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A theoretical framework for the net land-to-atmosphere CO_2 flux and its implications in the definition of "emissions from land-use change"

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Abstract

We develop a theoretical framework and analysis of the net land-to-atmosphere CO_2 flux in order to discuss possible definitions of "emissions from land-use change". The terrestrial biosphere is affected by two perturbations: the perturbation of the global Carbon-Climate-Nitrogen system (CCN) with elevated atmospheric CO_2, climate change and nitrogen deposition; and the Land-Use Change perturbation (LUC). Here, we progressively establish mathematical definitions of four generic components of the net land-to-atmosphere CO_2 flux. The two first components are the fluxes that would be observed if only one perturbation occurred. The two other components are due to the coupling of the CCN and LUC perturbations, which shows the non-linear response of the terrestrial carbon cycle. Thanks to these four components, we introduce three possible definitions of "emissions from land-use change", that are indeed used in the scientific literature, often without clear distinctions, and we draw conclusions as for their absolute and relative behaviors. Thanks to the OSCAR v2 model, we provide quantitative estimates of the differences between the three definitions, and we find that comparing results from studies that do not use the same definition can lead to a bias of up to 20 % between estimates of those emissions. After discussion of the limitations of the framework, we conclude on the three major points of this study that should help the community to reconcile modeling and observation of emissions from land-use change. The Appendix mainly provides more detailed mathematical expressions of the four components of the net land-to-atmosphere CO_2 flux.

1 Introduction

Land-use change has received a lot of attention as the second most important human-caused perturbation of the global carbon cycle, recently estimated to release an amount of $0.9 \pm 0.5\,\mathrm{GtC\,yr^{-1}}$ of CO_2 to the atmosphere (Le Quéré et al., 2012). Most of the land-use source is due to human-caused tropical deforestation. A better

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quantification of impacted biomass carbon stocks (Baccini et al., 2012), as well as of forest loss area (Hansen et al., 2010; Harris et al., 2012) helps to reduce uncertainties in the land-use change CO_2 flux. Differences in land-use flux estimates between studies (Houghton et al., 2012) are also due to different system boundaries (e.g. the inclusion of soil carbon dynamics after a change in land-use, or the account for regrowth after deforestation) and to different definitions of the human perturbation of ecosystems (e.g. the inclusion of shifting agriculture and forest degradation in the land-use change CO_2 flux) (Houghton, 2010). Yet, in this paper we show that a more insidious source of discrepancy in estimates lies in the definition of "emissions from land-use changes" as a component of the net land-to-atmosphere CO_2 flux. In order to investigate and quantify this definition-related uncertainty, we need to go back to the equations of the global carbon budget, and to discuss the partitioning of the net carbon dioxide flux from the terrestrial biosphere to the atmosphere.

It has become "usual" to define the instantaneous change in atmospheric CO_2 concentration (noted $[CO_2]$) as being the sum of four fluxes (Canadell et al., 2007; Denman et al., 2007). In this approach, two of those fluxes are emissions: one caused by fossil fuel burning and other secondary industrial processes (EFF), and another by land-use, land-use change and forestry (ELUC). The two other fluxes are natural responses of the carbon cycle. These responses have been generally negative since the beginning of the industrial era, i.e. they have been removing carbon dioxide from the atmosphere, acting as two sinks of CO_2: the oceanic sink (OSNK) and the land sink (LSNK). Thence, the instantaneous global carbon budget follows the equation:

$$\frac{\mathrm{d}[CO_2]}{\mathrm{d}t} = \mathrm{EFF} + \mathrm{ELUC} + \mathrm{OSNK} + \mathrm{LSNK}. \qquad (1)$$

In Eq. (1), EFF and OSNK describe CO_2 exchanges between the atmosphere and two different reservoirs (geological and oceanic reservoirs, respectively), while ELUC and LSNK are two terms used to describe exchanges with only one reservoir: the terrestrial carbon reservoir.

