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# The effect of land-use change on the net exchange rates of greenhouse gases: a meta-analytical approach

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## Abstract

One of the environmental impacts of land-use change (LUC) is a change in the net exchange of the greenhouse gases (GHGs) carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O). Here we summarize findings based on a new global database containing data sets of changes in soil organic carbon stocks and soil CH<sub>4</sub> and N<sub>2</sub>O fluxes. We combine that with estimates of biomass carbon stock changes and enteric CH<sub>4</sub> emissions following LUC. Data were expressed in common units by converting net CH<sub>4</sub> and N<sub>2</sub>O fluxes to CO<sub>2</sub> equivalents (CO<sub>2</sub> eq) using established global warming potentials, and carbon-stock changes were converted to annual net fluxes by averaging stock changes over 100 yr.

Conversion from natural forest to cropland resulted in the greatest increase in net GHG fluxes, while conversion of cropland to secondary forest resulted in the greatest reduction in net GHG emissions. Specifically, LUC from natural forest to crop and grasslands led to net fluxes of  $6.2 \pm 1.6$  (Mean  $\pm$  95 % confidence intervals) and  $4.8 \pm 1.6$  tCO<sub>2</sub> eq ha<sup>-1</sup> yr<sup>-1</sup> to the atmosphere, respectively. Conversely, conversion from crop and grasslands to secondary forest reduced net emissions by  $6.1 \pm 4.1$  and  $3.9 \pm 1.2$  tCO<sub>2</sub> eq ha<sup>-1</sup> yr<sup>-1</sup>, respectively. Land-use change impacts were generally dominated by changes in biomass carbon. A retrospective analysis indicated that LUC from natural forests to agricultural lands contributed a cumulative  $1326 \pm 449$  GtCO<sub>2</sub> eq between 1765 and 2005, which is equivalent to average emissions of  $5.5 \pm 1.6$  GtCO<sub>2</sub> eq yr<sup>-1</sup>. This study demonstrates how specific LUCs can positively or negatively affect net GHG fluxes to the atmosphere.

## 1 Introduction

Fossil-fuel emissions are clearly the dominant factor responsible for the enhanced greenhouse effect (Forster et al., 2007), but land use change (LUC) also contributes an important net greenhouse gas (GHG) exchange between the atmosphere and the

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where LUC involves changes to or from grazed grasslands, there can be large changes in CH<sub>4</sub> emissions by enteric fermentation of grazing animals (e.g., Kelliher and Clark, 2010; Cottle et al., 2011) that are likely to dominate the overall change in net CH<sub>4</sub> emissions.

5 Nitrous oxide is mainly produced in soils through three processes: (1) nitrification, the oxidation of ammonia (NH<sub>3</sub>) to nitrite (NO<sub>2</sub><sup>-</sup>) and nitrate (NO<sub>3</sub><sup>-</sup>) (Kowalchuk and Stephen, 2001); (2) denitrification, the stepwise conversion of NO<sub>3</sub><sup>-</sup> to NO<sub>2</sub><sup>-</sup>, NO, N<sub>2</sub>O and ultimately N<sub>2</sub>, by anaerobic bacteria that use NO<sub>3</sub><sup>-</sup> as electron acceptors for respiration under anaerobic conditions (Knowles, 1982); and (3) nitrifier denitrification by  
10 NH<sub>3</sub>-oxidizing bacteria that convert NH<sub>3</sub> to nitrite NO<sub>2</sub><sup>-</sup>, followed by the further conversion of NO<sub>2</sub><sup>-</sup> to nitric oxide NO, N<sub>2</sub>O and N<sub>2</sub> (Wrage et al., 2001). N input, land use and its management, and climatic conditions are generally considered to be the major controlling factors of N<sub>2</sub>O fluxes in soils (e.g., Snyder et al., 2009; Smith, 2010; Kirschbaum et al., 2012).

15 There has been increasing interest in the effect of LUC on SOC, and previous meta-analytical review papers have comprehensively summarized the effect of various LUCs on SOC (e.g., Murty et al., 2002; Guo and Gifford, 2002; Laganière et al., 2010; Don et al., 2011; Poeplau et al., 2011; Liao et al., 2012; Li et al., 2012). A growing number of studies have also reported the effect of LUC on CH<sub>4</sub> and N<sub>2</sub>O fluxes. This may reflect  
20 the current interest in the losses and gains of C, and the increase or decrease in the emission of other GHGs related to global climate change. However, we are not aware of any previous comprehensive and quantitative summary reports that have combined the effect of LUC on changes in biomass C, SOC, CH<sub>4</sub> and N<sub>2</sub>O fluxes.

25 This review is novel in that it takes a comprehensive approach in dealing with the effect of LUC on the exchange of GHGs between land and atmosphere through quantifying changes in biomass C, SOC, CH<sub>4</sub> and N<sub>2</sub>O fluxes. It thus tries to bring together as much of the published literature as we were able to obtain, summarize the findings, and express them in common and comparable units. The work thus tries to estimate

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the total GHG impact of specified LUCs based on empirical observations as far as they are available.

Our specific objectives were to: (1) summarize the effect of LUC on exchange of GHGs between the land and the atmosphere and identify any common patterns across studies; (2) convert the individual net emissions from different gases to common units and derive total integrated net GHG impact related to each LUC; and (3) discuss the underlying mechanisms and drivers of responses.

## 2 Methodology

### 2.1 Types of land-use change assessed in this study

In this study, we have considered the following types of LUC:

- Land-use change from natural forest to cropland, grassland, or secondary forest
- Land-use change from cropland to grassland or secondary forest
- Land-use change from grassland to cropland or secondary forest
- Land-use change from other natural lands, peat land or savannah, to cropland or grassland.

Natural forest includes all naturally growing forests in tropical, temperate, and boreal regions. Secondary forests can be local indigenous forests that are naturally regenerating or forests planted for specific human purposes, and they may include indigenous or introduced species. Savannah differs from grassland through the presence of trees, and both may be extensively grazed. There is no universal definition of the threshold of tree cover to separate these land-use or land-cover types. We followed the definitions used by the respective authors of different studies. Our study is only able to provide

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average effects for different LUCs without being able to provide any weighting by either the areal extent of different bioclimatic zones of each vegetation type or the global distribution of different LUCs.

