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Large differences in land use emission quantifications implied by definition discrepancies

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Abstract

The quantification of CO_2 emissions from anthropogenic land use and land use change (*e*LUC) is essential to understand the drivers of the atmospheric CO_2 increase and to inform climate change mitigation policy. Reported values in synthesis reports are commonly derived from different approaches (observation-driven bookkeeping and process-modelling) but recent work has emphasized that inconsistencies between methods may imply substantial differences in *e*LUC estimates. However, a consistent quantification is lacking and no concise modelling protocol for the separation of primary and secondary components of *e*LUC has been established. Here, we review the conceptual differences of *e*LUC quantification methods and apply an Earth System Model to demonstrate that what is claimed to represent total *e*LUC differs by up to $\sim 20\,\%$ when quantified from ESM vs. offline vegetation models. Under a future business-as-usual scenario, differences tend to increase further due to slowing land conversion rates and an increasing impact of altered environmental conditions on land–atmosphere fluxes. We establish how coupled Earth System Models may be applied to separate component fluxes of *e*LUC arising from the replacement of potential C sinks/sources and the land use feedback and show that secondary fluxes derived from offline vegetation models are conceptually and quantitatively not identical to either, nor their sum. Therefore, we argue that synthesis studies and global carbon budget accountings should resort to the "least common denominator" of different methods, following the bookkeeping approach where only primary land use emissions are quantified under the assumption of constant environmental boundary conditions.

1 Introduction

Anthropogenic emissions of CO_2 are the main driver for observed climate change (T. F. Stocker et al., 2013) and primarily result from the combustion of fossil fuels and anthropogenic land use and land use change (LUC) (Le Quéré et al., 2014). Conceptually, fossil fuel emissions can be regarded as an external forcing acting upon the carbon cycle–climate system. In contrast, LUC additionally modifies the response of terrestrial ecosystems to elevated CO_2 and changes in climate (Gitz and Ciais, 2003; Strassmann et al., 2008) and thereby affects the carbon cycle–climate feedback (Joos et al., 2001; Friedlingstein et al., 2006; B. D. Stocker et al., 2013). This leaves room for interpretations as to where the system boundaries of land use change emissions (eLUC) are to be drawn and how exactly they are to be defined – an issue that has led to confusion and inconsistencies in the published literature.

The definition of eLUC is highly relevant for the accounting of the global carbon budget (Ciais et al., 2013). Top-down derived land–atmosphere C fluxes that are not explained by bottom-up estimates of eLUC are commonly ascribed to a *residual terrestrial C sink*. Differences in the definition of eLUC thus directly translate into uncertainties in the terrestrial C sink, a major source of uncertainty in climate projections (Jones et al., 2013).

Common to almost all approaches is that eLUC is calculated as the difference in the global total land-to-atmosphere flux (F) between a realistic world where LUC is occurring (subscript LUC) and a hypothetical world, where no LUC is occurring (subscript 0):

$$eLUC = F_{LUC} - F_0. \tag{1}$$

However, the definition or model setup, under which F_{LUC} and F_0 are calculated, is relevant as it implies the inclusion of secondary fluxes. As pointed out by Pongratz et al. (2014) (henceforth termed PG14), numerous different definitions have been used in the published literature, implying a bewildering array of different combinations of component fluxes that are counted towards eLUC in the different studies. PG14 conclude that the choice of definition to follow is a “political rather than a scientific one”. Yet, there are fundamental science questions: which definition is most appropriate or inconsistent in a given context? And how large are the differences between different approaches for historical land use change and under a future scenario? We will demonstrate that such definition differences imply inconsistencies of estimated land use emissions on the order of 20 % on a global scale and may increase to 30 % under a future business-as-usual scenario. This is directly relevant for territorial C balance accountings and national greenhouse gas balances under the Kyoto Protocol and thus inherently carries a political relevance.

Early quantifications of the CO_2 emissions due to LUC were based on a bookkeeping approach for C inventory changes (Houghton et al., 1983). This implies the assumption of constant environmental boundary conditions (atmospheric CO_2, climate). This method, henceforth termed D1 following the classification by PG14 has the advantage that observations of C density in natural and agricultural vegetation can be used to calculate *e*LUC. Boundary conditions thus implicitly represent present-day conditions (time of observation of vegetation C density). (Updated) bookkeeping estimates of *e*LUC (Houghton, 1999; Houghton et al., 2012) still represent the benchmark against which process-based models with prognostic vegetation C density are often compared (Le Quéré et al., 2014).

Prognostically simulating vegetation C density instead of prescribing it has the advantage that secondary effects under LUC-induced environmental change can be simulated. The first such study using a set of process-based vegetation models with prescribed, transiently varying climate and CO_2 from historical data was presented by McGuire et al. (2001). In such a setup, termed D3 following the classification of PG14, *e*LUC implicitly includes secondary effects arising from increasing atmospheric CO_2, changing climate, and the replacement of natural vegetation.

For a comprehensive separation of different flux components in their dynamic vegetation model, Strassmann et al. (2008), henceforth thermed SM08, applied a reduced-form coupled Earth System Model (ESM) where climate and atmospheric CO_2 interactively evolve in response to anthropogenic land use change and fossil fuel emissions. Their "total land use flux" derived from the coupled setup corresponds to method E2 in PG14. Using a set of different model setups, they presented a scheme to separate total *e*LUC into a primary flux *e*LUC_0, analogous to the bookkeeping flux (D1 in PG14), and two indirect fluxes of a different nature. These are *replaced sources and sinks*, *e*RSS, arising from the replacement of natural vegetation by agricultural land which generally has a lower sink capacity for anthropogenic CO_2, and (ii) a *land use feedback flux*, *e*LFB, caused by elevated CO_2 and changes in climate as a result of LUC. They provide a quantitative comparison between *e*LUC derived from coupled vs. offline model setups.

