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Terminology as a key uncertainty in net land use flux estimates

J. Pongratz[1], **C. H. Reick**[1], **R. A. Houghton**[2], **and J. House**[3]

[1]Max Planck Institute for Meteorology, Hamburg, Germany
[2]Woods Hole Research Center, Falmouth, MA, USA
[3]Cabot Institute & Department of Geography, University of Bristol, Bristol, UK

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Correspondence to: J. Pongratz (julia.pongratz@zmaw.de)

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Abstract

Reasons for the high uncertainty in land use and land cover change (LULCC) emissions go beyond recognized issues to do with available data on land cover change and the fact that model simulations rely on a simplified and incomplete description of the complexity of biological and LULCC processes. The large range across published LULCC emission estimates is also fundamentally to do with the exact definition of the net land use flux with respect to the way it is calculated by models. We introduce a conceptual framework that allows us to compare the different types of models and simulation setups used to derive land use fluxes. We find that published studies are based on at least 9 different definitions of the net land use flux. Our analysis reveals three key processes that are accounted for in different ways: the land use feedback, the loss of additional sink capacity, and legacy (regrowth and decomposition) fluxes. We show that these terminological differences, alone, explain differences between published net land use flux estimates that are of the order of published estimates. While the decision to use a specific definition will depend on the scientific application and potential political considerations, our analysis shows that the uncertainty of the net land use flux can be substantially reduced when the existing terminological confusion is resolved.

1 Introduction

Future climate change and the required strength of our mitigation efforts depend strongly on the terrestrial emissions and sinks. Currently, the terrestrial biosphere is a net sink for carbon with 1.4 GtC yr^{-1} uptake over the 2000s (Le Quéré et al., 2013). This flux, called the "net biosphere flux", "net land flux", or "net land-atmosphere flux", is the result of two opposing fluxes, the "net land use flux" and the "terrestrial residual flux".

For centuries, human activities have released carbon to the atmosphere through conversion and management of land (referred to as "land use and land cover change", LULCC, or “Land Use, Land Use Change and Forestry” LULUCF) (e.g., Pongratz et al., 2009; Reick et al., 2010; Stocker et al., 2011). These losses of carbon from land are often referred to as “net land use flux”, because LULCC causes not just emissions to the atmosphere (e.g. when a forest is cleared, or harvested wood products are burnt or decay), but also uptake of CO_2 from the atmosphere (e.g. from growth of planted or recovering vegetation following anthropogenic disturbance). The net land use flux is in the order of $1.0 \pm 0.5\,\mathrm{GtC\,yr^{-1}}$ (Le Quéré et al., 2013), with a range across 13 different model results (each with specific definitions explained later) compiled in the meta-analysis of Houghton et al. (2012) of 0.8 to $1.5\,\mathrm{PgC\,yr^{-1}}$ for the 1990s.

The difference between the net biosphere flux and net land use flux implies a sink, typically known as the “residual terrestrial flux” as it is calculated as the residual of other directly estimated terms in the carbon budget (i.e. fossil-fuel and LULCC emissions minus atmospheric growth and ocean uptake). This sink amounts to $2.4 \pm 0.8\,\mathrm{GtC\,yr^{-1}}$ uptake over the 2000s (Le Quéré et al., 2013) and can be seen in inventories in pristine forests (e.g. Pan et al., 2011). It is thought to be primarily due to the indirect effects of anthropogenic environmental change on terrestrial ecosystems: the fertilizing effects of rising CO_2 in the atmosphere, changes in nutrient cycles, and climate change impacts (Zaehle et al., 2011; Le Quéré et al., 2013; Piao et al., 2013). The indirect effect of environmental change affect both managed and unmanaged (pristine) land. As will be shown in this article, the indirect effects are accounted for to very different extents in published estimates of the net land use flux.

The net land use flux is the most uncertain of the directly estimated terms in the global carbon budget, and this uncertainty propagates into estimating the residual flux. Since the net land use flux is not directly observable on the global scale, models are an essential tool to estimate it. However, model differences induce a major uncertainty in net land use flux estimates: of the 13 studies on LULCC emissions in Houghton et al. (2012), and five in Le Quéré et al. (2013), the underlying model estimates differed particularly with respect to the assumed rates of deforestation (partly but not entirely dependent on driving data), the carbon densities for vegetation cleared, and the inclusiveness of management activities. For example, estimates of biomass can be derived from observations, which only recently have become available on a spatially explicit basis for large regions of the world (Baccini et al., 2012); however, they are still subject to considerable uncertainty and will not be available for the pre-satellite era. Process-based models simulate biomass internally subject to simplifications in the causal representation and a large range of parameter assumptions. Differences due to input data and processes included in models have been described and sometimes quantified and account for about 50 % uncertainty in LULCC estimates (Houghton et al., 2012).

However, published estimates contain another source of uncertainty: terminological differences that result from differences in definition of which flux component to include in the net land use flux. These differences result from ad-hoc choices in the simulation setup, but are partly predetermined by the type of model used.

Estimates stem from three generations of models, which each simulate the CO_2 exchange between biosphere and atmosphere in different ways:

a. Bookkeeping models (e.g., Houghton et al., 1983) track changes using fixed carbon densities, growth and decay curves, which do not respond to transient changes in CO_2 and climate, but use inventory-based estimates.

b. Dynamic global vegetation models (DGVMs) simulate soil and plant processes, and their response to external CO_2 and climate drivers. These environmental conditions are prescribed from data externally, i.e. these are uncoupled simulations in which environmental conditions are not altered by the biospheric activity.

c. Earth system models (ESMs) link process-based vegetation models such as DGVMs interactively with carbon cycle and climate modeling and account for climate- and CO_2-mediated feedbacks that could not be represented in uncoupled DGVM simulations: for example, land use change emits CO_2 and causes biophysical changes in albedo and latent heat flux; these biogeochemical and biophysical changes affect climate and CO_2 concentrations, which in turn feed back on growth and decomposition rates; this in turn affects the net land use flux, closing the feedback loop.

The net land use flux is typically either explicitly or implicitly determined with respect to a reference state, i.e. the net land use flux F is defined as difference

$$F = \Phi_{\mathrm{LULCC}} - \Phi_{\mathrm{noLULCC}}, \tag{1}$$

where Φ_{LULCC} and Φ_{noLULCC} denote the net biosphere fluxes with and without LULCC disturbance. Yet the assumed reference state differs between studies, including the vegetation cover, carbon density and environmental drivers. We will show below how different estimates for the net land use flux differ by the assumed reference Φ_{noLULCC}.

To compare the terminology across published net land use flux estimates, we introduce a conceptual framework suitable for distinguishing the different methods. Others (Strassmann et al., 2008; Gasser and Ciais, 2013) have also developed conceptual frameworks to derive flux components for LULCC-induced carbon fluxes, but focus on selected concepts and consider only a subset of relevant flux components. By contrast, our study aims to give a comprehensive comparison of the various methods used in published estimates.

Terminological differences have increased the uncertainty range of estimates of the net land use flux unnecessarily, because they can be resolved more easily than intrinsic uncertainties in data availability, process understanding and model parameterizations. More and more climate models as well as economic and trade models have been extended to include LULCC over the past years, and new approaches of quantifying carbon stocks and fluxes directly from remote sensing are being developed (Baccini et al., 2012; Harris et al., 2012). To be able to consistently compare past and forthcoming estimates of the net land use flux, confusion about terminological issues should be resolved.

2 Materials and methods

2.1 Framework of flux partitioning for comparison of published estimates of the net land use flux

Our framework for comparison distinguishes between carbon fluxes induced by the direct effects of LULCC, carbon fluxes induced by the (indirect) effects of anthropogenic environmental changes, and synergy fluxes that arise due to the combination of direct LULCC effects and environmental changes.