## 2.2 Quantifying the impact of land-use change on net greenhouse gas exchange

The impact of LUC on net GHG exchange was determined through quantifying changes in biomass C, SOC, CH<sub>4</sub> production through enteric fermentation, and net soil fluxes of CH<sub>4</sub> and N<sub>2</sub>O. This was expressed in common units of CO<sub>2</sub> equivalents through multiplication by the respective global warming potentials (GWP) of different GHGs. Soil C changes through soil erosion were not included in this quantification since it remains problematic to assess the overall effect of soil erosion on C fluxes to the atmosphere (Tate et al., 2005; Kirschbaum et al., 2012; Sanderman and Chappell, 2013; see also Sect. 4.3 below).

### 2.2.1 Quantifying changes in biomass carbon stocks

Global average biomass C stocks in natural forests were estimated to be  $118 \pm 39 \text{ tC ha}^{-1}$  (Mean  $\pm 95\%$  confidence intervals; taking the average of biomass carbon in Table 1 in Kirschbaum et al., 2012). We assumed that 75% ( $89 \pm 29 \text{ tC ha}^{-1}$ ) of biomass C stocks in natural forests can accumulate in the biomass of secondary forests over 100 yr. Biomass C stocks in cropland, grassland and savannah (Table 1) were determined from estimates of global vegetation C provided by Eglin et al. (2010) divided by the area estimates of Ramankutty et al. (2008) as:

$$B_{p,i} = B_{t,i}/A_{t,i} \quad (1)$$

where  $B_{p,i}$  are the average biomass carbon stocks per unit of land of vegetation type  $i$ ,  $B_{t,i}$  is the estimated total global biomass carbon of vegetation type  $i$ , and  $A_{t,i}$  is the area globally covered by vegetation type  $i$ .

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Conversely, shortening the integration interval would have increased the inferred importance of carbon-stock changes. Greenhouse gas fluxes from these biomass C changes were then calculated simply as:

$$F_{b,ij} = (44/12)\Delta_{B,ij}/100 \quad (3)$$

where  $F_{b,ij}$  is the GHG flux ( $\text{tCO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ ) due to biomass C changes of land-use transition  $i$  to  $j$ . The constants 44 and 12 are the molecular weights of  $\text{CO}_2$  and C, respectively. The division by 100 apportions an overall one-off C-stock change equally over a period of 100 yr.

## 2.2.2 Quantifying change of soil organic carbon stocks

The change of SOC stocks for LUC from land use  $i$  to land use  $j$  over 100 yr ( $\Delta S_{i,j}$ ) was estimated as:

$$\Delta S_{i,j} = S_i \times \Delta S_{ij(100)} \quad (4)$$

where,  $S_i$  are the average pre-LUC soil-organic carbon stocks associated with land use  $i$ , and  $\Delta S_{ij(100)}$  is the fractional SOC change estimated over 100 yr, following a LUC from land use  $i$  to  $j$ .

The SOC in land prior to LUC and the change rates ( $\Delta$ ) of SOC in various types of LUC (Table 3; Fig. 1) were obtained by combining the global meta-data of Murty et al. (2002), Don et al. (2011), Poeplau et al. (2011), and Power et al. (2011) that include over 230 studies published from 1963 to 2010. Soil organic carbon appeared to reach new equilibrium values following different time courses under different LUCs. We tried to estimate those time courses from inspection of reported changes in SOC stocks reported for different time periods after LUC and fitting appropriate relationships to each transition. For the conversion of cropland to secondary forest, we used a linear relationship to describe the time course of change as:

$$\Delta S_{ij(t)} = s_{ij}t \quad (5)$$





that were conducted under diverse biophysical conditions using a range of methodologies for quantifying GHG emissions (e.g., sampling protocols, chamber design, and emission rate calculations), soil properties, and climatic factors.

We calculated the change in soil CH<sub>4</sub> and N<sub>2</sub>O emissions using the emissions values observed in paired-site studies:

$$\Delta_{m,ij} = E_{m,i} - E_{m,j} \quad (10a)$$

$$\Delta_{n,ij} = E_{n,i} - E_{n,j} \quad (10b)$$

where  $\Delta_{m,ij}$  and  $\Delta_{n,ij}$  are the differences in net soil CH<sub>4</sub> and N<sub>2</sub>O emissions between two land uses, respectively, and  $E_{m,i}$ , and  $E_{m,j}$ , are the net CH<sub>4</sub>, and  $E_{n,i}$  and  $E_{n,j}$  are the net N<sub>2</sub>O emission rates associated with land uses  $i$  and  $j$ , respectively.

Greenhouse gas fluxes related to the change in CH<sub>4</sub> ( $F_{m,ij}$ ) and N<sub>2</sub>O ( $F_{n,ij}$ ) as a result of specific LUCs were then expressed in units of CO<sub>2</sub> equivalents as:

$$F_{m,ij} = 25 \times \Delta_{m,ij} \quad (11a)$$

$$F_{n,ij} = 298 \times (44/28)\Delta_{n,ij} \quad (11b)$$

where 25 is the greenhouse warming potential of CH<sub>4</sub>, and 298 is the greenhouse warming potential of N<sub>2</sub>O (Forster et al., 2007). The constant 44/28 converts activity data of N<sub>2</sub>O that are given in N<sub>2</sub>O-N units to N<sub>2</sub>O units.

## 2.2.5 Quantifying the combined net greenhouse gas contributions of all greenhouse gases

After converting the specific activity data of all GHGs to the same units and analysing them over the same time interval (100 yr), we then calculated the total net GHG contribution from all gases and the different contributing factors as:

$$F_{t,ij} = F_{b,ij} + F_{s,ij} + F_{e,ij} + F_{m,ij} + F_{n,ij} \quad (12)$$

where  $F_{t,ij}$  (in tCO<sub>2</sub> eqha<sup>-1</sup> yr<sup>-1</sup>) is the total net GHG contribution of LUC from land use  $i$  to land use  $j$ , with the other terms having been defined above.

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## 2.3 Global estimate of total historical net greenhouse gases contribution by land-use change

We estimated the total net GHG contribution of LUC from forest to cropland or grassland from the areas estimated to have undergone different LUCs between 1765 and 2005 (Meiyappan and Jain, 2012) and applying the terms calculated in the present study (Eq. 12). Hence, the historical net GHG contributions from forest to agricultural uses,  $F_{t, fa}$ , were calculate as:

$$F_{h, fa} = A_{h, fc} \times F_{t, fc} + A_{h, fp} \times F_{t, fp} \quad (13)$$

where  $A_{h, fc}$  and  $A_{h, fp}$  are the areas (in ha) converted between 1765 and 2005 from forest to cropping or pasture, respectively, and  $F_{t, fc}$  and  $F_{t, fp}$  are the corresponding total net GHG emission rates associated with those respective LUCs as defined above.