Meanwhile, a number of studies have presented quantifications of *e*LUC and an almost equal number of notations and model setups have been applied. Pongratz et al. (2014) (PG14) provide a comprehensive analysis of these studies and show that their different definitions applied and their different methodological approaches taken (land use statistics, satellite data, vegetation modelling, Earth system modelling) imply different system boundaries as to what is counted towards *e*LUC. Following SM08, PG14 separate total *e*LUC into flux components corresponding to *e*RSS (referred to as “loss of additional sink capacity”) and *e*LFB and note the notorious key differences of any *e*LUC quantification done with coupled ESMs (E2 method) vs. offline vegetation models (D3 method). They state that the discrepancy between methods stems from the inclusion of the land use feedback on actual natural land. A related aspect has been mentioned in SM08 who noted that modelling studies with prescribed CO_2 concentrations neglect the effect of LUC on CO_2 and climate, and that the net uptake flux on natural land is simulated for prescribed (observed) CO_2 instead of the hypothetical CO_2 concentration corresponding to a scenario without LUC. This calls for a concise definition and quantification of these systematic differences.

The discrepancy between conventional ESM and offline vegetation model quantications of *e*LUC is highly relevant as results from offline vegetation model quantifications following the D3 method feature prominently in model intercomparison studies (Cramer et al., 2001; Sitch et al., 2008), the Global Carbon Project (Le Quéré et al., 2014) and the IPCC (Ciais et al., 2013). While PG14 provide some quantitative indication for the magnitude of these differences, a consistent and comprehensive quantification of the differences in *e*LUC arising from different methodological approaches for the past and the future is lacking. Gasser and Ciais (2013) (GC13) partly fill this gap and provide quantitative estimates for historical *e*LUC following different definitions. However, their analysis is limited to offline vegetation model quantifications (D1 and D3) and thus cannot address the aforementioned discrepancies between offline (D3) and ESM (E2) methods.

Here, we aim at a consistent quantifications of the discrepancy between *e*LUC derived from offline vegetation models and coupled ESMs. We concisely define and quantify two component fluxes that are inherently included in *e*LUC following the E2 method but cannot be separated by offline vegetation models. We discuss how *e*LUC quantifications may most appropriately be defined for global carbon budget accountings and how to resolve definition discrepancies in studies that rely on multiple methodological approaches. In such cases, we propose to resort to the “least common denominator”, following the bookkeeping approach (method D1 in PG14), where LUC emissions are defined without accounting for any indirect effects on terrestrial C storage caused by transient changes in CO_2 or climate.

2 Formalism

2.1 Flux component definition

ST08 and PG14 provide a discussion of different definitions total *e*LUC and its component fluxes. Here, we synthesise this to a formalism that allows us to establish the conceptual discrepancy between quantifications of *e*LUC provided by the offline DGVM setups (D3 method), coupled ESM model setups (E2 method), and the book-keeping aproach used in empirical studies (D1 method).

In spite of the variety of terminologies presented in the published literature, studies generally agree that the total CO_2 emissions from land use change, *e*LUC, can be split into primary emissions, $e\mathrm{LUC}_0$, which captures the direct effects of land conversion, and secondary effects due to environmental changes (CO_2, climate). Following SM08, the latter can be further separated into a flux from replaced potential C sources and sinks, *e*RSS, and a land use feedback flux, *e*LFB.

$$e\text{LUC} = e\text{LUC}_0 + e\text{RSS} + e\text{LFB} \tag{2}$$

The two secondary flux components are of a distinctive nature. *e*RSS arises due environmental changes (e.g. CO_2, climate, N-deposition, ozone, air pollution, etc.) which are not caused by LUC, whereas *e*LFB is due to environmental changes driven by LUC. eRSS can be defined as the difference in sources/sinks between natural land ($\Delta f_{\text{nat}}^{\text{FF}}$) and agricultural land ($\Delta f_{\text{agr}}^{\text{FF}}$) and scales with the area of land converted from natural to agricultural ΔA:

$$e\text{RSS} = \Delta A \left(\Delta f_{\text{agr}}^{\text{FF}} - \Delta f_{\text{nat}}^{\text{FF}} \right). \tag{3}$$

Following the formalism by GC13, Δf refers to the change in the area-specific land–atmosphere flux since a (pre-industrial) reference state, caused only by (non-LUC-related) changes in environmental conditions, excluding direct effects of land conversion. Here, the driver of changes in environmental conditions is labelled by the superscript. “FF” refers to “fossil fuel” emissions but also includes other relevant environmental changes that are not linked to LUC.

The LUC-feedback flux *e*LFB can be written as the flux arising as a consequence of LUC-induced environmental changes (e.g. CO_2, climate change). *e*LFB occurs on natural and agricultural land, with different sink strength.

$$e\text{LFB} = (A_0 - \Delta A)\Delta f_{\text{nat}}^{\text{LUC}} + \Delta A \Delta f_{\text{agr}}^{\text{LUC}} \tag{4}$$

A_0 is the area of natural vegetation at the reference point in time, commonly the pre-industrial state. Hence, $(A_0 - \Delta A)$ is the remaining area of natural vegetation after land conversion. *e*RSS arises from secondary effects of fossil fuel emissions (and N depostion, etc.), whereas *e*LFB is driven only by LUC. This is reflected by the fact that only superscript “LUC” occurs in the definition of *e*LFB, whereas only “FF” occurs in the definition of *e*RSS.

For clarity, we have dropped the temporal and spatial dimensions of fluxes and areas and have reduced the formalism to a distinction only between natural and agricultural land; the latter being representative for croplands and pastures. This is a simplification for a formal illustration and we note that the simulations presented in Sect. 4 account for the full complexity of fluxes across space, different agricultural and natural vegetation types, and time.