Carbon fluxes from direct LULCC effects involve different timescales. Methodological approaches typically distinguish between “instantaneous emissions” to the atmosphere upon a human intervention like land clearing fires (termed I; see Table 1 for list of abbreviations), and “legacy fluxes” (L) from the readjustment of the carbon stocks to the new type of vegetation and/or type and intensity of management. Legacy fluxes include respiration of plant residues (e.g. harvest slash, dead roots) and disturbed soil organic matter, changes in the stocks of products such as paper and timber, and recovery of the living carbon stocks. The legacy flux thus comprises sources and sinks. In sustainably managed forests with a harvest re-growth cycle, these gross sources and sinks may be large, but of the same order of magnitude over time and thus result in a small net flux (Pan et al., 2011; Houghton et al., 2012). The distinction between instantaneous emissions and legacy flux differs between methods to some extent and may refer to emissions at the instance of LULCC (e.g. Pongratz et al., 2009) or all emissions within a year (Houghton et al., 2012). As most methods discussed below quantify both fluxes together and temporal distribution is affected more than the climate-relevant cumulative emissions, such differences are not relevant for our study.

Underlying all processes involved in the legacy flux is a disequilibrium between carbon uptake and loss. For an ecosystem, this disequilibrium is caused by a mismatch of net primary productivity (NPP), and heterotrophic respiration (Rh). Calling NEP = NPP – Rh net ecosystem productivity, NEP $\neq$ 0 is the signature of disequilibrium. The direct effects of LULCC cause a disequilibrium between NPP and Rh that often lasts decades to centuries, but without further disturbance systems tend to recover from this imbalance. An equilibrium may also be reached in managed systems, if on average a the amount of carbon that is extracted from the ecosystem is balanced by regrowth, like e.g. in sustainable forestry.

A NPP-Rh-disequilibrium may not only be induced by direct LULCC effects, but any time the environmental conditions are altered (we denote carbon fluxes due to environmental changes by “E”). This happens because NPP and Rh react in different ways and on different timescales to environmental changes. Both NPP and Rh are influenced by environmental conditions, in particular via CO_2-fertilization effects on NPP and dependence of soil respiration on temperature and moisture. Further, Rh also depends on NPP. Due to the slow turnover rates of many carbon stocks, Rh follows the evolution of NPP with a time lag. For example, an increase in NPP initially leads to a carbon sink due to NEP as long as NPP and Rh are in disequilibrium.

Environmental changes may be induced by the effects of LULCC, or by other human activities, most notably the burning of fossil fuels. LULCC can therefore influence land carbon fluxes *directly* via anthropogenic changes in vegetation distribution and carbon stocks, and *indirectly* by altering environmental conditions. The latter is often referred to as “land use feedback” in modeling studies (Strassmann et al., 2008).

To summarize, the whole net biosphere flux following LULCC, including direct and indirect effects of LULCC and potential other changes in environmental conditions, can be written as

$$\Phi_{\mathrm{LULCC}} = I + L + E. \tag{2}$$

The component fluxes can occur on various types of land and under various environmental conditions. A minimal set of environmental conditions needed to distinguish different published methods comprises undisturbed environmental conditions (subscript u), fossil-fuel-induced changes in environmental conditions (f), and LULCC-induced changes in environmental conditions (l). A minimal set of land types needed to distinguish the different methods comprises managed land, including recovering areas (m), natural land unaffected by direct LULCC activity (n), and potential natural vegetation on managed land (p) (see Table 2 for detailed definitions).

In the following, $F_{x,y}$ means that the carbon flux F belongs to land of type x, where $x = m, n$, or p, and arises under environmental conditions of type y, where $y = u, f, l$, or lf, the latter denoting the environmental conditions of l and f combined. Figure 1 uses the partitioning based on type of land and environmental conditions to further specify the flux components of Eq. (2) in the following.

2.2 Direct effects of LULCC on carbon fluxes under undisturbed environmental conditions

We start our considerations with two areas of natural and managed land in Fig. 1a (n: gray plus dashed rectangle, m: beige rectangle) with a certain amount of carbon (indicated by C_n and C_m). Direct effects of a LULCC event are considered, where a certain part of the area under natural vegetation (dashed in Fig. 1a) is transformed to managed land. During this transformation, there is a release of instantaneous emissions to the atmosphere, and carbon stock changes occur that will be part of the legacy flux – including emissions as well as uptake in regrowing vegetation (dark red arrows in Fig. 1a). Note that while we use the case of transformation of natural to managed land as illustration in Fig. 1a, our considerations hold also for a change from one type of management to another and for recovery of managed land to a quasi-natural state.

If we assume, as the simplest base case, that the direct effects of LULCC occur under environmental conditions unaffected by human disturbance, then $I = I_u$, $L = L_u$, and $E = E_u = 0$, and Eq. (2) can be specified as

$$\Phi_{\text{LULCC}} = I_u + L_u + E_u = I_u + L_u \tag{3}$$

We have dropped the term E_u ($E_u = 0$) because under environmental conditions undisturbed by human activity a disequlibrium of NPP and Rh arises only due to natural climate variability and natural long-term trends in climate. We can assume the effects of climate variability on NPP and Rh to largely cancel on longer timescales. Natural long-term trends in climate are an order of magnitude smaller than human-induced trends over the centennial timescale that LULCC has become significant (Forster et al., 2007).

2.3 Adding carbon fluxes induced by the effects of changes in environmental conditions

The impact of environmental change on carbon fluxes is represented by two terms $\delta_l E$ and $\delta_f E$; the "δ" notation indicates that the additional terms come from changed environmental conditions that are either due to LULCC (l, green colour in Fig. 1a) or due to fossil-fuel burning (f, blue colour in Fig. 1a). Carbon fluxes due to environmental changes occur on both managed (δE_m), and natural (δE_n) land. This is true even for the LULCC-induced environmental changes, because both biophysical effects and changes in atmospheric CO_2 as direct effects of LULCC act beyond the individual location where LULCC has occurred.

With this in mind, we can write (knowing $E_u = 0$)

$$E = \delta E = \sum_x (\delta_l E_x + \delta_f E_x), \text{where} \;\; x = n, m \tag{4}$$

Depending on the simulation setup, environmental changes may refer to LULCC-induced changes, fossil-fuel-induced changes, or both, and accordingly all or just a subset of the additional terms occur.

2.4 Adding synergy fluxes of direct LULCC effects and effects of environmental changes

The fluxes caused by environmental changes alter carbon stocks on land ($\delta_y C_x$, $y = l, f$, $x = m, n$, in Fig. 1a). This implies that at the instance of a LULCC event such as deforestation, the amount of carbon available for l and L has been changed, and that carbon sinks in L such as occur during plant regrowth also adjust to the altered environmental conditions. Thus, also I_u and L_u from above have to be complemented by fluxes $\delta_l I$, $\delta_l L$, and $\delta_f I$, $\delta_f L$:

$$I = I_u + \delta_l I + \delta_f I \tag{5}$$

$$L = L_u + \delta_l L + \delta_f L \tag{6}$$

In our framework, the effects of environmental changes on instantaneous emissions, δI, and legacy flux, δL, are a consequence of the existence of δE prior to the LULCC event. While the distinction between $\delta I + \delta L$ on the one hand and δE on the other may thus seem artificial, published studies may account for δI and δL, but not δE, depending on how they account for environmental changes (see Sect. 3): (1) environmental changes may be simulated in the realistic transient way, which implies a NPP-Rh-disequilibrium – in this case, fluxes δI, δL, and δE are all simulated. (2) Environmental changes may be accounted for because observational data of carbon densities are used (as will be discussed in method B later); observational data implicitly capture the current disequilibrium, but observations are a snapshot so that changes are not accounted for in a transient way – in this case, fluxes δI, δL, and δE are simulated, but δE-fluxes are 0. (3) Environmental changes are simulated in a non-transient way by assuming they have changed as compared to conditions undisturbed by human acitivity, but that they have reached a new equilibrium state – in this case too, δI and δL are simulated (albeit they are overestimated by assuming an artificial equilibrium, see discussion of method D5), but because no NPP-Rh-disequilibrium exists in this setup, δE-fluxes are not simulated.