## 2.4 Statistical analysis

The uncertainty of our estimates of GHG emissions and biomass carbon changes was assessed by calculating the means and standard errors calculated from the values reported in individual studies. All tests were conducted with SAS<sup>®</sup> ver. 9.2 (SAS Institute, Cary, NC, USA) and SigmaPlot<sup>®</sup> ver. 11.0 (Systat Software Inc., San Jose, CA, USA).

The goodness of relationships fitted to our compiled observations of changes in soil organic carbon were assessed by calculating model efficiencies, EF, determined as (Nash and Sutcliffe, 1970):

$$EF = 1 - \frac{\sum (y_o - y_m)^2}{\sum (y_o - \bar{y})^2} \quad (14)$$

where  $y_o$  are the individual observations,  $y_m$  the corresponding model values, and  $\bar{y}$  the mean of all observations.

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For estimating 95 % confidence intervals of our estimates of soil C changes after 100 yr, we used the delta method (Weisberg, 2005). It is available as a package (al3) in the R statistical computing environment (version 2.15.2) and was applied to our data of changes in soil organic carbon as a function of time for different LUCs. The delta method allows for the calculation of functions of random variables using Taylor expansions (Seber, 1982; Lyons, 1991; Bolker, 2008).

Uncertainty in the estimates of other quantities was assessed by treating the numbers reported in different studies as independent observations and calculating 95 % confidence intervals of those observations.

## 3 Results

### 3.1 Change in biomass carbon stocks following land-use change

Depending on the type of LUC, perennial vegetation may be removed (i.e. deforestation) and replaced either by different perennial types of vegetation (i.e. tree plantation) or crops or pastures with much lower C stocks. We estimated changes in biomass C stocks following LUC to range from  $-115.7 \pm 39.2$  (Mean  $\pm 95$  % confidence intervals)  $\text{tCha}^{-1}$  to  $86.7 \pm 29.4 \text{tCha}^{-1}$  after 100 yr (Table 2). As forests contained much greater biomass than agricultural land, any conversion from forest to other land uses led to large C losses, while the conversion from agricultural land to secondary forest led to C gains. The average C contents of savannahs and grassland were also greater than the C contents of cropland, thus also making a small difference in any conversions.

### 3.2 Changes in soil organic carbon stocks following land-use change

Average SOC in soils prior to LUC ranged from 31.3 to 93.9  $\text{tCha}^{-1}$  (Table 4), and SOC changed by between  $-50.6$  % and 88.5 % over 100 yr under different LUCs (Tables 3, 4 and Fig. 1). Conversion from forest and secondary forest to cropland resulted

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in SOC loss of  $35.3 \pm 4.9\%$  and  $50.6 \pm 3.4\%$ , respectively, and most SOC losses occurred over the initial 10 yr after conversion (Fig. 1a, h). Conversely, any conversion from cropland to either grassland or secondary forest, and conversion from grassland to secondary forest led to SOC gains. While SOC losses generally occurred rapidly over the initial 10 yr after conversion (Fig. 1a, h), SOC gains were generally slower and more protracted (Fig. 1d, e). Conversion from cropland to grassland or secondary forest led to SOC gains of  $48.7 \pm 20.0\%$  and  $88.5 \pm 21.6\%$  over 100 yr, respectively, and conversion from grassland to secondary forests led to eventual SOC increases of about  $23.0 \pm 17.1\%$  over 100 yr (Fig. 1g).

Combining average SOC stocks in soils before LUC with rates of SOC change following LUC resulted in changes in SOC stocks following LUC to range from  $-44.5$  to  $59.0 \text{ tC ha}^{-1}$  over 100 yr (Table 4). Largest losses were seen in the conversions from primary or secondary forest to cropland ( $-33.1 \pm 11.2$  and  $-44.5 \pm 12.3 \text{ tC ha}^{-1}$ , respectively), while largest gains were possible when cropland was converted to secondary forest ( $59.0 \pm 19.2 \text{ tC ha}^{-1}$ ).

### 3.3 Changes in $\text{CH}_4$ and $\text{N}_2\text{O}$ emissions

Table 5 summarized the effects of LUC from natural forests to croplands, grasslands and secondary forest on rates of enteric fermentation and net soil emissions rates of  $\text{CH}_4$  and  $\text{N}_2\text{O}$ , with more detailed information provided in the Supplement (Tables A–C). Conversion from natural forests to crop and grasslands, and conversion from savannah to grasslands mostly increased net  $\text{CH}_4$  and  $\text{N}_2\text{O}$  emissions. Conversion from natural forest to secondary forest and conversion from croplands to grasslands mostly increased net  $\text{CH}_4$  emissions but decreased  $\text{N}_2\text{O}$  emissions.

When LUC involved a change to or from grazed grasslands, changes in overall net  $\text{CH}_4$  emissions tended to be dominated by changes in enteric fermentation which were about an order of magnitude larger than changes in net soil  $\text{CH}_4$  emissions. Conversion from croplands to secondary forest, and conversion from secondary forest to croplands mostly decreased net  $\text{CH}_4$  and  $\text{N}_2\text{O}$  emissions. A particularly high reduction in

net emissions was recorded for the conversion from wetland to cropland related to the draining of land, which prevented the anaerobic conditions responsible for large wetland emissions. Changes in CH<sub>4</sub> and N<sub>2</sub>O emissions need to be interpreted cautiously due to the limited amount of available data and their high variability.

### 5 3.4 Combined effect on net greenhouse gas emissions

We then combined changes in biomass C, SOC, CH<sub>4</sub> emissions from enteric fermentation and soil processes, and soil N<sub>2</sub>O emissions following LUC into a combined assessment. It showed that deforestation of primary forests to any other land use increased net GHG emissions (Figs. 2 and 3; Table 6). Conversion from natural forest to cropland led to the largest net GHG emissions, followed by conversion from secondary forest to cropland. This was primarily due to the loss of biomass C, but N<sub>2</sub>O emissions also tended to increase, and net CH<sub>4</sub> emissions increased especially for any conversions to grazed grasslands (Fig. 3). Increased GHG emissions were largely, but not completely, reversible over 100 yr if agricultural land was further converted to secondary forest.

Conversely, conversion from cropland to secondary forest led to the largest reduction of net GHG emissions, followed by conversion from grassland to secondary forest. Conversion from croplands to grasslands also decreased net GHG emissions because of decreased N<sub>2</sub>O emissions and slightly increased biomass and soil C stocks (Figs. 2 and 3; Table 6).