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The partition of the net land-to-atmosphere CO_2 flux (noted NetFlux hereafter) between ELUC and LSNK aims to separate the direct anthropogenic effect of land-use activities (ELUC; mainly emissions through tropical deforestation) and the indirect effect of all anthropogenic activities (LSNK; the natural response of the terrestrial biosphere, expected to be a sink driven by the combined effect of regional climate change, N-fertilization and global CO_2-fertilization). However, exact definitions of ELUC and consequently of LSNK vary among studies. For instance, in studies on the global carbon budget, based on observations (e.g. Denman et al., 2007; Khatiwala et al., 2009; Le Quéré et al., 2009), the natural response of the terrestrial biosphere, LSNK, is calculated as the residue in Eq. (1), knowing $d[CO_2]/dt$, EFF, ELUC and OSNK. In global vegetation modeling studies, the problem is opposite: most models cannot make the partition between ELUC and LSNK. When they do, they may use definitions of ELUC that are inappropriate for intercomparison.

The goal of this study is to provide a rigorous mathematical framework suitable for defining different terms of the net land-to-atmosphere CO_2 flux, so as to be able to compare estimates from different modeling approaches as well as from observations. First, we break down the net land-to-atmosphere CO_2 flux into four components. Second, we combine those four components to propose three definitions of "emissions from land-use changes" (ELUC) and provide examples of published studies falling into each definition. The aim is to clarify the definitions of ELUC so that the scientific community can dispose of estimates whose differences do not reflect the choice of different definitions. The mathematical aspect of this study ensures that the results are exact and applicable for any approach used to calculate that kind of emissions. For the purpose of illustration, however, we give numerical applications so as to roughly quantify definition-related differences in ELUC, using the OSCAR v2 carbon cycle model (Gasser et al., 2013, see also Appendix B).

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2 The CCN and LUC perturbations

2.1 Historical simulation without land-use (Exp. 1: CCN perturbation)

In our first (thought) experiment, we consider an historical simulation without any land-use activity. In this experiment, the terrestrial biosphere is disturbed only by three indirect effects of human activities: (i) the increase in atmospheric CO_2; (ii) the increase in nitrogen deposition; and (iii) the change in climate resulting from radiative forcing of greenhouse gases and aerosols produced by diverse human activities. The two first perturbations have a fertilization effect on the productivity of the biosphere, enhancing the CO_2 removal, while the third one leads to regional responses of various signs as for the CO_2 removal (Denman et al., 2007). We call this indirect perturbation of the carbon balance of the terrestrial biosphere the "CCN" perturbation, for "Carbon, Climate and Nitrogen". There are other processes affecting the terrestrial carbon cycle such as the effect of elevated O_3 (Sitch et al., 2007), altered P cycling (Goll et al., 2012), SO_4 aerosols deposition on wetland plants (Gauci et al., 2004), but their effects are assumed to be smaller in magnitude. It should be noticed that here we consider the CCN perturbation to be exogenous to the simulation, whereas the CCN perturbation actually impacts atmospheric CO_2 and then climate (and ultimately the CCN perturbation itself through a feedback loop). However, taking an exogenous or endogenous CCN perturbation does not change the mathematical demonstrations that follow.

In this simulation, at each time t, the net land-to-atmosphere CO_2 flux over a geographical and biological point (g, b) can be expressed as:

$$F(g, b) = f(g, b) S(g, b) \tag{2}$$

where $F(g, b)$ is the extensive net flux over an area $S(g, b)$ typically expressed in $\mathrm{gC\,yr^{-1}}$, and $f(g, b)$ is the intensive (areal) net flux typically expressed in $\mathrm{gC\,m^{-2}\,yr^{-1}}$. By convention, the fluxes $F(g, b)$ and $f(g, b)$ are positive if they correspond to an emission of CO_2 to the atmosphere. Depending on the model used, for instance a box model, an Earth Model of Intermediate Complexity (EMIC) or an Earth System Model

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(ESM), g can be a gridcell, a country or even the whole globe in very simple models; while b can be a Plant Functional Type (PFT), a specific biome or even the global "mean" vegetation in the simplest case.