In Fig. 1a, the additional δ-terms to I_u and L_u are indicated in orange. Carbon fluxes now form a closed feedback loop: an initial disturbance by a LULCC event leads to a carbon flux that alters environmental conditions, which feeds back on E and carbon stocks, so that emissions of subsequent LULCC events are altered. To summarize, this feedback loop includes direct effects of LULCC (I_u and L_u), indirect effects of LULCC through environmental change ($\delta_l E$), (indirect) effects of other anthropogenic-driven changes in environmental conditions ($\delta_f E$), and fluxes that arise because of the synergy of direct and indirect effecs of LULCC ($\delta_l I$ and $\delta_l L$) or of direct effects of LULCC and effects of other anthropogenic changes in environmental conditions ($\delta_f I$ and $\delta_f L$).

2.5 Potential vegetation and loss of additional sink capacity

Forests have large amounts of woody biomass and typically have a slower turnover rate than e.g. cropland. An increase in biomass due to CO_2-fertilization would therefore be expected to lead to larger carbon stores and longer-term storage in forest than in non-woody vegetation. Thus, upon deforestation this possibility of surplus storage following an increase in atmospheric CO_2 is lost and leads to a "loss of additional sink capacity" (LASC). To quantify this loss, changes in NEP due to environmental changes have to be compared for managed land with a hypothetical situation where that particular land had not been converted, i.e. when it would be covered with "potential natural vegetation". Accordingly,

$$\text{LASC} = \delta E_m - \delta E_p \tag{7}$$

The LASC is thus a synergy effect of LULCC and environmental changes. The general effect of the LASC plays a role in the "net land use amplifier effect" quantified by Gitz and Ciais, 2004 and the "replaced sources/sinks" quantified by Strassmann et al. (2008) (but the exact definitions of "net land use amplifier effect", "replaced sources/sinks", and LASC differ, see Pongratz et al., 2009).

In Fig. 1a, the area of potential natural vegetation is the same as that of the land transformed to managed land in the LULCC event, and excludes the area of land that has already been under management at our initial state of consideration (or simulation). This reflects the setup of most of the modeling studies discussed in the Sect. 3: without-LULCC simulations as well as the model spinup usually use the land use map of the reference year at which the simulations start (e.g., pre-industrial LULCC extent at 1850), not a global map of potential natural vegetation. Therefore, only the carbon fluxes caused by *changes in LULCC following the reference year* are simulated. If instead a global map of potential natural vegetation without any land use were used for without-LULCC simulation and spinup, the LASC would occur on a larger area and be globally more significant. The choice of reference year (modeling studies referenced below start at 10 000 BC, 800 AD, 1700, 1850, and later) explains part of the differences between estimates of the net land use flux for those studies that include the LASC effect.

2.6 Multiple feedbacks and linearity of fluxes

Figure 1a illustrates that feedbacks of second order may occur in the coupled model system, as e.g. δI and δL in turn influence environmental conditions. Further, the NPP-Rh-disequilibrium fluxes are consequence of the two-way interaction between biosphere and atmosphere. This becomes relevant for the different vegetation distributions in with/without-LULCC simulations – because δE_m and δE_p are different in the two simulations, environmental conditions will also differ. This has subsequent consequences on all other fluxes: for example, $\delta_f E_n$, although not dependent on LULCC directly or in any first-order feedback, will slightly differ in the with/without-LULCC cases. Such second-order effects occur only in the subset of methods that include feedbacks (namely, those using coupled ESMs; see Sect. 3), but they must be expected to be small compared to the first-order effects of LULCC.

2.7 Derivation of the flux components for with/without-LULCC simulations

Simulations that account for all fluxes and feedbacks illustrated in Fig. 1a consider as difference between the with/without-LULCC simulations (Eq. 1) both direct and indirect LULCC effects (a change in vegetation distribution and in environmental conditions, respectively):

$$F = \Phi_{\mathrm{LULCC}} - \Phi_{\mathrm{noLULCC}} = \Phi_{mn,\lambda} - \Phi_{pn,\gamma} \tag{8}$$

To avoid distinguishing between including and excluding environmental changes due to fossil-fuel emissions at this point, we introduce two new terms: λ refers to environmental conditions that are influenced by LULCC (cases l and lf); γ is the reference conditions, which refers to the same environmental conditions excluding the effects of LULCC (cases u (if $\lambda = l$) and f (if $\lambda = lf$); see Table 2).

We can extend Eq. (8) by subtracting and adding the same simulation $\Phi_{\mathrm{mn},\gamma}$:

$$F = \Phi_{\mathrm{mn},\lambda} - \Phi_{pn,\gamma} = \underbrace{\Phi_{mn,\lambda} - \Phi_{mn,\gamma}}_{\text{indirect effects}} + \underbrace{\Phi_{mn,\gamma} - \Phi_{pn,\gamma}}_{\text{direct effects}} \tag{9}$$

This extension is helpful to distinguish between the direct and indirect effects of LULCC. The individual flux components included in each group become clear when we derive the flux components for each of the simulations separately collecting the terms from Eqs. (3)–(6):

$$\Phi_{mn,\lambda} = I_u + L_u + \delta_\lambda I + \delta_\lambda L + \delta_\lambda E_m + \delta_\lambda E_n \tag{10a}$$

$$\Phi_{mn,\gamma} = I_u + L_u + \delta_\gamma I + \delta_\gamma L + \delta_\gamma E_m + \delta_\gamma E_n \tag{10b}$$

$$\Phi_{pn,\gamma} = \delta_\gamma E_p + \delta_\gamma E_n \tag{10c}$$

The direct LULCC effects under given environmental conditions then are

$$\Phi_{mn,\gamma} - \Phi_{pn,\gamma} = I_u + L_u + \delta_\gamma I + \delta_\gamma L + (\delta_\gamma E_m - \delta_\gamma E_p) \tag{11a}$$

and thus include

1. instantaneous emissions (I_u),
2. legacy flux (L_u),

3. potential additional effects of the reference environmental conditions on I ($\delta_\gamma I$) and $L(\delta_\gamma L)$, and
4. loss of additional sink capacity (LASC; $\delta_\gamma E_m - \delta_\gamma E_p$)

The indirect LULCC effects at the given (actual) vegetation distribution are (using $\delta_\gamma - \delta_\lambda = \delta_l$ and $\delta_u X = 0$)

$$\Phi_{mn,\lambda} - \Phi =_{mn,\gamma} = \delta_l I + \delta_l L + \delta_l E_m + \delta_l E_n \tag{11b}$$

and thus include

1. synergy effects of direct and indirect LULCC effects ($\delta_l I$ and $\delta_l L$) and
2. other indirect LULCC effects ($\delta_l E_m + \delta_l E_n$).

Equations (11a) and (11b) indicate all potential components (summarized in Fig. 1b), but not all occur for all environmental conditions, as will become clear in Sect. 3 when we apply these equations to the various published methods to quantify the net land use flux.

The previous paragraphs of Sect. 2.7 implicitly referred to the setup of coupled ESM simulations. The key difference to typical uncoupled DGVM setups lies in the assumptions on λ and γ. In the ESM case, where λ and γ differ by the influence of LULCC on environmental conditions, the additional effect of γ in Eq. (11a) refers only to effects of fossil-fuel-induced environmental changes (f). For DGVM simulations, however, we have to reconsider Eq. (8) and allow both with/without-LULCC simulation to use the same environmental conditions (i.e., in the uncoupled DGVM case, $\lambda = \gamma =$ either u, l, f, or lf). Then, Eq. (11a) may additionally include the indirect LULCC effects, and Eq. (11b) becomes 0.

3 Results

Reviewing studies using Earth system models, uncoupled DGVMs, and bookkeeping models, we show in the following that as little as two component fluxes ($I_u + L_u$) and as many as 10 component fluxes of Eq. (11a) and 11b have been included in publications as part of the "net land use flux", with an amazing variety of constellations between these two extremes. Figure 2 compares the flux components included in each method.