For all LUCs involving forests, the change of biomass C was the major contributor to net GHG emissions (58.4–81.3 % of the net change; Table 6). In the conversion of cropland to grassland, the change of N<sub>2</sub>O emissions (75.9 % of the net change; Table 6) was the main contributor to net GHG emissions.

Globally, historical LUC from natural forests to crop and grasslands has contributed a cumulative  $1326 \pm 449$  GtCO<sub>2</sub> eq between 1765 and 2005, equivalent to average emissions of  $5.5 \pm 1.6$  GtCO<sub>2</sub> eq per year (Fig. 4; Table F). Conversion to cropping was responsible for about 3/4 (76 %) of that GHG contribution. Regionally, North America (18 %), Latin America (27 %) and South and South-East Asia (21 %) together were re-

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sponsible for about 2/3 of those net emissions, with conversion to cropping dominating in all regions except Latin America.

## 4 Discussion

### 4.1 Changes in Biomass

5 Since woody biomass consists of 46–51 % carbon (Aalde et al., 2006), any loss or gain of woody biomass through LUC corresponds to an equivalent CO<sub>2</sub> flux to or from the atmosphere. Considering the large change of woody biomass in most LUCs, it is not surprising that changes in biomass carbon dominated overall net GHG changes (Table 6; Figs. 2 and 3).

10 In the present study, we used an estimated global mean forest biomass of  $118 \pm 20 \text{ tCh}^{-1}$ , based on the data compilation of Kirschbaum et al. (2012), but there is much variation within that global average (Goodale et al., 2002; Houghton, 2005; Aalde et al., 2006; Kindermann et al., 2008), with the largest amount of biomass recorded for tropical forests in South America and *Pinus radiata* plantations in New Zealand, while  
15 lowest amounts of biomass have been reported for marginal forests in Russia, China, Canada and Australia (Kirschbaum et al., 2012).

In addition, the loss of carbon in tree roots is often ignored in carbon counting involving deforestation. Trees usually have root-shoot ratios of 0.2–0.5, with higher values under drier or less fertile conditions (Mokany et al., 2006). This contribution is usually  
20 included in the assessment of live biomass carbon, but after deforestation, there is no consistent treatment of dead roots. Dead roots usually remain in the soil where they slowly decompose (Ludovici et al., 2002; Boutton et al., 2009). Fine roots may decompose within a year or two (Silver and Miya, 2001), while the decay of coarse roots can range from a few years (Garrett et al., 2012) to decades (Chen et al., 2001; Olajuyigbe  
25 et al., 2011). That carbon is either respired as CO<sub>2</sub> or incorporated into SOC with the immobilisation of nitrogen (Kirschbaum et al., 2008). Despite these important roles,

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and their quantitative significance (Kirschbaum et al., 2008; Dean et al., 2012; Wang et al., 2012), the decay of roots has not been well quantified for most ecosystems.

Biomass carbon losses through deforestation can also occur very rapidly, especially if it involves slash burning, while gains in biomass carbon following re/afforestation tend to be much slower and can take decades to centuries, depending on the climate, nutrient availability and growth properties of specific forests. Losses of biomass carbon through deforestation therefore cannot simply be reversed, because full reversal of the loss of biomass carbon stocks requires decades to centuries. We used a 100 yr time frame in the present study to quantify carbon-stock changes, but the numeric outcome would have been different if a different time horizon had been used, with shorter time horizons increasing the calculated importance of carbon-stock changes and time horizons of more than 100 yr reducing it.

## 4.2 Changes in SOC

### 4.2.1 Impact of changed C dynamics

For some land uses, especially those to or from cropland, changes in SOC were the next most important factors. When forest was converted to cropland, SOC decreased by about 35–50 % over the following 10 yr before stabilizing (Fig. 1a, h). That pattern is usually considered to be linked to intensive agricultural land management, including soil disturbance so that croplands lose SOC until a new balance between carbon inputs and outputs is established. In contrast, when natural forest was converted to grassland, there was no clear pattern in SOC change, but individual sites showed a wide range of possible changes, ranging from –60 % to 80 % over 100 yr (Fig. 1b). Similar results were reported in previous studies that summarized SOC changes after deforestation to pasture: Murty et al. (2002) found no consistent changes in soil carbon stocks, while Guo and Gifford (2002) reported a small and statistically significant increase in SOC of about 8 %. The wide range of changes reported in individual studies suggest that converted grasslands could be either carbon sinks or sources depending on specific

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local management and environmental conditions (Murty et al., 2002). Previous studies suggested overgrazing may cause soil compaction which may reduce plant productivity and carbon inputs to the soil, which in turn may result in a loss of SOC (e.g., Fearnside and Barbosa, 1998).

5 Reforesting agricultural lands to secondary forest was found to lead to increases in SOC stocks (Fig. 1e, g). When cropland was converted to secondary forest, SOC increased linearly over 100 yr (Fig. 1e), reversing the carbon loss seen when forests were deforested, although the change was much slower than the carbon loss upon deforestation. It indicates that the factors that cause the decrease in SOC under cropping, probably related to frequent soil disturbance and reduced carbon inputs, can be reversed when that disturbance ceases. The increase in SOC may also be affected by soil type. A meta-analysis of soil carbon changes after reforesting cropped soils found that soil carbon did not change in low-clay soils, but increased by an average of 26 % for sites with higher clay contents (Laganière et al., 2010).

15 In the conversion from grassland to secondary forest, there also was an increase of SOC by about 28 % after 100 yr and 39 % after 200 yr (Fig. 1g). Previous meta-analyses reported divergent results on SOC change after reforesting pastures. Some studies reported losses of SOC by about 10 % (Guo and Gifford, 2002; Paul et al., 2002; Davis and Condrón, 2002; Tate et al., 2005), while others reported gains of SOC by up to 28 % (Laganière et al., 2010; Don et al., 2011; Poepflau et al., 2011; Power et al., 2011). The present study combined all the data summarized in these previous studies and this combined data confirmed the result of the more recent analyses in showing that carbon gains following reforestation of pastures are more common than carbon losses.

25 Switching between different agricultural land-use types, such as between cropland and grassland, also showed clear patterns in SOC changes (Fig. 1d, f). Converting cropland to grassland increased SOC by nearly 50 % (Fig. 1d), whereas converting grassland to cropland decreased SOC by about 45 % (Fig. 1f) and was largely com-

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pleted within the first 10 yr after conversion. This difference is usually attributed to loss of SOC in cropland due to cultivation and soil disturbance (e.g., Mann, 1986; Lal, 2004).