2.2 Methods to quantify land use emissions

Following the bookkeeping approach (D1 method), *e*LUC is derived assuming constant environmental boundary conditions.

$$e\mathrm{LUC}_{\mathrm{D1}} = F^0_{\mathrm{LUC}} - F^0_0 \tag{5}$$

Hence, $e\mathrm{LUC}_{\mathrm{D1}}$ does not include any secondary effects of LUC and therefore equivalent to primary emissions $e\mathrm{LUC}_0$ referred to above. $e\mathrm{LUC}_{\mathrm{D1}}$ captures CO_2 emissions occurring during deforestation and C uptake during regrowth, as well as delayed (legacy) emissions from wood product decay and the gradual re-adjustment of C stocks to altered input levels and turnover times. Depending on the model, $e\mathrm{LUC}_{\mathrm{D1}}$ may also include effects of shifting cultivation (cycle of cutting forest for agriculture, then abandoning), wood harvest and abandonment of agriculture. $e\mathrm{LUC}_{\mathrm{D1}}$ is fully determined by C inventories in natural and agricultural land and the response time scales of C pools after conversion. This data may be provided from observational data of C inventories in natural and agricultural land (Houghton et al., 2012; Gasser and Ciais, 2013), or may be prognostically simulated by vegetation models. In the former case, environmental boundary conditions implicitly represent conditions under which the observations are taken, i.e. climate, CO_2, and N-deposition levels of recent decades. In the latter case, constant environmental boundary conditions may be chosen for to represent present-day (PD) conditions for best comparability with observational data, or a preindustrial

(PI) reference state for practicality reasons (start from common model spinup, guaranteeing continuity between model development cycles).

F_0^0 is the land–atmosphere flux in the reference state, which may either represent the land use distribution the beginning of the transient simulation (commonly preindustrial) or zero anthropogenic land use. This choice affects secondary fluxes but, after model spinup and equilibration of C pools, F_0^0 is zero in either case except for short-term net land–atmosphere CO_2 fluxes occurring due to stationary inter-annual climate variability, which is commonly included in model-based reference simulations. Subtracting F_0^0 guarantees that these fluxes are not counted towards *e*LUC, while any LUC-related modification of the short term variability is included.

*e*LUC calculated by method E2 can be shown to be equal to the sum of primary emissions ($e\text{LUC}_0$), *e*RSS, and *e*LFB (see Appendix A).

$$e\text{LUC}_{\text{E2}} = F_{\text{LUC}}^{\text{FF+LUC}} - F_0^{\text{FF}} = e\text{LUC}_0 + e\text{RSS} + e\text{LFB} \tag{6}$$

This method is commonly followed by emission-driven Earth System Models. In contrast, vegetation-only models rely on a setup where climate and atmospheric CO_2 concentrations are prescribed and the vegetation model is run without any coupling between land use change-related emissions and environmental conditions. This is referred to as an “offline” setup and is commonly applied to stand-alone Dynamic Global Vegetation Models (DGVM) and terrestrial ecosystem models (TEM). These models account for the transient effects of changing environmental conditions on C stocks and fluxes in the terrestrial biosphere. The crucial point is that the same environmental conditions are prescribed in simulations representing the world with and the world without LUC. Therefore, what is usually referred to as “total land use change emissions”, is calculated as

$$e\text{LUC}_{\text{D3}} = F_{\text{LUC}}^{\text{FF+LUC}} - F_0^{\text{FF+LUC}} \neq e\text{LUC}_0 + e\text{RSS} + e\text{LFB}. \tag{7}$$

This corresponds to the setup used in GC13. Their “CCN” perturbation is analogous to what the superscript “FF + LUC” represents. It denotes that environmental conditions are forced by the combination of fossil fuel, LUC, and N-deposition effects.

While primary emissions $e\mathrm{LUC}_0$ can be consistently derived from offline DGVMs by simply holding environmental conditions constant, the secondary fluxes derived from such studies are neither equal to *e*RSS, nor *e*LFB as defined above, nor the sum of the two.

By expanding terms (see also Appendix) and assuming that environmental effects from LUC and FF combine linearly ($\Delta f^{\mathrm{FF+LUC}} = (\Delta f^{\mathrm{FF}} + \Delta f^{\mathrm{LUC}})$), it can be shown that the difference between *e*LUC quantifications from the E2 and the D3 methods is

$$e\mathrm{LUC}_{\mathrm{E2}} - e\mathrm{LUC}_{\mathrm{D3}} = \Delta f^{\mathrm{LUC}}_{\mathrm{nat}} A_0. \tag{8}$$

The discrepancy can thus be interpreted as the land use feedback flux occurring on natural land. The area A_0 in Eq. (8) indicates that the difference is in the additional flux occurring over natural land as distributed at the (preindustrial) reference state. Unlike suggested by PG14, the formal treatment presented here reveals that the difference is related to the land use feedback for the reference distribution of natural land and not the actual distribution.

3 Methods

In order to quantify the individual flux components and the discrepancy between the different quantifications of *e*LUC outlined in Sect. 2.2, we apply the emission-driven, coupled Bern3D-LPX Earth System Model of Intermediate Complexity as described in B. D. Stocker et al. (2013) and the offline DGVM model setup where the LPX DGVM is driven by prescribed CO_2 concentrations and climate as described in Stocker et al. (2014). Model is spun up at constant boundary conditions representing year 1700 (CO_2 insolation, land use distribution, recycled 1901–1931 CRU TS 2.1 climate, Mitchell and Jones, 2005). For the historical period and the future “business-as-usual” scenario (RCP8.5), we apply CMIP5 standard inputs (Taylor et al., 2012). Land use change is simulated following the Generated Transitions Method described in Stocker et al. (2014). This accounts for effects of shifting cultivation-type agriculture and wood

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

harvesting. In contrast to the previous studies by B. D. Stocker et al. (2013) and Stocker et al. (2014), we apply the model at a coarser spatial resolution (2.5° × 3.75°, instead of 1° × 1°). Cumulative CO_2 emissions from land use change are calculated as the difference in terrestrial C storage from the simulation with and without LUC using Eq. (5) for the bookkeeping, Eq. (6) for the coupled, and Eq. (7) for the offline setup. In the coupled ESM setup, atmospheric CO_2 concentrations and climate evolve interactively in response to the respective forcings. In the offline model setup following the D3 method, we directly prescribe climate fields and CO_2 concentrations to the vegetation component (LPX model). In this case, climate and CO_2 are taken from the output of the coupled ESM simulation, driven by FF and LUC ($F_{\mathrm{LUC}}^{\mathrm{FF+LUC}}$), and is prescribed to both offline simulations, with and without LUC. This corresponds to the common setup chosen for D3-type simulations, but instead of prescribing CO_2 and climate from observations (which is the result of FF and LUC as well), we prescribe it from the coupled model output here in order to exclude differences in forcings between the coupled (E2) and offline (D3) setups.