3.1 ESM simulations: coupled with/without-LULCC simulations including LULCC feedbacks

We start our review with ESM methods that perform directly the simulations of Eq. (9) and have the potential to include all carbon fluxes and feedbacks illustrated in Fig. 1a. The usual approach is to perform with/without-LULCC simulations in a coupled setup, although methods differ with respect to the reference environmental conditions γ, which may either inlucde (E1) or not include (E2) fossil-fuel emissions. Replacing the generic terms in Eq. (9) with these two simulation setups yields:

E1. γ does not account for fossil-fuel burning, i.e. $\gamma = u$

$$F = \Phi_{\mathrm{mn},l} - \Phi_{\mathrm{mn},u} + \Phi_{\mathrm{mn},u} - \Phi_{\mathrm{pn},u} = \delta_l I + \delta_l L + \delta_l E_m + \delta_l E_n + I_u + L_u \tag{12a}$$

This method has been used by Pongratz et al. (2009) (Fig. 2). They included the additional simulation $\Phi_{mn,u}$ to be able to distinguish between instantaneous emissions plus legacy flux on the one hand (called "primary emissions" in that publication) and the feedbacks induced by the LULCC-induced environmental changes (called "coupling flux"). The resulting overall flux was called "net land use flux", but "primary emissions" was the term compared to other published net land use emission estimates.

E2. γ accounts for fossil-fuel burning

$$F = \Phi_{mn,lf} - \Phi_{mn,f} \qquad + \Phi_{mn,f} - \Phi_{pn,f} = \\ \delta_l I + \delta_l L + \delta_l E_m + \delta_l E_n + I_u + L_u + \delta_f I + \delta_f L + (\delta_f E_m - \delta_f E_p) \tag{12b}$$

This method has been used by Strassmann et al. (2008), calling F "land use flux" or "net carbon emissions" and by Arora et al. (2010), calling F "land use change emissions" or "net land use flux". Unlike E1, this method includes, in the term $\delta_f E_m - \delta_f E_p$, the LASC due to fossil-fuel-induced changes in environmental conditions.

The most prominent difference of both methods E1 and E2 over any of the following methods is that the "net land use flux" includes the carbon fluxes due to LULCC-induced environmental changes ("land use feedback"). They occur on both managed land ($\delta_l E_m$) and natural vegetation ($\delta_l E_n$) and have, historically, caused a carbon sink (see Sect. 4).

3.2 ESM simulations: one single coupled LULCC simulation

This method performs one single coupled with-LULCC simulation with an ESM. No reference simulation is performed, which allows only an incomplete subset of fluxes to be quantified.

$$F = \Phi_{\mathrm{LULCC}} = \Phi_{mn,\lambda} \tag{13}$$

This method can be applied to environmental conditions including and excluding fossil-fuel burning, but only the first method is found in the literature:

S. γ accounts for fossil-fuel burning

$$F = \Phi_{mn,lf} = I_u + L_u + \delta_{lf} I + \delta_{lf} L + \delta_{lf} E_m + \delta_{lf} E_n \tag{13a}$$

These are the same terms as in E1, except that the indirect effects account for environmental changes due to both LULCC and fossil-fuel burning at once. This method has been used by Lawrence et al. (2012) as "land use flux". However, Lawrence et al. (2012) report only direct emissions and product pool fluxes, i.e. I components and a part of the L components of above equation, not the E components. Referring only to product pool changes, the L components in the study by Lawrence et al. (2012) ignore fluxes related to regrowth or respiration of on-site residues; the implications of this are discussed in Sect. 4.3.

3.3 Uncoupled DGVM simulations

Unlike the previous coupled ESM simulations, environmental conditions are uncoupled from vegetation processes in the DGVM setup, so that the same reference environmental conditions are used in both simulations. Therefore, Eq. (8) becomes:

$$F = \Phi_{mn,\gamma} - \Phi_{pn,\gamma} \tag{14}$$

Note that while the coupled approach that accounts for LULCC always represents transient environmental conditions, the uncoupled approach can also prescribe constant environmental conditions (undisturbed by human activities, or constant at a disturbed point in time). Uncoupled simulations are often inconsistent: a static vegetation distribution may be used together with environmental changes that account for LULCC effects, or vice versa.

We again distinguish published methods by the type of reference environmental conditions:

D1. γ represents undisturbed, constant environmental conditions (u)

$$F = \Phi_{mn,u} - \Phi_{pn,u} = I_u + L_u \tag{14a}$$

This method yields the "bookkeeping flux" by Strassmann et al. (2008) and the "primary emissions" by Pongratz et al. (2009) (see method E1) and Stocker et al. (2011). Note that these simulations prescribe climate corresponding to the pre-industrial era (AD 1700 or 800, respectively), which is indeed largely undisturbed by human activity, although some effects of LULCC on environmental conditions may have occurred by this time (Ruddiman, 2003; Pongratz et al., 2009).

D2. γ represents transiently changing environmental conditions influenced by LULCC (l)

$$F = \Phi_{mn,l} - \Phi_{pn,l} = I_u + L_u + \delta_l I + \delta_l L + (\delta_l E_m - \delta_l E_p) \tag{14b}$$

Note that in this setup, the LASC is induced by LULCC effects (unlike the LASC induced by fossil-fuel burning in method E2). This method is not commonly used (simulations have been performed by Pongratz et al. (2009) to isolate the LASC due to LULCC-induced environmental changes); like the other uncoupled approaches it assumes an inconsistent set of LULCC and environmental conditions (potential natural vegetation linked with environmental changes influenced by LULCC), but further depends on environmental conditions (l) that are not directly observable in this isolated form today (but can be obtained from ESM simulations).

D3. γ represents transiently changing environmental conditions influenced by both LULCC and fossil-fuel burning (lf)

$$F = \Phi_{mn,lf} - \Phi_{pn,lf} = I_u + L_u + \delta_{lf} I + \delta_{lf} L + (\delta_{lf} E_m - \delta_{lf} E_p) \tag{14c}$$

This widely used method was introduced by McGuire et al. (2001), with the resulting flux called “release in net carbon storage associated with cropland establishment and abandonment”. It has also been quantified by Pongratz in Houghton et al. (2012) as “net land use flux LUC + CO2”; by Piao et al. (2009) as “land use change emissions”; by van Minnen et al. (2009) as “land-use emissions”; by Arora et al. (2010) as “land use change emissions when with and without LUC simulations see same atmospheric CO_2”; by Zaehle et al. (2011) as “net carbon loss from land-cover changes"; and by Jain et al. (2013) as "net LULUC emissions". Note that the latter two studies also inlcude the nitrogen cycle and transient effects of N_2O emissions.

D4. γ represents transiently changing environmental conditions influenced by both LULCC and fossil-fuel burning; different to method D3, however, only the atmospheric CO_2 conditions are prescribed as identical in the with/without-LULCC simulations (indicated here by "lf_CO2"), while the other environmental conditions are simulated interactively and thus differ between the two simulations

$$\begin{aligned} F &= \Phi_{mn,lf\_CO2} - \Phi_{pn,lf\_CO2} \\ &= I_u + L_u + \delta_{lf\_CO2} I + \delta_{lf\_CO2} L + (\delta_{lf\_CO2} E_m - \delta_{lf\_CO2} E_p) \end{aligned} \tag{14d}$$

This method has been applied in the LUCID-CMIP5 study (Brovkin et al., 2013) to quantify LULCC-induced changes in carbon stocks across a range of models for two scenarios of future LULCC and climate. This method is a hybrid between uncoupled DGVM and coupled ESM simulations: the atmospheric CO_2 concentration is derived from the transient scenarios of the representative concentration pathways (RCP), which account for LULCC emissions as well as fossil-fuel emissions. In both with/without-LULCC simulations the atmospheric CO_2 concentration seen by the terrestrial biosphere (and relevant for climate) is identical, as is typical of uncoupled DGVM simlations. However, because environmental conditions other than the atmospheric CO_2 concentration, most notably climate, are simulated in a coupled way typical of ESMs, they differ between the with/without-LULCC simulations by the (non-CO_2-related) influence of LULCC; that is, the biogeophysical effects of LULCC influence climate in the with-LULCC, but not in the without-LULCC simulation. Therefore, the land use feedback is taken into account in the D4 method and could be represented as in method E2, but it occurs only for biogeophysical effects. The land use feedback on global carbon fluxes via the biogeophysical effects, however, is of secondary importance to the land use feedback via the atmospheric CO_2 concentration and has been simulated in one model to cancel on the global scale (Pongratz et al., 2009b).