#### 4.2.2 Impact of soil erosion

Land-use change from natural forest to agricultural land can also cause soil erosion by wind and water (e.g., Pimentel et al., 1995; Lal, 2003). Erosion can cause large site C losses (e.g., Lal, 2003; Post et al., 2004; Gaiser et al., 2008). Conversely, converting agricultural lands to secondary forest can reduce soil erosion and prevent further site C losses. However, while erosion clearly depletes local carbon stocks, its effect on the global carbon budget is less clear as carbon lost from a site may not necessarily be lost to the atmosphere but may be buried and stabilised in deep ocean sediments, instead.

If most C is lost before deposition or stabilisation, then erosion is likely to constitute a net source of CO<sub>2</sub> to the atmosphere (e.g., Lal, 2003; Polyakov and Lal, 2008). However, if most C can be deposited in ocean sediments or stabilized without being oxidised (e.g., Govers et al., 1994; Dunne et al., 1998; Brackley et al., 2010), and if eroded sites can regain their lost soil C stocks, then erosion could even constitute as a net sink of CO<sub>2</sub> (e.g., Dymond, 2010; Quinton et al., 2010; Dotterl et al., 2012; Van Oost et al., 2012). It therefore remains problematic to assess the overall effect of LUC induced soil erosion on global warming (Tate et al., 2005; Kirschbaum et al., 2012; Sanderman and Chappell, 2013). Because of incomplete understanding and quantification of the key erosion processes it still remains difficult to assess with confidence the overall effect of LUC on carbon exchange with the atmosphere (Kuhn et al., 2009). While the role of erosion in the global C cycle remains uncertain, it should not detract from the fact that erosion clearly is a massive problem for local food production (e.g., Godfray et al., 2010; Lal, 2010) and siltation of downstream water reservoirs (e.g., Pimentel et al., 1995; Thothong et al., 2011).

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### 4.3 Changes in N<sub>2</sub>O

Our meta-data showed that conversion of forest to cropland or grassland increased N<sub>2</sub>O emissions, which was reversible when cropland or grassland was converted to secondary forest. N<sub>2</sub>O emissions are mainly associated with the turnover of N in the soil. These natural processes have been intensified through human interventions, mainly through agricultural activities, and principally through the increased use of N fertilisers (e.g., Del Grosso et al., 2009; Kirschbaum et al., 2012; Kim et al., 2012). Changes in N<sub>2</sub>O emissions following LUC can thus be principally related to changes in the amount of N inputs. Cropland and grassland usually receive larger N inputs than forests through applied organic and inorganic N fertilizers and animal excreta. Consequently, nitrification and denitrification processes are intensified, and more N<sub>2</sub>O can be produced during N-transformation processes in the soil (e.g., Robertson and Tiedje, 1987; Bouwman, 1996; Kim et al., 2012). In addition, increase in soil acidity due to excessive synthetic fertilizer use (Barak et al., 1997; Bulluck et al., 2002), and increased soil compaction by intensive soil management (e.g., Bilotta et al., 2007) can further increase N<sub>2</sub>O emissions by decreasing N<sub>2</sub>O reductase activity (e.g., Christensen, 1985; Struwe and Kjøller, 1994; Raut et al., 2012). In contrast, conversion of cropland and grassland to forest is usually associated with reduced N inputs to soils, leading to less N<sub>2</sub>O being produced in soils.

### 4.4 Changes in CH<sub>4</sub> emissions from enteric fermentation

CH<sub>4</sub> emissions from enteric fermentation for any conversions to or from grasslands can be 3–20 times larger than changes in net soil CH<sub>4</sub> emissions resulting from LUC (Table 5). Change in CH<sub>4</sub> emissions from enteric fermentation is thus a critical component of altered GHG balances following LUC. In this study, a global average value of 13.0 kg CH<sub>4</sub> ha<sup>-1</sup> yr<sup>-1</sup> was applied to CH<sub>4</sub> emission from grazed pastures, but this value is more than an order of magnitude lower than CH<sub>4</sub> emissions of 150 (for sheep) and 240 (for cattle) kg CH<sub>4</sub> ha<sup>-1</sup> yr<sup>-1</sup> used as typical values for intensively managed

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grasslands (Kirschbaum et al., 2013). This highlights the limitation of using average enteric fermentation values from a global assessment that would have included areas with very low CH<sub>4</sub> emissions from enteric fermentation. The contribution of CH<sub>4</sub> emissions from enteric fermentation can thus change greatly with the global region where LUC may occur and with the productive potential of those regions. The amount of CH<sub>4</sub> produced by enteric fermentation depends on the type of animal and the amount and type of feed consumed.

#### 4.5 Net soil CH<sub>4</sub> emission

A final, but generally small, factor is the net soil CH<sub>4</sub> flux. Our meta-data showed that the conversion of forest to cropland or grassland increased net CH<sub>4</sub> emissions, and conversion of cropland or grassland to secondary forest decreased net CH<sub>4</sub> emissions.

While most well-drained soils can act as either a sink or source of CH<sub>4</sub> (e.g., Price et al., 2010), CH<sub>4</sub> oxidation generally tends to dominate, and changes in net fluxes tend to be mainly related to changes in a soil's CH<sub>4</sub> oxidation potential. Forests create favourable soil conditions for CH<sub>4</sub> oxidation that can remove  $\approx 1\text{--}5 \text{ kg CH}_4 \text{ ha}^{-1} \text{ yr}^{-1}$  from the atmosphere (Smith et al., 2000). However, it may take over 100 yr to recover maximal CH<sub>4</sub> oxidation rates after disturbance by deforestation (Allen et al., 2009; Smith et al., 2000; Singh and Singh, 2012). Changed CH<sub>4</sub> fluxes after LUC have been shown to be related to changes in the composition (Singh et al., 2007, 2009) and abundance (Menyailo et al., 2008) of the methanotroph communities, and various studies (e.g., Singh et al., 2007; Dörr et al., 2010; Nazaries et al., 2011) found that increased CH<sub>4</sub> oxidation following afforestation was directly linked to a shift towards type-II methanotrophs.

#### 4.6 Draining wetlands

It has been estimated that globally, about 50 % of wetlands have been converted to agricultural and other land uses (Zedler and Kercher, 2005; Verhoeven and Setter,

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2010), with a potentially significant effect on overall global GHG fluxes. Among the different LUCs, the conversion from wetland to cropland caused the largest decrease in net soil CH<sub>4</sub> emissions (Table 5) as wetlands are major natural sources of CH<sub>4</sub> emissions (e.g., Saarnio et al., 2009; Jiang et al., 2009). It also caused a minor change in N<sub>2</sub>O emissions (Table 5). Natural wetlands are also typically small C sinks (Mitsch et al., 2012).