The model is run in a set of simulations that allows us to disentangle individual flux components. The setups are described in Table 2. As outlined in Appendix A, the replaced sinks/sources flux component can be derived as

$$e\mathrm{RSS} = F_{\mathrm{LUC}}^{\mathrm{FF+LUC}} - F_{\mathrm{LUC}}^{\mathrm{LUC}} - F_{0}^{\mathrm{FF}}. \tag{9}$$

This also follows intuition. It represents the flux induced by environmental conditions caused by fossil fuel emissions in a world with LUC ($F_{\mathrm{LUC}}^{\mathrm{FF+LUC}} - F_{\mathrm{LUC}}^{\mathrm{LUC}}$) and a world without LUC ($F_0^{\mathrm{FF}} - F_0^{0}$). The last term is zero as neither LUC nor environmental conditions are acting. According to the derivation outlined in Appendix A, the land use feedback flux can be derived as

$$e\mathrm{LFB} = F_{\mathrm{LUC}}^{\mathrm{LUC}} - F_{\mathrm{LUC}}^{0}. \tag{10}$$

Also this can be understood intuitively. *e*LFB represents the total land–atmosphere flux in a world with LUC (but without fossil fuel emissions), $F_{\mathrm{LUC}}^{\mathrm{LUC}}$, minus the direct effects of LUC, F_{LUC}^{0}. In other words, it represents the secondary flux caused by LUC alone.

4 Results

Figure 1 illustrates annual emissions from LUC as quantified from the different approaches. During the historical period, the offline quantification (D3) suggests ∼ 23 % higher emissions than the coupled setup (E2). Cumulative emissions amount to 164 GtC with D3 and 133 GtC with E2 (AD 1850–2005, see Table 3). The bookkeeping method yields cumulative historical fluxes of 152 and 177 GtC under preindustrial and present-day environmental conditions. Primary emissions under preindustrial and present-day background exhibit largely identical temporal trends but differ in absolute magnitude. 16 % higher emissions under present-day conditions are due to generally larger C density in natural (non-cropland and non-pasture) vegetation and soils simulated under elevated CO_2 (364 ppm) and the warmer climate (corresponding to years 1982–2012 AD in the CRU TS 3.21 dataset; Mitchell and Jones, 2005). Differences in constant environmental conditions thus have qualitatively the same effect as uncertainty in C stocks on natural and agricultural land. I.e. $e\mathrm{LUC}_{\mathrm{D1}}$ scales linearly with simulated differences in natural and agricultural land and the trends in $e\mathrm{LUC}_{\mathrm{D1}}$ derived under preindustrial and present-day environmental conditions are identical, but markedly different from trends in $e\mathrm{LUC}_{\mathrm{D3}}$ and $e\mathrm{LUC}_{\mathrm{E2}}$.

Cumulative historical emissions following the D1 method under preindustrial (present-day) conditions are 14 % (33 %) higher than suggested by the E2 method. These differences are substantial and are on the order of the model range as presented in intercomparison studies (Sitch et al., 2008; Le Quéré et al., 2014) or on the order of effects of accounting for wood harvest and shifting cultivation (Stocker et al., 2014). For the future period (AD 2006–2099) following RCP8.5, cumulative emissions (2004–2099) for the D3 and E2 method are on the same order (192 and 188 GtC), but considerably higher than for the D1 method (133 and 153 Gt C under preindustrial and present-day conditions). Differences with respect to the relative increase from present-day emission levels (average over 1995–2004) to projected levels in the last decade of the 21st century are even larger. Following the D1 method, the increase is 22 % (34 %) when holding conditions constant at preindustrial (present-day) levels. Due to different inclusion of secondary fluxes, the projected increase following the D3 method is 67 and 121 % following E2.

Figure 2 illustrates the different flux components and reveals the underpinnings of the discrepant levels and trends of emissions when quantified with different methods. During the historical period (AD 1850–2005), *e*RSS contributes 6 % and *e*LFB 21 % to cumulative total emissions with opposing signs. At present-day, *e*RSS and *e*LFB are of similar magnitude, hence total ($e\mathrm{LUC}_{\mathrm{E2}}$) and primary emissions are at approximately the same level. In RCP8.5, atmospheric CO_2 and temperatures continue to grow, while land conversion rates and primary emissions are stabilised. As a result *e*LFB is stabilised, while *e*RSS continues to increase and contributes ~ 50 % to total emissions in 2100. This explains the different trends in total (based on E2 and D3) vs. primary emissions.

The difference between $e\mathrm{LUC}_{\mathrm{E2}}$ and $e\mathrm{LUC}_{\mathrm{D3}}$ is of approximately the same magnitude as *e*LFB, although slightly smaller, and exhibits a trend that is closely matched by *e*LFB until roughly AD 2030 (see dashed line in Fig. 2). This is expected as the difference is derived in Eq. (8) to be equal to ($\Delta f_{\mathrm{nat}}^{\mathrm{LUC}} A_0$), thus resembles the definition of *e*LFB (see Eq. 4). The deviation between the difference and *e*LFB towards the end of the 21st century is most likely attributable to non-linearities arising from interactions of LUC and FF-induced carbon cycle and climate change.

5 Discussion

To quantify the differences in *e*LUC quantifications by coupled ESM (E2 method), offline DGVMs (D3 method), and the bookkeeping method (D1 method), we applied a model setup where differences stemming from driving data are removed and discrepancies in total *e*LUC different methods are merely due to the experimental design. Our results suggest that this discrepancy is substantial for the historical period and implies strikingly different trends in *e*LUC for a future business-as-usual scenario. These differences stem from the implicit inclusion of secondary flux components. As we have pointed out, secondary fluxes derived from offline vegetation model setups are conceptually not identical to what is commonly referred to as the replaced sinks/sources flux or the land use feedback, nor the sum of the two.