D5. γ represents present-day environmental conditions ("lf_today"); simulations are equilibrium simulations

$$F = \Phi_{mn,lf\_today} - \Phi_{pn,lf\_today} = I_u + L_u + \delta_{lf\_today} I^* + \delta_{lf\_today} L^* \tag{14e}$$

This approch has been used by Shevliakova et al. (2009), where lf_today are recent environmental conditions including interannual variability cycled in a quasi-equilibrium. Unlike in realistic transient simulations, LASC is not accounted for because equilibrium simulations do not simulate a NPP-Rh-disequilibrium (i.e. $E = 0$). However, the effect of today's environmental changes on direct emissions and legacy fluxes is accounted for ($\delta_{lf} I$ and $\delta_{lf} L$). This also reveals two slight inconsistencies: first, LULCC, even if it occurs far back in the past, acts on biomass stocks under today's environmental conditions. Second, these biomass stocks are unrealistically assumed to be in equilibrium with today's transiently changing climate (indicated by * above). Because the NPP-Rh-disequilibrium currently causes a carbon sink, simulating carbon stocks to an artificial equilibrium state likely leads to an overestimate of carbon stocks in natural vegetation and thus to an overestimate of LULCC-induced emissions.

3.4 Bookkeeping model

Bookkeeping models calculate carbon fluxes for the direct effects of LULCC based on changes in land use area combined with observation-based estimates of the carbon density and growth and decay rates of specific vegetation types in different regions. Unlike in ESM and DGVM studies, the without-LULCC simulation is performed only implicitly: when an area is transformed from one vegetation type to another, the carbon loss or gain is determined by the difference between the two vegetation types' observation-based parameters. The observational data is taken from inventories or remote sensing and is thus derived from one specific time period. This implies that it does not account for transient changes and the reference environmental conditions are those at the time of the inventory:

$$F = \Phi_{mn,\gamma} - \Phi_{pn,\gamma} = \Phi_{mn,\gamma\_\mathrm{inventory}} - \Phi_{pn,\gamma\_\mathrm{inventory}} \tag{15}$$

Because inventories are performed under actual environmental conditions influenced by both LULCC and fossil-fuel burning, only one choice exists for γ ($\gamma = lf\_\mathrm{inventory}$).

B.

$$\begin{aligned} F &= \Phi_{mn,lf\_\mathrm{inventory}} - \Phi_{pn,lf\_\mathrm{inventory}} \\ &= I_u + L_u + \delta_{lf\_\mathrm{inventory}} I + \delta_{lf\_\mathrm{inventory}} L + \delta_{lf\_\mathrm{inventory}} E_m - \delta_{lf\_\mathrm{iventory}} E_p \end{aligned} \tag{15a}$$

This means that the resulting equation for this method is similar to Eq. (14e) derived for present-day equilibrium simulations with DGVMs (D5). However, two key differences exist: first, in the bookkeeping approach, carbon stocks are not assumed to be in an artificial equilibrium, and second, they refer not necessarily to today, but the (often older) time period of the inventory.

The $\mathrm{LASC}_{lf\_\mathrm{inventory}} = \delta_{lf\_\mathrm{inventory}} E_m - \delta_{lf\_\mathrm{inventory}} E_p = 0$ arises because observed carbon stocks are not in equilibrium; it is 0, however, because method B does not account for changes in environmental conditions after the inventory and thus $\delta_{lf\_\mathrm{inventory}} E_m = \delta_{lf\_\mathrm{inventory}} E_p = 0$ (see Sect. 2.4). The effect of changes in environmental conditions on carbon stocks are instead captured by the $\delta_{lf\_\mathrm{inventory}} I$ and $\delta_{lf\_\mathrm{inventory}} L$ terms.

This method has been introduced by Houghton et al. (1983). Several recent estimates of the net land use flux apply a version of Houghton's bookeeping scheme

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(Achard et al., 2004; DeFries et al., 2002; Houghton et al., 2010; Reick et al., 2010; Baccini et al., 2012). Carbon densities vary across studies but are all based on a range of inventories. The inventories often rely on data from the 1970s or earlier and thus capture only part of present-day human disturbance (with the notable exception of Baccini et al. which uses satellite data to estimate biomass carbon density). Similar to D5, the δ-fluxes based on recent inventories under environmental change are considered to be representative throughout the historical past despite the fact that environmental changes were very small prior to the 20th century.

4 Discussion

Our review of the multitude of methods to estimate the net land use flux reveals three key differences: the inclusion or exclusion of indirect effects of LULCC (also called land use feedback); accounting for the loss of additional sink capacity; full accounting of legacy fluxes.

4.1 Key difference 1: land use feedback

The key difference of coupled ESM simulations with/without LULCC to all other methods is the inclusion of the land use feedback (for example the effect of higher concentrations of atmospheric CO_2 as a result of emissions from LULCC). The land use feedback on managed land is taken into account in some of the uncoupled DGVM methods (D2–4), but always as part of the LASC in reference to the disequilibrium flux on potential vegetation (see next section). In the ESM simulations, by contrast, it is included as additional carbon sink. A larger discrepancy between methods, however, stems from the inclusion of the land use feedback *on natural land*, which includes highly productive vegetation, such as tropical rainforest.

Three studies have quantified the strength of the land use feedback (Strassmann et al., 2008; Pongratz et al., 2009; Arora et al., 2010), finding that they amount to about 25–50 % of the net land use flux that excludes these feedbacks (Fig. 3, Table 3). Studies including the land use feedback find a net land use flux about half that of earlier studies (which excluded the feedback) (Arora et al., 2010). The largest difference is expected to stem from the land use feedback on natural land, which was included in the net land use flux estimate of Arora et al. (2010).

The land use feedback reflects genuine changes in atmospheric CO_2 concentration as a result of human acitivity on the land, and as such should be quantified for full carbon accounting. The question becomes whether it should be accounted as part of the net land use flux (as they are indirectly a result of LULCC even though they affect all land, including unmanaged lands), as done in method E1 and E2; this definition, however, conflicts with the majority of scientific studies and the approach taken in policy in the past (Denman et al., 2007). Alternatively, the net land use flux can be defined as to include only the feedback on managed land, while the feedback on unmanaged lands is counted as part of the residual terrrestrial flux, as done by methods D2–4 as part of the LASC. Finally, the net land use flux can also be defined as to account only for fluxes associated with direct effects of human activity (i.e. I and L, possibly also the synergy terms δI and δL) and feedbacks be accounted as the residual terrestrial flux, as done by all other methods reviewed here. The question becomes even more complicated considering practical limitations such as that many model setups do not allow for isolating the indirect effects of LULCC from the (indirect) effects of fossil-fuel burning (e.g., because they prescribe the atmospheric CO_2 concentration to include effects of LULCC and fossil-fuel burning combined, as methods D3 to D5 do), or that computational considerations limit the number of simulations that can be performed to isolate flux components.

4.2 Key difference 2: loss of additional sink capacity

The LASC is accounted for whenever environmental conditions are changing over time and their effects on carbon fluxes from managed land are different from those on potential vegetation (i.e., with/without-LULCC simulations). The LASC is thus included in the uncoupled DGVM methods with transient changes in environmental conditions (D2–4) and in the ESM simulations that include fossil-fuel burning (E2) (see Fig. 2). However, the LASC is included in these methods to different extents: as response to changes in environmental conditions induced by only LULCC (D2), by only fossil-fuel burning (E2), or by both (D3–4). In these methods, the net land use flux usually also comprises the effect of environmental changes on instantaneous emissions and legacy fluxes.

Strassmann et al. (2008) and Pongratz et al. (2009) agree in that the LASC and effects of environmental changes on direct emissions and legacy flux amount to only a few Gt carbon historically. However, Strassmann et al. have simulated that these effects will be the dominant term of net land use flux for future scenarios – roughly doubling estimated future net land use emissions if included in calculations. It needs to be noted, however, that the LASC depends strongly on processes such as CO_2-fertilization that are not well understood, and on the assumed scenario. Strassmann et al. (2008) assume a scenario of continued clearing and very large environmental changes in particular due to fossil-fuel burning. Smaller environmental changes and afforestation will reduce the LASC as well as instantanous emissions and legacy fluxes.