Any LUC that involves the draining of wetlands is likely to lead to a large reduction in CH<sub>4</sub> emissions. However, draining wetland usually also leads to the release of large amounts of stored C into the atmosphere (Crooks et al., 2011), with an eventual loss of their total soil C stocks (e.g., Glenn et al., 1993; Langeveld et al., 1997; Santín et al., 2009; Crooks et al., 2011). In the overall GHG balance of drained wetlands, C losses from drained wetlands can therefore dominate the overall GHG balance even after accounting for the respective greenhouse warming potentials of CO<sub>2</sub> and CH<sub>4</sub> (e.g., Janssens et al., 2005).

#### 4.7 Comparison with other comprehensive assessments

There appear to have been few previous studies that attempted to comprehensively assess the total GHG implications of LUC, with the study most closely comparable to our work being that by Kirschbaum et al. (2013). Their work differed from the present study by modelling the GHG effects of LUC in greater detail, including the atmospheric longevity of different GHGs and parameterising their model from agricultural lands with high CH<sub>4</sub> and N<sub>2</sub>O activities. Consequently, biomass and SOC changes were relatively less important in their study than we found here based on a global data compilation.

Kirschbaum et al. (2013) also found that conversion from forest to grazed pastures generally had greater GHG impacts than conversion to cropland. That, too, was related to studying systems with higher grazing activity than the global average. In these high-activity systems, N<sub>2</sub>O emissions and CH<sub>4</sub> emissions from enteric fermentation had a similar effect on overall GHG balances as C-stock changes. As these emissions are higher for grasslands than croplands (Fig. 3), it increased the GHG impacts of

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conversion of forests to grasslands even though for cropland, soil C losses added to the GHG impacts of conversion to those systems (Fig. 3).

#### 4.8 Implication and suggested future studies

Although net changes in CH<sub>4</sub> and N<sub>2</sub>O emissions are numerically relatively small compared to the contribution of change in biomass carbon or SOC, they are nonetheless important for global warming because of the high global warming potential of these gases (Forster et al., 2007). This is particularly important for N<sub>2</sub>O since it also has a long atmospheric longevity (Forster et al., 2007) so emissions will still contribute to global warming even centuries after its emission. Emissions therefore cannot be readily reversed even if that were warranted through rising global environmental concerns.

In the present study, forest biomass C stocks were estimated from reported forest biomass stocks in different parts of the world, while other biomass C stocks were estimated by dividing global biomass estimates by the total area, and changes in CH<sub>4</sub> and N<sub>2</sub>O emissions were estimated from a limited number of available studies. This approach can only provide a first estimate, and the results need to be interpreted cautiously. Further studies could refine activity estimates especially for systems with few current observations. However, the GHG impact of LUC also differs greatly from site to site based on differences in the key determinants at respective sites. This is obviously the case with respect to differences in biomass for any deforestation activity as “forest” biomass can vary greatly based on regional differences (e.g., Kirschbaum et al., 2012) or with the specific local properties of cleared forests.

#### 5 Conclusions

Land-use change from natural forest to agricultural lands can contribute net GHG fluxes averaged over 100 yr of between 4.7 to 6.2 tCO<sub>2</sub> eq ha<sup>-1</sup> yr<sup>-1</sup> to the atmosphere. In contrast, conversion from agricultural lands to secondary forest can reduce net emissions

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of GHGs by 3.9 to 6.1 tCO<sub>2</sub> eqha<sup>-1</sup> yr<sup>-1</sup>. These changes are generally dominated by biomass changes. Together, they demonstrate that LUC can play an important role in contributing to net GHG fluxes to the atmosphere.

**Supplementary material related to this article is available online at**  
[http://www.biogeosciences-discuss.net/11/1053/2014/  
bgd-11-1053-2014-supplement.pdf](http://www.biogeosciences-discuss.net/11/1053/2014/bgd-11-1053-2014-supplement.pdf).

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**Table 1.** Biomass carbon (C) stocks in crop land, grass land and savannah. Estimates of global vegetation C were obtained from Eglin et al. (2010) and area estimates from Ramankutty et al. (2008).

	Total Biomass C ( $B_{t,i}$ )	Total area covered ( $A_{t,i}$ )	C stocks per unit area ( $B_{p,i}$ )
Cropland	$3.5 \pm 1.0^a$ Gt C	1.5 Gha	$2.3 \pm 0.6$ tCha <sup>-1</sup>
Grassland	$16 \pm 13.7$ Gt C	1.43 Gha	$11.2 \pm 9.6$ tCha <sup>-1</sup>
Savannah	$72.5 \pm 12.7$ Gt C	1.92 Gha	$38.0 \pm 6.7$ tCha <sup>-1</sup>

<sup>a</sup> Means  $\pm$ 95 % confidence intervals; it was determined from the originally provided ranges of total biomass C in Eglin et al. (2010).

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**Table 2.** Change in biomass carbon stocks ( $\Delta$ Biomass C) for various land use changes and their contribution as carbon dioxide ( $\text{CO}_2$ ) to the atmosphere (by dividing the carbon-stock change by 100 yr). Note that a negative carbon-stock change (i.e. a loss of carbon from a site) leads to a positive change in atmospheric  $\text{CO}_2$  and makes a warming contribution. Forest biomass was calculated from the data in Kirschbaum et al. (2012), and other biomass estimates were taken from Table 1. Means  $\pm$ 95 % confidence intervals.

Land use type		Biomass C ( $\text{tCh}^{-1}$ )		$\Delta$ Biomass C ( $\text{tCh}^{-1}$ )	Contribution to the atmosphere ( $\text{tCO}_2 \text{ha}^{-1} \text{yr}^{-1}$ )
Pre	Post	Pre	Post	Post – Pre	Pre – Post
Forest	Crop land	$118 \pm 39.2$	$2.3 \pm 0.6$	$-115.7 \pm 39.2$	$4.2 \pm 1.4$
Forest	Grass land	$118 \pm 39.2$	$11.2 \pm 9.6$	$-106.8 \pm 40.4$	$3.9 \pm 1.5$
Forest	Secondary forest	$118 \pm 39.2$	$89 \pm 29.4$	$-29 \pm 49.0$	$1.1 \pm 1.8$
Crop land	Grass land	$2.3 \pm 0.6$	$11.2 \pm 9.6$	$8.9 \pm 9.6$	$-0.3 \pm 0.4$
Crop land	Secondary forest	$2.3 \pm 0.6$	$89 \pm 29.4$	$86.7 \pm 29.4$	$-3.2 \pm 1.1$
Grass land	Crop land	$11.2 \pm 9.6$	$2.3 \pm 0.6$	$-8.9 \pm 9.6$	$0.3 \pm 0.4$
Grass land	Secondary forest	$11.2 \pm 9.6$	$89 \pm 29.4$	$77.8 \pm 30.9$	$-2.9 \pm 1.1$
Secondary forest	Crop land	$89 \pm 29.4$	$2.3 \pm 0.6$	$-86.7 \pm 29.4$	$3.2 \pm 1.1$
Wetland	Crop land	<sup>a</sup> –	$2.3 \pm 0.6$	–	–
Savannah	Grass land	$38.0 \pm 6.7$	$11.2 \pm 9.6$	$-26.9 \pm 11.7$	$1.0 \pm 0.4$

<sup>a</sup> Data are not available.