Land use change is a substantial driver of the observed CO_2 increase and has contributed about 25 % to total anthropogenic CO_2 emissions for the period 1870–2014 (Le Quéré et al., 2014). Current (2014–2013) emission levels are $0.9 \pm 0.5\,\mathrm{Gt\,C\,yr^{-1}}$ (Le Quéré et al., 2014). Reducing emissions from deforestation and forest degradation is now an important part of international climate change mitigation efforts under the United Nation Framework Convention on Climate Change. Periodically issued synthesis reports by the IPCC (Ciais et al., 2013), annually updated CO_2 flux quantifications by the Global Carbon Project (Le Quéré et al., 2013, 2014), as well as multi-model intercomparison projects (CMIP5, 2009; CMIP6, 2014; TRENDY, 2015) provide valuable and highly cited information on LUC CO_2 emissions for policy makers and the public. However, reported values are commonly derived from different approaches (observation-driven bookkeeping, models, anthropogenic fires) and their uncertainty ranges partly stem from implicit methodological differences. The lack of a standard methodological protocol for LUC emission estimates and the inclusion of secondary fluxes also obscures the scientific interpretation of model results and their comparison with observational data. Below, we outline two different perspectives on what “emissions from LUC” may represent and discuss their methodological implications.

5.1 Carbon budget accounting

On local to regional scales, the land carbon budget on natural (or weakly managed) land is derived from forest inventory data (Pan et al., 2011), net ecosystem exchange estimates from eddy flux towers (Valentini et al., 2000; Friend et al., 2007), growth assessments from tree ring data, satellite data (Baccini et al., 2012; Harris et al., 2012), and atmospheric inversions of the CO_2 distribution using transport models (Gatti et al., 2014). It is in general not possible to disentangle to which extent such observation-based estimates of the local net air–land carbon flux are driven by environmental change induced by fossil fuel combustion or by remote LUC. Fossil fuel emission estimates do not, by definition, include any such secondary effects. Only *e*LUC estimates following the D1 method, which exclude secondary fluxes, are thus conceptually consistent with reported values for fossil fuel emissions and up-scaled local-to-regional scale observation-based information

This is relevant for continental-to-global scale carbon budget accountings, where CO_2 exchange fluxes between the major reservoirs (ocean, atmosphere, land, fossil fuel reserves) are quantified. By definition, estimates for *e*LUC directly translate into the magnitude of the implied residual terrestrial C sink (see Fig. 3). Inclusion of secondary LUC fluxes thus determines where the system boundaries between *e*LUC and the residual terrestrial sink are drawn. Ascribing replaced sinks/sources (*e*RSS) to *e*LUC implies that the residual terrestrial sink represents a hypothetical state before land conversion. The inclusion of secondary LUC fluxes (*e*RSS and/or *e*LFB) in *e*LUC and in turn in estimates of the implied residual sink is misleading when comparing to observational data of other C budget terms (fossil fuel emissions, ocean C uptake, atmospheric growth rate) and observation-based land–atmosphere fluxes.

Processes determining primary emissions are directly observable (i.e. C stocks in vegetation and soils, C loss during deforestation, fate of product pools, soil carbon evolution after conversion). Such information may be used to benchmark simulated $e\mathrm{LUC}_{\mathrm{D1}}$. Our results also demonstrated the differences in $e\mathrm{LUC}_{\mathrm{D1}}$ implied by prescribing preindustrial vs. present-day environmental conditions (see Fig. 1). It may be argued that prescribing present-day conditions allows best comparability with bookkeeping estimates where observational data of C density in natural and agricultural land is used, that inherently represents conditions of the recent past. However, we note that total terrestrial C storage is 1775, 1838, 1982 Gt C in our simulations for $F_{\mathrm{LUC}}^{\text{0-PI}}$, $F_{\mathrm{LUC}}^{\mathrm{FF+LUC}}$, and $F_{\mathrm{LUC}}^{\text{0-PD}}$ (mean over years 2000–2004; superscript "0-PI" ["0-PD"] refers to constant preindustrial [present-day] environmental conditions). I.e. the case where C stocks are responding to transient changes in CO_2 and climate ($F_{\mathrm{LUC}}^{\mathrm{FF+LUC}}$ – the closest analogue to what observational data represent) is farther from its equilibrium to be attained under present-day conditions than its equilibrium under preindustrial conditions. In other words, quantifying $e\mathrm{LUC}_{\mathrm{D1}}$ under preindustrial conditions is a viable and pragmatic solution.

Adopting the D1 method for benchmarking, model-intercomparison studies and syntheses based on multiple methods also has the critical practical advantage of being the "least common denominator" that can be followed using empirically-based bookkeeping methods, offline vegetation models, as well as Earth System Models. Quantification of $e\mathrm{LUC}_{\mathrm{D1}}$ simply requires a preindustrial control simulation (no forcings, constant environmental conditions) which is already part of the CMIP6 DECK simulations (CMIP6, 2014), and one additional run with transient LUC while environmental conditions are held constant at preindustrial levels (see Appendix B). This could be achieved by Earth System Models without computationally demanding coupled model setups involving interactive atmosphere and ocean, but using prescribed preindustrial climate and CO_2 and their land models in a stand-alone mode instead. Serving as an "entry card" for future model intercomparisons, this would guarantee continuity and comparability between model development cycles and periodically repeated syntheses. In summary, we recommend not to rely on results from method D3 or E2 in the context of the global (or regionalized) carbon budget, but to apply method D1 (under preindustrial conditions).

5.2 LUC in the Earth system

LUC effects on climate and the Earth system are not fully captured by their CO_2 emissions. Vegetation cover change affects the local surface energy and water balances. Deforestation by purposely set fires is associated with emissions of a range of radiatively active compounds (e.g. CH_4, CO, NO_x) and the application of mineral fertiliser and manure on agricultural land increases soil N_2O emissions and sets in motion a cascade of detrimental environmental effects (Galloway et al., 2003), many of which directly or indirectly affect climate (Erisman et al., 2011).

