurements, higher emissions from land under LULUC in fact imply a greater sink in land not experiencing LULUC and are therefore consistent with inventories finding greater sinks in unmanaged forests. The total net flux the atmosphere 'sees' from the land is the same; in that sense our results do not imply different climate impacts. But our results do have implications for modeling of anthropogenic vs. natural land fluxes (both natural and anthropogenic sources and sinks are underestimated without the N cycle), and thus for climate policy around estimating human-induced emissions and mitigation potential on the land.

We evaluate the uncertainties in LULUC emissions estimates resulting from uncertainties in determining land-cover change using three historical LULUC reconstructions based on our best estimate of LULUC that include not only climate and CO_2 but also N. Over the period 1900–1970, our model results for the global LULUC emissions based on three different LULUC reconstructions exhibit substantially different trends (Fig. 1). The global total emissions are very similar thereafter, with emissions increasing until about 1990 and then declining. Uncertainty in LULUC emissions due to the underlying data set constitutes about ± 0.2 GtC yr^{-1} over the period 1980–2009.

While the three LULUC estimates show reasonably good agreement at the global scale, there are significant disagreements between them at the regional scale (Table 2). Regional discrepancies in location of CO_2 emissions are irrelevant to the global climate impacts of CO_2 as it is a well-mixed gas in the atmosphere. However, they indicate that a much larger uncertainty still exists in underlying LULUC data than is implied by looking at global decadal averages and this uncertainty may affect the overall amount of global LULUC emissions and thus climate. The regional differences also have implications for national-level greenhouse gas reporting and accounting under the United Nations Framework Convention on Climate Change and Kyoto Protocol, and for assessing future LULUC mitigation potential. Therefore, the results presented here suggest that the uncertainty in regional LULUC data need to be reduced to improve climate change projections.

Regional differences in forest cover will affect regional climate through biophysical properties such as albedo, surface roughness, heat transfer, and water recycling: for example afforestation in mid to high-latitudes reduces albedo and has a warming affect that runs counter to the cooling effect of CO_2 uptake (e.g., Brovkin *et al*., 2006; Findell *et al*., 2007; Pitman *et al*., 2009; Kvalevåg *et al*., 2010; Pongratz *et al*., 2010). However, assessing the implications of regional data differences on biophysical climate effects is beyond the scope of this study.

Ongoing improvements in satellite data and interpretation for measuring not only changes in land cover but also land management (e.g., shifting cultivation and selective logging) and biomass density will be critical in reducing uncertainties. Reconciling and improving data sets produced from different sources (e.g., FAO forest assessments and FAO agricultural assessments), to provide more information about land-use transitions is also expected to further reduce uncertainties.

Data Access

The three annual (1800–2010) estimates of C emissions from LULUC presented here can be downloaded from the Carbon Dioxide Information Analysis Center (ftp://cdiac.ornl.gov/pub/Atul_Jain_etal_Land_Use_Fluxes/). The three historical reconstructions of LULUC (Meiyappan & Jain, 2012) used in this study can be downloaded from the National Center for Atmospheric Research Climate Data Guide (http://climatedataguide.ucar.edu/guidance/historical-land-cover-changes-and-land-use-conversions-global-data-set-meiyappan-and-jain).

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