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**Table 3.** Parameters of fitted lines for changes in soil organic carbon in land-use changes. Means  $\pm$  95 % confidence intervals.

Land use change type	$\Delta_{ij,max}$	$k_{ij}$	$s_{ij}$	EF <sup>a</sup>
Forest to cropland	$-35.3 \pm 4.9$	$0.3 \pm 0.2$	–	0.10
Forest to grassland	–	–	–	
Forest to secondary forest	–	–	–	
Cropland to grassland	$48.7 \pm 20.0$	$0.1 \pm 0.1$	–	0.37
Cropland to secondary forest	–	–	$0.89 \pm 0.14$	0.68
Grassland to cropland	$-46.2 \pm 9.0$	$0.4 \pm 0.4$	–	0.22
Grassland to secondary forest	$36.4 \pm 31.0$	$0.01 \pm 0.02$	–	0.04
Secondary forest to cropland	$-50.6 \pm 3.4$	$0.8 \pm 0.2$	–	0.95

Most data sets could be well described with single exponential or linear relationships (Eqs. 5 and 6). Even for LUCs where the data showed a linear dependence of soil-carbon changes, there are obvious ecophysiological limits to the temporal extent of such linear dependencies. The relationships should therefore not be extrapolated beyond the range of the data.

<sup>a</sup> EF refers to model efficiency (Eq. 14).

<sup>b</sup> For conversions for which no parameters are listed, fitted lines provided no significant relationships, and therefore only means  $\pm$  standard errors are given.

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**Table 4.** Change of soil organic carbon stocks ( $\Delta S$ ) following various land use changes and their contribution to atmospheric carbon dioxide ( $\text{CO}_2$ ) averaged over 100 yr. The SOC in pre-land use change (LUC) were obtained from the combined global meta data of Murty et al. (2002), Don et al. (2011) and Poeplau et al. (2011). Percentage changes were calculated from the 100 yr values of the fitted curves in Fig. 1, with the parameters given in Table 3.  $\Delta S$  was calculated as the product of the numbers in the preceding columns. Note that a site-level loss of SOC corresponds to an increase in atmospheric  $\text{CO}_2$ . Means  $\pm 95\%$  confidence intervals.

Land use type		SOC in pre-LUC $\text{tCha}^{-1}$	Change after 100 yr %	$\Delta S$ after 100 yr $\text{tCha}^{-1}$ , 100 yr	Contribution to the atmosphere $\text{tCO}_2 \text{ha}^{-1} \text{yr}^{-1}$
Pre	Post				
Forest	Crop land	$93.9 \pm 28.8$	$-35.3 \pm 4.9$	$-33.1 \pm 11.2$	$1.2 \pm 0.4$
Forest	Grass land	$47.1 \pm 21.8$	$6.3 \pm 5.8$	$3.0 \pm 3.1$	$-0.1 \pm 0.1$
Forest	Secondary forest	53.7	$-15.3 \pm 12.5$	$-8.2 \pm 6.7$	$0.3 \pm 0.3$
Crop land	Grass land	$36.8 \pm 27.4$	$48.7 \pm 20.0$	$17.9 \pm 15.2$	$-0.7 \pm 0.6$
Crop land	Secondary forest	$66.7 \pm 14.3$	$88.5 \pm 21.6$	$59.0 \pm 19.2$	$-2.2 \pm 0.7$
Grass land	Crop land	$31.1 \pm 31.9$	$-46.2 \pm 9.0$	$-14.4 \pm 15.0$	$0.5 \pm 0.6$
Grass land	Secondary forest	$69.7 \pm 16.1$	$23.0 \pm 17.1$	$16.0 \pm 12.5$	$-0.6 \pm 0.5$
Secondary forest	Crop land	$88.0 \pm 23.5$	$-50.6 \pm 3.4$	$-44.5 \pm 12.3$	$1.6 \pm 0.5$

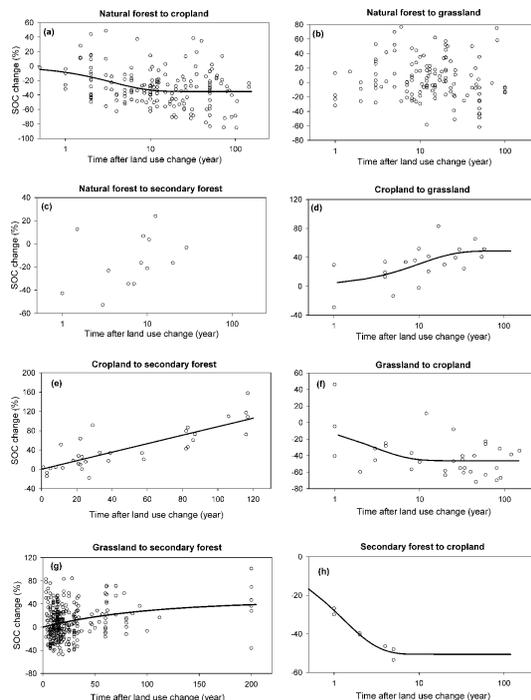
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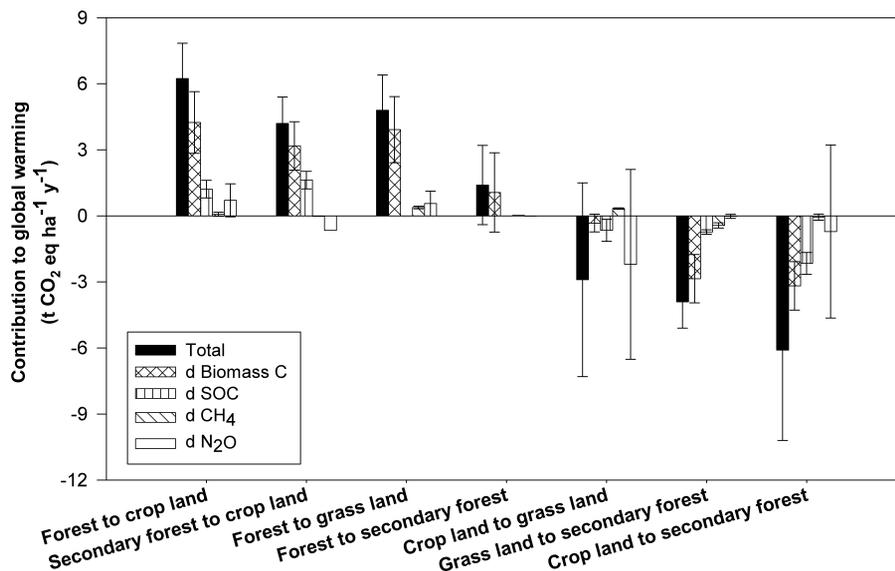