Apart from these direct effects where LUC can be regarded as a forcing acting upon the Earth system, LUC also modifies the land response to external forcings. E.g. the replacement of woody vegetation with crops reduces the CO_2-driven fertilisation sink. Thus, LUC affects the strength of the land–climate feedback (B. D. Stocker et al., 2013). Furthermore, primary LUC emissions induce a secondary C uptake flux as a feedback to elevated CO_2 concentrations caused by primary emissions. These feedback effects are captured by the LUC flux components *e*RSS and *e*LFB. Coupled Earth System Models featuring an active carbon cycle, require a preindustrial control simulation and a fossil carbon emission-driven simulation over the industrial period where transient LUC and other climate and environmental forcings are activated to quantify the sum of primary and secondary land use carbon emissions (method E2). Such an emission-driven, land use-enabled simulation may become part of the CMIP6 protocol. Additional simulations are required to quantify individual components separately (see Appendix).

The results presented here demonstrate the importance of secondary fluxes under slowing land conversion rates and continuously increasing CO_2. In RCP 8.5, *e*RSS is set to increase to ±1 $\mathrm{Gt\,C\,yr^{-1}}$ and make up around half of $e\mathrm{LUC}_{\mathrm{E2}}$ by the end of the 21st century. Hence, in order to capture the overall effect of LUC on the terrestrial C cycle feedback, these must be accounted for. However, we recommend to account for the effect of secondary LUC-related fluxes in global carbon budget assessments as an anthropogenic modification of the terrestrial C sink. We argue that offline-vegetation model setups are not capable of separating *e*RSS and *e*LFB as defined here.

6 Conclusions

Estimates of CO_2 emissions from land use are essential to quantify the global carbon budget and inform climate change mitigation policy. However, inconsistent methodologies have been applied in multi-model and multi-method syntheses. In order to guarantee comparability and continuity, we recommend that modelling studies provide estimates derived under constant, preindustrial boundary conditions (D1 method). This method can be followed by offline vegetation models and Earth System Models, and is best comparable to observation-based estimates following the bookkeeping approach. This implies that the residual terrestrial sink derived from the global C budget includes the sink flux stimulated by environmental changes in response to LUC and reflects effects of replacement of potential C sinks due to land conversion. We have suggested how coupled, emission-driven Earth System Models may be applied to separate component fluxes defined here. Such analyses are essential to capture the full impact of LUC on climate and CO_2.

Appendix A: Flux component decomposition

It is shown that $e\mathrm{LUC}_{\mathrm{E2}}$ is equal to the sum of primary emissions, the replaced sinks/sources flux, and the land use feedback flux. In a coupled, emission-driven ESM model setup, total LUC emissions are derived as the difference

$$e\mathrm{LUC}_{\mathrm{E2}} = F_{\mathrm{LUC}}^{\mathrm{FF+LUC}} - F_0^{\mathrm{FF}}. \tag{A1}$$

Follwoing GC13, the total flux in the FF + LUC world can be written as the sum of fluxes ocurring on undisturbed land (natural vegetation) and disturbed land (agricultural land).

$$F_{\mathrm{LUC}}^{\mathrm{FF+LUC}} = \underbrace{\Delta f_{\mathrm{nat}}^{\mathrm{FF+LUC}}(A_0 - \Delta A)}_{\text{undisturbed lands}} + \underbrace{\left(f^0 + \Delta f_{\mathrm{agr}}^{\mathrm{FF+LUC}}\right)\Delta A}_{\text{disturbed lands}} \tag{A2}$$

ΔA is the total area that has been converted from natural to agricultural up to the point in time of interest. f_{nat} is the area-specific flux occurring on natural land and $\Delta f_{\text{nat}}^{\text{FF+LUC}}$ is its change due to environmental impacts caused by the combination of FF, including N deposition, and LUC. In GC13, $\delta \boldsymbol{A}^{+}$ is a vector representing land area cohorts that have transitioned from natural to agricultural land at a given time and $\boldsymbol{f}^{0}$ is a vector containing the net fluxes occurring in these cohorts (after their conversion) under pre-industrial conditions, and $\Delta \boldsymbol{f}^{\text{FF+LUC}}$ is the perturbation of these fluxes as a result of CO_2 and climate changes since pre-industrial. Here, we drop the vector notation for individual age cohorts after conversion and lump these into a scalar representing non-natural (agricultural) land of varying age.

By assuming that environmental effects due to FF and LUC combine linearly, thus $\Delta f^{\text{FF+LUC}} = \Delta f^{\text{FF}} + \Delta f^{\text{LUC}}$, we can expand Eq. (A2) and re-arrange terms.

$$
\begin{aligned}
F_{\text{LUC}}^{\text{FF+LUC}} = & A_0 \Delta f_{\text{nat}}^{\text{FF}} && (e\text{PS}) && \text{(A3)} \\
& + \Delta A \left(\Delta f_{\text{agr}}^{\text{FF}} - \Delta f_{\text{nat}}^{\text{FF}} \right) && (e\text{RSS}) && \text{(A4)} \\
& + (A_0 - \Delta A) \Delta f_{\text{nat}}^{\text{LUC}} + \Delta f_{\text{agr}}^{\text{LUC}} \Delta A && (e\text{LFB}) && \text{(A5)} \\
& + f^{0} \Delta A && (e\text{LUC}_0) && \text{(A6)}
\end{aligned}
$$

The first term is the *potential sink*, ePS, the flux due to environmental effects from FF, that would occur in a world without LUC. This corresponds to F_0^{FF}. Hence,

$$
e\text{LUC}_{\text{E2}} = e\text{LUC}_0 + e\text{RSS} + e\text{LFB}. \qquad \text{(A7)}
$$

Appendix B: Flux expansion for model setups

The flux components $e\text{LUC}_0, e\text{RSS}, e\text{LFB}$, and can be separated using four different model setups and Eqs. (9) and (10). This section provides an intuitive interpretation for each setup and its formal flux decomposition.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