Despite its potential future importance, it has not been discussed much in literature whether the LASC should be accounted for. The LASC is an unrealized flux, a lost sink instead of actual emissions, not reflected in any real change in atmospheric CO_2 concentration. However, it shows up in the budget of atmospheric CO_2 compared to a reference world without LULCC (often approximated by the late pre-industrial era) reflecting the overall impact that land use change has (or will) have. If the net land use flux is chosen to be defined as to include the LASC, the modeling protocol for spinup and reference simulation becomes particularly important: as discussed in Sect. 2.5, the simulated strength of the LASC is larger when the simulations for model spinup and for the reference without-LULCC case are done with potential natural vegetation as opposed to a map representative e.g. of the late pre-industrial era that includes substantial areas under land use already.

4.3 Key difference 3: regrowth and on-site legacy flux

The study by Lawrence et al. (2012) differs from all other methods in that it reports only a part of the legacy flux – the changes in product pools – thereby missing processes such as respiration of on-site residues, recovery of living vegetation, and adjustment of dead carbon stocks. It most notably excludes NEP changes due to regrowth of vegetation. With their "land use flux" of 119 PgC plus wood harvest of about 64 PgC emitted historically since 1850, their net land use flux estimate is within the (wide) range of previous estimates. They are, however, substantially larger than other estimates for the future time periods, e.g. the LUCID-CMIP5 study that investigated the same scenarios (Brovkin et al., 2013). Missing the NEP-related carbon sink in regrowth, even the scenario of strong afforestation (RCP 6.0) leads to emissions larger than in the historical period. For scenarios RCP 2.6 and 8.5 this method yields a "land use flux" that is about 4–6 times larger compared to the majority of the LUCID-CMIP5 models (exclusive one outlier).

4.4 Consistency with observable fluxes?

None of the methods identified in the published literature quantifies a flux that would be observable on the local or global scale. Site-based measurements of flux or stock change in lands subject to land use (management) or land use change would capture all fluxes shown over managed land in Fig. 1 (minus product pool changes that may occur off-site). However, methods E2 and D2–D4 account for the non-realized LASC effects; methods E1 and D1–D2 ignore all or part of the environmental changes; method *S* only accounts for part of the legacy flux; and methods B and D5 assume present-day conditions to have prevailed throughout history. This discrepancy between the flux observed and the individual flux components that models simulate may be one of the largest obstacles in reducing uncertainties resulting from modeling assumptions.

Comparison of site-based observations to model simulations may also be hampered by the fact that not all ESMs and DGVMs track carbon fluxes separately for natural and managed land. While most models allow for tracking carbon fluxes separately for different vegetation types (e.g., forest vs cropland), they often lump together natural and managed/recovering areas within a vegetation type (e.g., lump together unmanaged and managed/recovering forest within a grid cell) to calculate carbon fluxes.

Difficulties in reconciling observational and modeling data may also stem from differences in accounting period. In certain regions, a large part of the observed terrestrial carbon sink may indeed be the result of the legacy flux rather than indirect environmental changes, i.e. the sink seen in many managed forests today is due to past land use or management changes such as afforestation. In particular in Europa, China, and the Eastern US large areas under agricultural and forest management have been abandoned, sometimes more than a century ago. This leads to carbon sinks primarily due to the legacy flux up until today, but is difficult to disentangle from environmental effects. This is particularly true if information on historical LULCC is not available or the starting date of model simulations is too recent.

4.5 Handling of indirect effects

A recent study (Houghton, 2013) argues that indirect effects of environmental changes should be kept separate from the net land use flux for political considerations, for lowering the uncertainty of the net land use flux, and for consistency in explanatory mechanism (direct LULCC effects are structural, while indirect effects are metabolic). Our study illustrates that a decision for excluding indirect effects, or including only specific flux components, will face major obstacles in its implementation. First, observational data available as model inputs or for model validation implicitly include direct and indirect effects. Second, many of the methods reviewed here are not able to isolate and exclude all of the component fluxes induced by indirect effects due to their specific modeling setup (including Houghton's bookeeping approach, but see also Cowie et al., 2007). Third, a clear definition is required to identify which of the flux components count towards the "indirect effects": environmental changes can be (1) induced by LULCC (land use feedback) or by fossil-fuel emissions; (2) can induce changes in NPP-Rh-disequilibrium fluxes either on managed land ($\delta_l E_m$, $\delta_f E_m$) – often compared to potential vegetation (i.e., $\delta_l E_m - \delta_l E_p$, $\delta_f E_m - \delta_f E_p$) – or on natural vegetation ($\delta_l E_n$, $\delta_f E_n$); and (3) can alter instantaneous emissions and legacy flux ($\delta_l I$, $\delta_l L$, $\delta_f I$, $\delta_f L$). All of these fluxes can be counted towards the indirect effects.

Which fluxes are included in the residual sink will depend on which are included in the land use flux. For example, when the net land use flux is from the bookkeeping approach (Le Quéré et al., 2013), the residual flux refers to fluxes $\delta_l E_m + \delta_f E_m + \delta_l E_n + \delta_f E_n$ (plus additional fluxes caused by other unknown processes). However, up to three of these four fluxes are included in the net land use flux in the majority of other published estimates based on ESMs and DGVMs (Fig. 2). Thus, when DGVM results are used independently to infer the residual terrestrial flux (e.g. Le Quéré et al., 2010, 2013) (runs with transient CO_2 and climate but without LULCC), some indirect effects are counted twice. Furthermore, even fluxes on natural vegetation have been included in the net land use flux by some studies (method E1–E2) if related to LULCC-induced environmental changes.

Our study highlights the importance of a common way to account for indirect effects: two of the three key differences in terminology identified here refer to indirect effects (land use feedback and LASC); but even studies that agree in excluding or including land use feedback or LASC, differ in most cases with respect to the assumed environmental changes (u, l, or f in Fig. 2). So far, agreement has only been that indirect effects induced by fossil-fuel burning on natural vegetation ($\delta_f E_n$) are not part of the net land use flux. Our study identifies and discusses the multitude of possibilities for defining the net land use flux in scientific research. However, the choice of definition, in particular the handling of indirect effects, is a political and ethical choice rather than a scientific one.

Reporting and Accounting for Annex I countries under the Kyoto Protocol attempts to give credit or debit for activities that are a direct result of human activity and thus to “factor out” indirect environmental effects. This aims at avoiding credits for e.g. land sinks due to fossil-fuel emissions by reporting on carbon stock changes in managed lands only. However, even in managed forests there are sinks due to environmental changes, and due to legacy effects from past management. For the second commitment period, it has become mandatory to report on managed forests using reference level accounting in an attempt to factor out past activity and indirect effects from activity since 1990[1]. In reference level accounting a projection of forest growth is made based on previous management and environmental effects (using methods from simple trend analysis through to forest growth models that either do or do not include climate and CO_2 effects), and only deviations from this reference level attributable to management changes can be accounted. In reality it is difficult to spearate direct and indirect fluxes (Cowie et al., 2007) due to the use of observational data from ecosystems that have already been affected by environmental change, and due to the model set-ups.

5 Conclusions

The net land use flux, independent of its exact definition, is not observable at the global scale, but must be inferred with the help of models. As models make different assumptions and rely on different datasets, they cannot necessarily be expected to yield the same results. Such differences in methods together with uncertainties in extent of LULCC cause an uncertainty of about 50 % (Houghton et al., 2012). Some of these uncertainties will be reduced with better availability of data from satellites and inventories.

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[1] Since the Durban Conference of Parties in 2011. See Decision 2/CMP.7 http://unfccc.int/resource/docs/2011/cmp7/eng/10a01.pdf

While we will not be able to fully eliminate uncertainties due to model differences, a large source of confusion can be attributed to inconsistent definitions of what the net land use flux actually consists of. Here, we have shown that simply because of terminological differences, model estimates differ by a factor of 2 for the historical period of pre-industrial to today. Estimates for future scenarios will likely be affected even more (a factor 6 difference has been found, although this range includes model differences as well). Eliminating terminological differences will thus greatly reduce the uncertainty range currently put on the net land use flux.