**Fig. 1.** Changes in soil organic carbon (SOC) plotted against time after land use change from various land use changes as specified in each panel. Lines in different panels are fitted curves, forced through 0 at time 0 in each case. We used linear relationships in conversion of cropland to secondary forest (**e**), and first-order exponential relationship for other panels. Note that the time axis uses a linear scale for (**e**) and (**g**) and exponential scale for the other panels. The parameters for each fitted curve are given in Table 3. No relationships were fitted when changes were not significantly different from 0. The data shown here combine the information compiled for the earlier reviews of Murty et al. (2002), Don et al. (2011), Poeplau et al. (2011) and Power et al. (2011).

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**Fig. 2.** Histogram of the global warming contributions by changes in biomass carbon ( $\Delta$ Biomass C), soil organic carbon ( $\Delta$ SOC), total net methane ( $\Delta$ CH<sub>4</sub>) and soil nitrous oxide ( $\Delta$ N<sub>2</sub>O) emissions following land-use changes. Positive numbers indicate a warming contribution (i.e. carbon loss or increased CH<sub>4</sub> or N<sub>2</sub>O emissions from the land use changes). Error bars indicate 95% confidence intervals.

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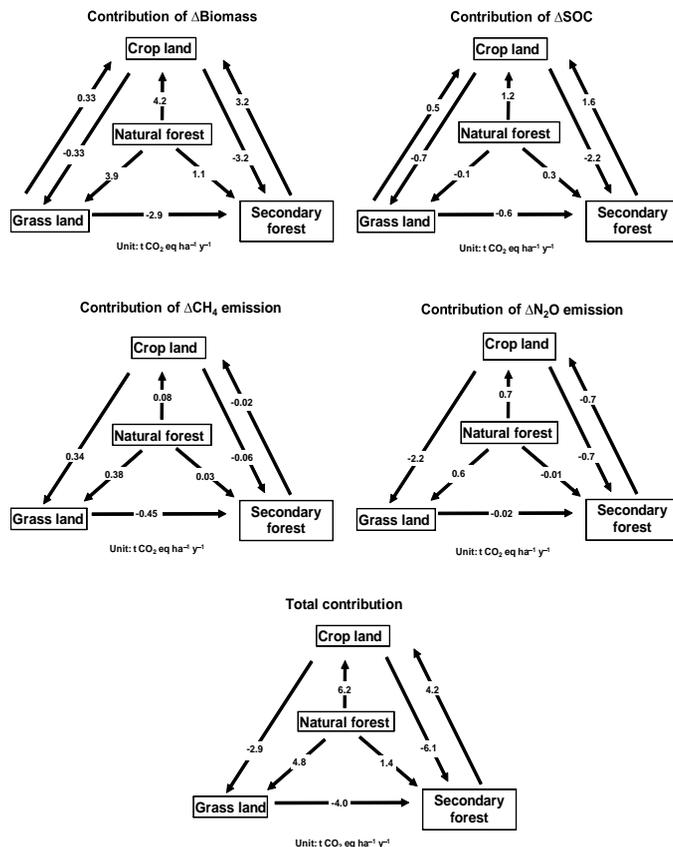
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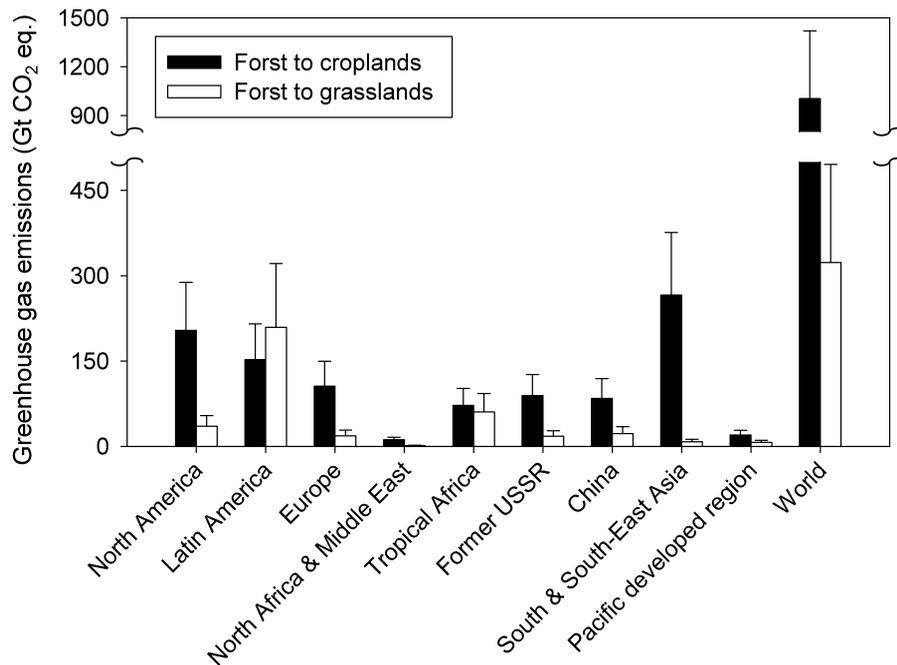
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**Fig. 3.** Contribution to global warming by various changes in biomass carbon ( $\Delta$ Biomass C), soil organic carbon ( $\Delta$ SOC), total net methane ( $\Delta$ CH<sub>4</sub>), soil nitrous oxide ( $\Delta$ N<sub>2</sub>O) emissions, and the combined effect of all gases following land use changes. Positive numbers indicate a warming contribution.

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**Fig. 4.** Greenhouse gas emissions resulting from land use changes from forest to crop or grasslands between 1765 and 2005. Error bars indicate 95 % confidence intervals.

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