1. A run where fossil fuel emissions are prescribed but without LUC:

   $$F_0^{\mathrm{FF}} = A_0\,\Delta f_{\mathrm{nat}}^{\mathrm{FF}}.$$

2. A run with LUC but where the land does not "see" any changes in climate and $\mathrm{CO_2}$ (no fossil fuel emissions):

   $$F_{\mathrm{LUC}}^{0} = \Delta A\, f^{0}.$$

3. A run with prescribed fossil fuel emissions and LUC:

   $$F_{\mathrm{LUC}}^{\mathrm{FF+LUC}} = \Delta A\, f^{0} + (A_0 - \Delta A)\Delta f_{\mathrm{nat}}^{\mathrm{FF+LUC}} + \Delta A \Delta f_{\mathrm{agr}}^{\mathrm{FF+LUC}}.$$

4. A run with LUC where the land "sees" resulting changes in climate and $\mathrm{CO_2}$ (no fossil fuel emissions):

   $$F_{\mathrm{LUC}}^{\mathrm{LUC}} = \Delta A\, f^{0} + (A_0 - \Delta A^{-})\,\Delta f_{\mathrm{nat}}^{\mathrm{LUC}} + \Delta A \Delta f_{\mathrm{agr}}^{\mathrm{LUC}}.$$

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Table 1. Model setups. F is the simulated total net flux of carbon from the terrestrial biosphere to the atmosphere. Fluxes where climate and CO_2 evolves interactively are computed with the coupled ESM Bern3D-LPX. In this case, simulated temperature changes relative to preindustrial are added to a 31 year baseline climate representing years 1901–1931 in the CRU TS 3.21 dataset. Fluxes with prescribed or constant climate and CO_2 are computed with the stand-alone vegetation model LPX. In the case of $F_0^{\mathrm{FF+LUC}}$, monthly climate fields and atmospheric CO_2 is prescribed from the output of $F_{\mathrm{LUC}}^{\mathrm{FF+LUC}}$. Simulations with superscript "0" are forced by constant environmental (climate and CO_2) conditions. This could either be at preindustrial or present-day levels. LUC (i.e. a time series of maps for cropland, pasture, and built-up area fractions) is prescribed for from the LUH dataset by Hurtt et al. (2006). N-deposition ("N-dep.") is prescribed from Lamarque et al. (2011).

Flux	Climate	CO_2	LUC	FF	N-dep.
$F_{\mathrm{LUC}}^{\mathrm{FF+LUC}}$	interactive	interactive	on	on	on
$F_{\mathrm{LUC}}^{\mathrm{LUC}}$	interactive	interactive	on	off	const.
F_0^{FF}	interactive	interactive	const.	on	on
$F_0^{\mathrm{FF+LUC}}$	from $F_{\mathrm{LUC}}^{\mathrm{FF+LUC}}$	from $F_{\mathrm{LUC}}^{\mathrm{FF+LUC}}$	const.	–	on
F_{LUC}^{0}	constant	constant	on	–	const.
F_0^{0}	constant	constant	const.	–	const.

Table 2. Flux definitions. *e*LUC are CO_2 emissions due to anthropogenic land use change as quantified by the method given in the subscript. *e*RSS is the component flux of *e*LUC arising from replaced potential C sinks/sources (see Eq. 9). *e*LFB is the land use feedback flux (see Eq. 10). F is the simulated total net flux of carbon from the terrestrial biosphere to the atmosphere evaluated from a simulation with/without LUC (subscript) and environmental conditions affected by fossil fuel emissions (including N deposition) and/or LUC (superscript).

Flux	Formula	Reference
$e\mathrm{LUC}_{\mathrm{D1}}$	$F_{\mathrm{LUC}}^{0} - F_{0}^{0}$	Eq. (5)
$e\mathrm{LUC}_{\mathrm{D3}}$	$F_{\mathrm{LUC}}^{\mathrm{FF+LUC}} - F_{0}^{\mathrm{FF+LUC}}$	Eq. (7)
$e\mathrm{LUC}_{\mathrm{E2}}$	$F_{\mathrm{LUC}}^{\mathrm{FF+LUC}} - F_{0}^{\mathrm{FF}}$	Eq. (6)
$e\mathrm{RSS}$	$F_{\mathrm{LUC}}^{\mathrm{FF+LUC}} - F_{\mathrm{LUC}}^{\mathrm{LUC}} - F_{0}^{\mathrm{FF}}$	Eq. (9)
$e\mathrm{LFB}$	$F_{\mathrm{LUC}}^{\mathrm{LUC}} - F_{\mathrm{LUC}}^{0}$	Eq. (10)

Table 3. Cumulative emissions (Gt C) over historical and future period for different methods ($e\mathrm{LUC}_{\mathrm{D1}}$, $e\mathrm{LUC}_{\mathrm{D3}}$, $e\mathrm{LUC}_{\mathrm{E2}}$) and component fluxes ($e$RSS, eLFB). $e\mathrm{LUC}_{\mathrm{D1}}$-PI and $e\mathrm{LUC}_{\mathrm{D1}}$-PD refer are quantified under preindustrial (PI) and present-day (PD) environmental conditions.

	1850–2004	2005–2099
$e\mathrm{LUC}_{\mathrm{D1}}$-PI	152	133
$e\mathrm{LUC}_{\mathrm{D1}}$-PD	177	153
$e\mathrm{LUC}_{\mathrm{D3}}$	164	192
$e\mathrm{LUC}_{\mathrm{E2}}$	133	188
eRSS	9	71
eLFB	−26	−17