The publications reviewed in this study provided at least 9 different definitions of the net land use flux and differ in particular with respect to accounting for the land use feedback, the loss of additional sink capacity, and of regrowth and on-site legacy fluxes. The choice of definition depends on the scientific or policy question (e.g., whether or not unrealized carbon fluxes are of interest; whether the interest is in full carbon accounting or accounting for direct human activity).

Unlike intrinsic uncertainties in data availability, process understanding and model parameterizations, terminological differences can be largely eliminated by careful choice and declaration of the component fluxes to be included in net land use flux estimates. As a wealth of new estimates of the net land use flux are being compiled e.g. in the framework of the IPCC's 5th Assessment Report, it is particularly important at this point in time to understand the different approaches and their terminologies so that in comparing and understanding model results and their implications for climate policy we can identify and address the real uncertainties in carbon flux estimates.

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Table 1. Carbon stocks and fluxes used in our conceptual framework for comparison of published studies. See Table 2 for meaning of subscripts.

Abbreviation	Meaning
C_x	Carbon stored initially in land type x, with $x = m, p$, or n.
ΔC_x	Change in land carbon storage due to a LULCC event in different types of land ($x = m, p$, or n).
F	Net land use flux.
$I = I_u + \delta I$	Instantaneous emissions: Carbon emissions that occur instantaneously at the time of the LULCC event, as a direct consequence of LULCC.
$L = L_u + \delta L$	Legacy flux: The delayed carbon fluxes that occur as direct consequence of LULCC; it results from a LULCC-induced NPP-Rh-disequilibrium.
$E = E_u + \delta E$	Carbon flux due to an NPP-Rh-disequilibrium induced by environmental changes. E_u is 0 by definition. Unlike I and L, which occur only on managed land, E can occur also on natural and potential natural land.
$\delta = \delta_l$, δ_f, or δ_{lf}	This symbol is used as a prefix to various quantities to indicate that the effect on the considered quantity arises from changes in the environmental conditions. These environmental changes can be caused by LULCC (δ_l), by fossil-fuel burning (δ_f), or by both(δ_{lf}).[a]
δD	Contribution to the direct flux D induced by environmental changes.
δL	Contribution to the legacy flux L induced by environmental changes.
δD^*, δL^*	As δD and δL, but assuming an artificial equilibrium of carbon stocks to changes in environmental conditions.
δE	Contribution to E induced by environmental changes.
$\mathrm{LASC} = \delta E_m - \delta E_p$	"Loss of additional sink capacity" (LASC): Accumulated mass of carbon that would occur from CO_2 fluxes in response to environmental changes if the vegetation distribution had not been altered by LULCC.

[a] In this paper we assume that fluxes add linearly ("$\delta_l + \delta_f = \delta_{lf}$"); while this is not necessarily the case (e.g., the effects of CO_2-fertilization on plants tend to saturate at high levels), this issue is of secondary importance compared to the relevance of terminological differences between published estimates. We use "δ" without subscript as a general term to refer to any fluxes due to environmental changes, be they induced by only LULCC, only fossil-fuels, or both combined.

Table 2. Definitions of land types and environmental conditions needed to distinguish the different methods to estimate the net land use flux[a].

(a) Environmental conditions		
Subscript	Name	Definition
u	undisturbed environmental conditions	In many methods land fluxes are estimated assuming environmental conditions that are unaffected by anthropogenic activities and exhibit no long-term trend (natural interannual variability may be included). This usually refers to pre-industrial conditions.
f	fossil-fuel induced changes in environmental conditions	Simulations account for changes in environmental conditions due to fossil-fuel emissions causing a long-term upward trend in atmospheric CO_2 concentration (by about 80 ppm since pre-industrial times), associated climate change and other effects such as nitrogen deposition (Denman et al., 2007).
l	LULCC-induced changes in environmental conditions	Simulations account for emissions from LULCC. The atmospheric CO_2 concentration has increased by about 20 ppm due to LULCC emissions, and climate is affected by both biogeochemical and biogeophysical effects (Brovkin et al., 2004; Pongratz et al., 2010).
λ	environmental conditions for a specific simulation	In the case of ESM simulations, λ refers to environmental conditions that are influenced by LULCC (cases l and lf). In the case of uncoupled DGVM simulations, $\lambda = \gamma$ = either u, l, f, or lf.
γ	reference environmental conditions to λ	In the case of ESM simulations, γ is the reference conditions, which refers to the environmental conditions defined in λ but excluding the effects of LULCC (cases u and f, respectively). In the case of uncoupled DGVM simulations, $\lambda = \gamma$ = either u, l, f, or lf.
(b) Land types		
Subscript	Name	Definition
m	managed land	Areas of vegetation disturbed by direct LULCC activity. This includes actively managed areas under agricultural or forest management; these areas may be in disequilibrium due to recent LULCC, or may have reached a quasi-equilibrium in their managed state. It also includes abandoned areas, which have been managed at some point in the past but are no longer under management; they are developing towards the potential natural vegetation but have not fully recovered in terms of carbon stocks.
n	natural land	Areas under natural vegetation that have never been disturbed by direct LULCC activity or that have been abandoned sufficiently long ago so that they have fully recovered and are no longer distinguishable from undisturbed vegetation in terms of carbon stocks.
p	potential natural vegetation	The same areas as “managed land”, but assuming hypothetically that the vegetation state is the potential undisturbed vegetation instead of actual managed.

[a] Note that the distinction between managed and natural vegetation is often artificial as human impact can alter vegetation structure and species composition in subtle ways beyond those commonly classified as distinct by observation-based LULCC datasets. Often, natural vegetation will not fully recover due to ecosystem degradation; this effect is accounted for in some of the studies discussed here (e.g., Houghton et al., 2003). These effects are of secondary importance to our study, and the overly sharp distinction between natural and managed land is introduced here for highlighting different assumptions made in published net land use flux estimates.

Table 3. Key processes that explain the largest differences between various estimates of the net land use flux. LASC is loss of additional sink capacity.

Process	Change in net land use flux if process were accounted for	Reference
Land use feedback	−25 to −50 %	Strassmann et al. (2008); Pongratz et al. (2009); Arora et al. (2010)[a]
LASC	Less than +10 % historically, up to +105 % by 2100 (for SRES A2 scenario)	Strassmann et al. (2008) (historical and future); Pongratz et al. (2009) (historical)[b]
Exclusion of regrowth and on-site legacy flux	Within reported range historically, but 256 PgC as compared to 25–62 PgC 2006–2100 (RCP 8.5), i.e. +300 to 600 %	Lawrence et al. (2012) compared to Brovkin et al. (2013)[c]

[a] The three studies used different setups to quantify the land use feedback, see caption to Fig. 3 for details.

[b] Pongratz in Houghton et al. (2012); estimate that the net land use flux quantified by method D3 is 8 % larger than quantified by method D1, which is a result of counteracting effects: carbon sinks on managed land due to CO_2-fertilization are overwhelmed by the non-realized higher carbon sinks on potential vegetation (i.e., LASC), and by higher instantaneous emissions and legacy flux. Estimates in Strassmann et al. (2008) refer to the bookkeeping vs replaced sources/sinks (their Table 3). [c] Estimates for Lawrence et al. (2012) refer to their Table 4 “land use”; this is exclusive of wood harvest, which makes this estimate better comparable to Brovkin et al. (2013) (their Table 4), because all models apart from the outlier MPI-ESM exclude wood harvest.

