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Review

The effect of land-use change on the net exchange rates of greenhouse gases: A compilation of estimates

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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_2), methane (CH_4) and nitrous oxide (N_2O). Here we summarize data of changes in soil organic carbon (SOC) stocks and net soil CH_4 and N_2O emissions associated with LUC. We combine that with estimates of biomass carbon (C) stock changes and enteric CH_4 emissions following LUC. Data were expressed in common units by converting net CH_4 and N_2O fluxes to CO_2 equivalents (CO_2 eq) using established 100-year global warming potentials, and carbon-stock changes were converted to annual net fluxes by averaging stock changes over 100 years. Conversion from natural forest to cropland or grassland resulted in a change in net emissions of 7.3 ± 0.6 (mean $\pm$ 95% confidence intervals) or 5.9 ± 0.3 t CO_2 eq ha^{-1} y^{-1}, respectively, while conversion of cropland or grassland to secondary forest reduced emissions by 5.3 ± 0.9 or 3.6 ± 0.7 t CO_2 eq ha^{-1} y^{-1}, respectively. In all LUCs involving forests, changes in biomass C dominated the overall change in net GHG emissions. A retrospective analysis indicated that LUC from natural forests to agricultural lands contributed a cumulative 1569 ± 43 Gt CO_2 eq between 1765 and 2005, which is equivalent to average emissions of 6.5 ± 0.2 Gt CO_2 eq per year.

Contents

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1. Introduction

The enhanced greenhouse effect is currently dominated by the increase in CO_2 concentration, which contributes a radiative forcing of about 1.68 W m^{-2}, and the direct effect of increases in CH_4 and N_2O add a further 0.48 W m^{-2} and 0.17 W m^{-2}, respectively (Myhre et al., 2013). Fossil-fuel emissions are clearly the dominant factor responsible for the enhanced greenhouse effect (Forster et al., 2007), but LUC also leads to changes in the net flux of CO_2, CH_4 and N_2O through altered biogeochemical processes (Forster et al., 2007; Houghton et al., 2012; Kirschbaum et al., 2012). Globally, 130 million ha were deforested between 1990 and 2009, while the areas of cropland and grassland have increased by 11 and 21 million ha, respectively (FAOSTAT, 2013). Annual mean global C emissions from LUC were estimated to be 4.1 Gt CO_2 y^{-1} between 1870 and 2013 (Le Quéré et al., 2013) and 4.0 Gt CO_2 y^{-1} between 1980 and 2000 (Houghton et al., 2012). With ongoing concern about global climate change, the effect of LUC on the emission of all these GHGs needs to be critically evaluated.

The effect of LUC on CO_2 fluxes is directly related to changes in SOC and C in vegetation biomass since any loss of biospheric C stocks increases atmospheric CO_2. While the changes in SOC following LUC are mainly attributable to shifts in the balance between carbon-input rates and specific decomposition rates of organic matter (e.g., Murty et al., 2002; Guo and Gifford, 2002; Don et al., 2011). Soil erosion may play an additional role in erosion-prone landscapes (e.g., Lal, 2003; Post et al., 2004; Gaiser et al., 2008) and, where fire is associated with LUC, it may also deplete SOC stocks (e.g., van der Werf et al., 2006, 2010).

The effect of LUC on CH_4 fluxes is related to enteric fermentation by grazing animals and any soil processes that produce or consume CH_4. The net CH_4 flux in the soil is the result of the balance between methanogenesis (microbial CH_4 production mainly under anaerobic conditions) and methanotrophy (microbial CH_4 consumption) (Dutaur and Verchot, 2007; Kirschbaum et al., 2012). Methanogenesis occurs via the anaerobic degradation of organic matter while methanotrophy occurs by methanotrophs metabolizing CH_4 as their source of C and energy (Hanson and Hanson, 1996). In cases where LUC involves changes to or from grazed grasslands, there can also be large changes in CH_4 emissions by enteric fermentation of grazing animals (e.g., Kelliher and Clark, 2010; Cottle et al., 2011).

N_2O is produced in soils through three main processes: (1) nitrification, the oxidation of ammonia (NH_3) to nitrate (NO_3^-) (Kowalchuk and Stephen, 2001); (2) denitrification, the stepwise conversion of NO_3^- to N_2O and ultimately N_2 by anaerobic bacteria that use NO_3^- as electron acceptors for respiration under anaerobic conditions (Knowles, 1982); and (3) nitrifier denitrification by NH_3-oxidizing bacteria that convert NH_3 to N_2O and N_2 (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_2O production in soils (e.g., Snyder et al., 2009; Smith, 2010; Kirschbaum et al., 2012).

There has been increasing interest in the effect of LUC on SOC, and previous review papers have comprehensively summarized the effect of various LUCs on SOC (e.g., Murty et al., 2002; Guo and Gifford, 2002; Laganiére 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_4 and N_2O fluxes. This may reflect 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_4 and N_2O fluxes. This makes this review novel in that it takes a comprehensive approach in dealing with the effect of LUC on the biogenic exchange of GHGs between land and atmosphere through quantifying changes in all these important fluxes.

Our specific objectives were to: (1) summarize the effects of LUC on exchange of GHGs between the land and the atmosphere, and (2) quantify the total integrated net GHG impact related to each LUC and GHG component.

2. Methodology

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

Considering the common types of LUC and available data, we have considered the following types of LUC:

- Change from natural forest to cropland, grassland, or secondary forest
- Change from secondary forest to cropland
- Change from cropland to grassland or secondary forest
- Change from grassland to cropland or secondary forest

Natural forest includes all naturally growing forests in tropical, temperate, and boreal regions. Secondary forests include local indigenous forests that are naturally regenerating, or forests planted for specific human purposes, and they may be indigenous or introduced species. Croplands exclude rice paddies, while grasslands include both extensively and intensively managed grasslands. We aimed to cover changes in all biogenic components but did not consider changes in any associated fossil-fuel emissions.

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 five key biogenic GHG exchanges, consisting of changes in biomass C, SOC, CH_4 production through enteric fermentation, and net soil emissions of CH_4 and N_2O. They were expressed in common units of CO_2 eq through multiplication by the respective 100-year global warming potentials (GWPs; Myhre et al., 2013) of different GHGs.

2.2.1. Biomass carbon stocks

Global average biomass C stocks in natural and secondary forests, including above and below-ground biomass, dead wood and litter (Table 1), were estimated based on information available in FAO (2010) and WBGU (1998). Global average C stocks for all forests were calculated as 99.8 t C ha^{-1} (FAO, 2010). This included both undisturbed natural and secondary forests. According to information compiled by WBGU (1998), biomass carbon stocks of secondary forests are, on average, about 50% of that of primary forests. Considering that 27.3% of global forests can be considered as natural and undisturbed (FAO, 2010), it follows that the global average C stock for all forests consists of 156.8 t C ha^{-1} in natural forests and 78.4 t C ha^{-1} in secondary forests (Table 1). Biomass C

Table 1
Biomass carbon (C) stocks in natural forest, secondary forest, cropland, and grassland. C stocks for natural and secondary forest, including above and below-ground biomass, dead wood and litter, were estimated using data in FAO (2010) and WBGU (1998) as described in the text. Biomass C stocks of cropland and grassland were obtained from IPCC (2001).

Type	C stocks per unit area ($B_{p,i}$)
Natural forest	156.8 t C ha^{-1}
Secondary forest	78.4 t C ha^{-1}
Cropland	2.5 t C ha^{-1}
Grassland	10.0 t C ha^{-1}