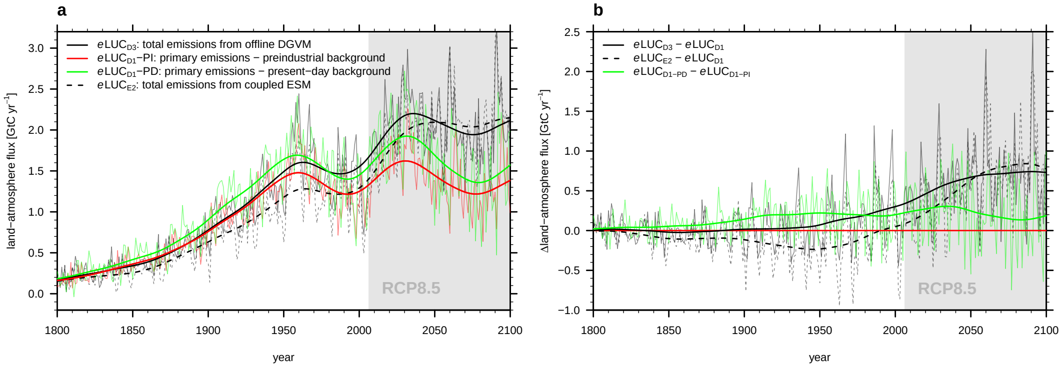

Figure 1. (a) Annual land use change emissions as quantified following different methods. **(b)** Difference of different *e*LUC definitions relative to *e*LUC$_{\mathrm{D1}}$-PI. Total emissions derived from an offline, concentration-driven DGVM setup (D3 method) are given by black solid lines. Total emissions derived from a coupled, emission-driven ESM setup (E2 method) are given by black dashed lines. Primary emissions are given by colored lines under constant pre-industrial (red) and constant present-day (green) environmental conditions (climate, CO$_2$, N deposition). Bold lines are splines of annual emissions given by thin lines. Results are from simulations following CMIP5 model inputs (historical until 2005, RCP8.5 until 2099).

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

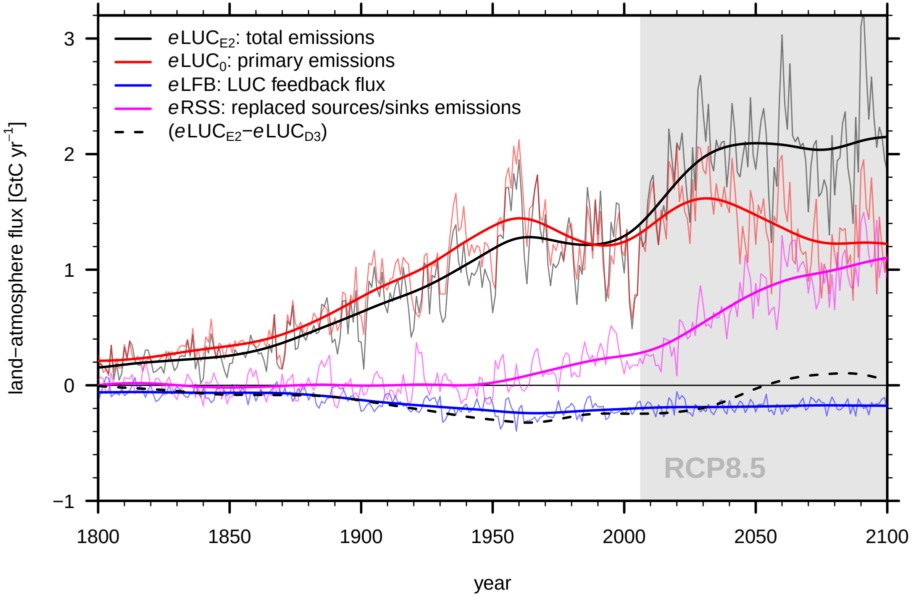

Figure 2. Flux components of land use change emissions. Total emissions as derived from an emission-driven, coupled ESM setup (E2 method), and calculated with Eq. (6), are given by the black lines. Primary emissions under preindustrial boundary conditions are given by red lines. These correspond to curves in Fig. 1. The replaced sinks/sources flux (*e*RSS) and the land use change feedback flux (*e*LFB) are given by magenta and blue lines, respectively. The difference between total emissions quantified by D3 method (see black solid line in Fig. 1) and E2 method is given by the black dashed line. Bold lines are splines of annual emissions given by thin lines. Results are from simulations following CMIP5 model inputs (historical until 2005, RCP8.5 until 2099).

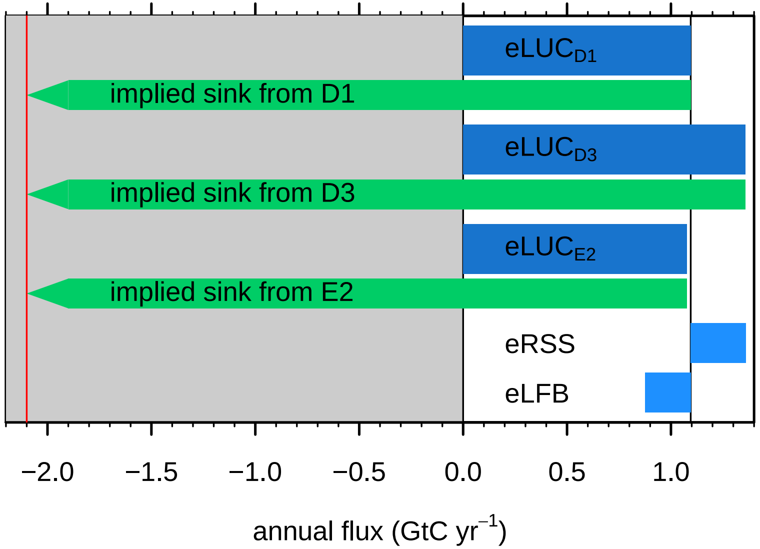

Figure 3. Land use change emissions (*e*LUC, dark blue bars) calculated from different methodologies and their implied residual terrestrial C sink (annual flux in GtC yr^{-1}, mean over 1996–2005). The total terrestrial C balance is constrained by atmospheric measurements and is −2.1 GtC yr^{-1} (mean over 1996–2005, Le Quéré et al., 2014, left vertical line), and is independent of *e*LUC estimates. The residual terrestrial C sink (green arrow) is defined as the difference of *e*LUC and the total terrestrial C balance. Depending on the definition of *e*LUC, the residual C sink is affected by inclusion of secondary fluxes (light blue bars, *e*RSS and *e*LFB) into *e*LUC.