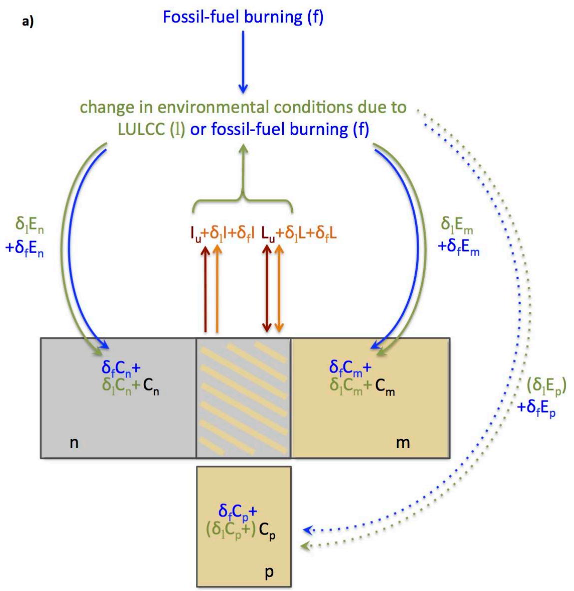

Fig. 1. Conceptual definition of land-atmosphere carbon fluxes. **(a)** Illustration of the effects of LULCC and changing environmental conditions on carbon stocks and fluxes. Colors indicate steps in the causal chain set off by a LULCC event. Black: initial state. Dark red: effects of changes in vegetation distribution due to LULCC (dashed rectangle being transformed from natural to managed land) on carbon stocks ("direct LULCC effects"). Green: feedbacks of LULCC via environmental conditions on carbon stocks and fluxes. The LULCC feedback is put in paranthesis for potential natural vegetation because in coupled (ESM) simulations, this flux will not occur due to the absence of LULCC; however, in uncoupled (DGVM) simulations the atmospheric CO_2 concentration can be prescribed as to include both LULCC and fossil-fuel effects, and $\delta_l E_p$ occurs. Orange: subsequent changes in carbon fluxes from changes in vegetation due to LULCC-induced environmental changes ("indirect LULCC effects). Blue: additional effects from fossil-fuel burning and other externally induced environmental changes.

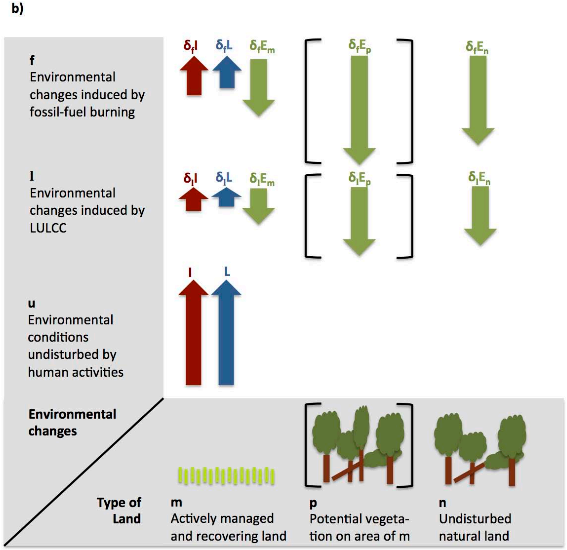

Fig. 1. (b) Summary of carbon fluxes related to LULCC from **(a)**, distinguished by the environmental conditions under which they occur (*u*: undisturbed environmental conditions, *l*: LULCC-induced changes in environmental conditions, *f*: fossil-fuel induced changes in environmental conditions. Note that *lf* used in the text refers to combined LULCC- and fossil-fuel effects.) and by the vegetation state of the area the fluxes occur on (*m*: managed land, *n*: natural land, *p*: potential vegetation on the area of managed land). Note that in an individual model simulation, the vegetation state will be composed of either natural and managed land, when LULCC is accounted for, or natural and potential natural (instead of managed) land, when no LULCC is considered. *I*: instantaneous emissions from LULCC, *L*: legacy flux, *E*: NPP-Rh disequilibrium fluxes due to environmental changes. δ_u-fluxes are 0 by definition and not depicted.

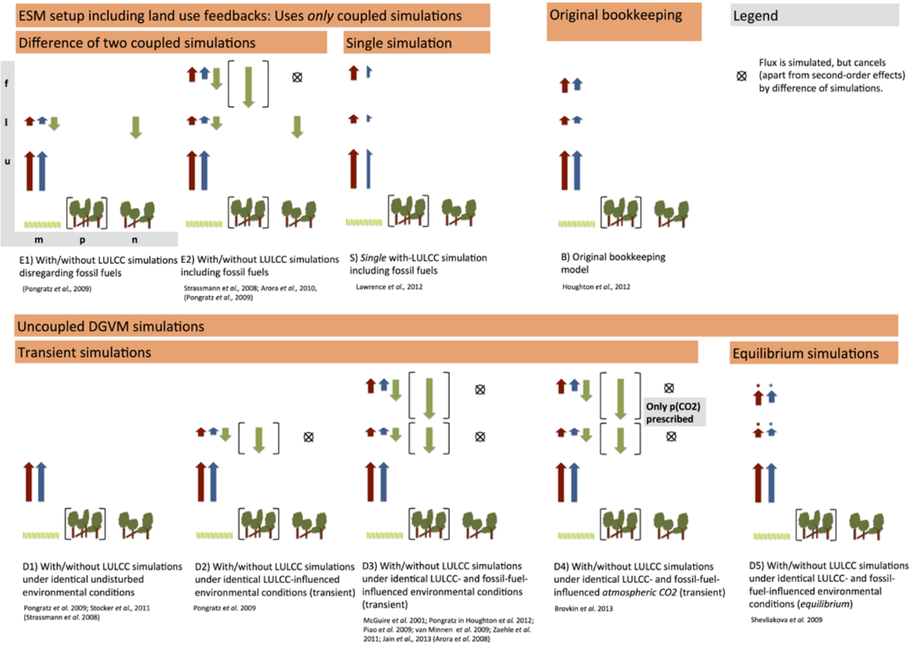

Fig. 2. Comparison of published methods to estimate the net land use flux with respect to flux components that are included or excluded. The complete set of flux components has been shown in Fig. 1b. Note that all fluxes apart from instantaneous emissions (*I*) may act as source or sink of carbon on land. The direction indicated here loosely refers to historical evidence. References in parentheses indicate fluxes that were studied by the authors but not intended to represent their interpretation of the "net land use flux", instead they were to diagnose the influence of different approaches or flux terms, or to compare with other published studies.

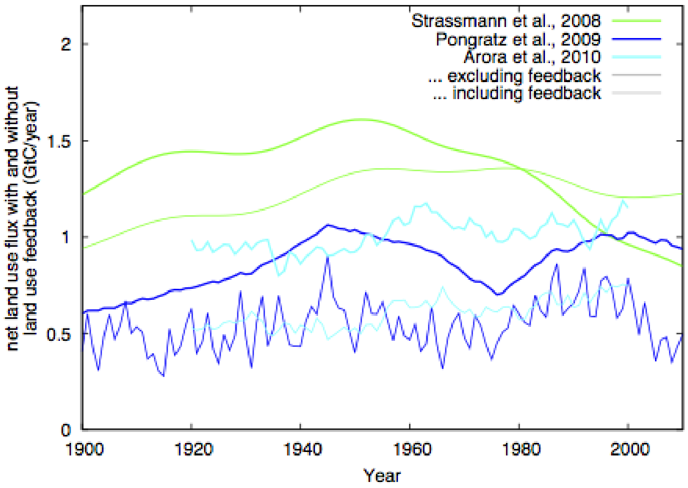

Fig. 3. Fluxes including and excluding the land use feedback from Strassmann et al. (2008); Pongratz et al. (2009); Arora et al. (2010). The following methods were used in the individual studies: For the flux excluding the land use feedback: D1 (uncoupled DGVM simulations under undisturbed environmental conditions) by Strassmann et al. (2008) and Pongratz et al. (2009) and D3 (uncoupled DGVM simulations under transiently changing environmental conditions influenced by both LULCC and fossil-fuel burning) by Arora et al. (2010). For the flux including the land use feedback: E1 (ESM simulations not accounting for fossil-fuel burning) by Pongratz et al. (2009) and E2 (ESM simulations accounting for fossil-fuel burning) by Strassmann et al. (2008) and Arora et al. (2010). Difference of the methods (as can be derived from Sect. 3 or Fig. 2) yields the exact flux components. The land use feedback is on the order of 25 % for Strassmann et al. (2008) and of 50 % for Pongratz et al. (2009) and Arora et al. (2010) of the net land use flux excluding the land use feedback.