Each variable can be broken down into a preindustrial value (subscript 0) and a perturbation at t since preindustrial times (prefix Δ). Hence:

$$F(g, b) = (f_0(g, b) + \Delta f(g, b))\, S_0(g, b). \tag{3}$$

Note that the area S has no perturbation term since we made the hypothesis of no land-use change in this section. Under the hypothesis of a preindustrial equilibrium of the carbon cycle, the net carbon flux is equal to zero and the carbon stock of each couple (g, b) remains unchanged; thus the preindustrial terms $F_0(g, b)$ and $f_0(g, b)$ are equal to zero. Consequently, the global net land-to-atmosphere CO_2 flux at time t is:

$$\mathrm{NetFlux_{CCN}} = \iint_{g,b} \Delta f(g, b) S_0(g,b). \tag{4}$$

One could write $f = \epsilon + \mathrm{hr} - \mathrm{npp}$ where ϵ is the areal emissions due to sporadic natural disturbances such as insect outbreaks and wildfires, hr is the heterotrophic respiration and npp is the net primary productivity. Under present-day conditions, it is generally admitted that net primary productivity is higher than during preindustrial times because of fertilization effects of N deposition and increased atmospheric CO_2 (i.e. $\Delta\mathrm{npp} > 0$); that heterotrophic respiration is a delayed response to increased NPP (i.e. $\Delta\mathrm{hr}(t) = \Delta\mathrm{npp}(t - \tau) < \Delta\mathrm{npp}(t)$ where $\tau > 0$ is the delay); and that there is no significant change in sporadic activities since preindustrial times (i.e. $\Delta\epsilon \approx 0$). In that example, the net CO_2 flux is negative ($\Delta f < 0$) and the terrestrial biosphere is a sink of CO_2. Yet, this example ignores two processes: (i) the natural variability of climate; and (ii) the natural long-term migration of vegetation induced by climate change and CO_2 (e.g. Cramer et al., 2001). These two effects will be discussed in Sect. 4. They can

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be incorporated in our definition framework under some minor hypothesis, but would unnecessarily complicate the notations in the following.

2.2 Simulation with land-use at preindustrial times (Exp. 2: LUC perturbation)

There are two types of land-use activities. The first type regroups activities that do not affect land-cover (i.e. no change in $S(g,\ b)$) while the second type corresponds to activities that come with land-cover change (i.e. an area transition δS from $(g,\ b_1)$ to $(g,\ b_2)$ typically expressed in $m^2\ yr^{-1}$). The first land-use type encompasses what IPCC calls "land-use" and "forestry" while the second formally corresponds to "land-use change" in the "LULUCF" terminology (Watson et al., 2000). Houghton (2010) provides a detailed discussion of land-use and land-use changes, and on the anthropogenic activities that are generally included in the definition. In the following, we consider only "land-use change" activities, but the first type of activities can be represented as well by a partial transition from one biome to itself (i.e. δS from $(g,\ b_1)$ to $(g,\ b_1)$). Land-use change activities induce a local perturbation of the terrestrial carbon cycle that leads to a net emission or absorption of CO_2 over time. A long time after the perturbation, we suppose that a new equilibrium is reach where the net land-use-induced CO_2 flux has returned to zero. We call this perturbation the "LUC" perturbation.

In this second experiment, we consider that the LUC perturbation is occurring under preindustrial conditions, i.e. with a CCN perturbation equal to zero. As previously, we suppose that this CCN perturbation is exogenous, remaining equal to zero at all times, despite the actual effect of the LUC perturbation over the CCN perturbation (through CO_2 emissions and then changes in atmospheric CO_2 and climate). Under the hypothesis of no CCN perturbation, all perturbation variables (the ones with the Δ-prefix, in our notation) are equal to zero, except for the area S affected by land-use changes and that we break down into:

$$S(g,\ b) = S_0(g,\ b) - \Delta S^-(g,\ b) + \Delta S^+(g,\ b) \tag{5}$$

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where ΔS^- is the cumulative destroyed area of primary ecosystems, and ΔS^+ is the cumulative created area of secondary ecosystems, of b over g since preindustrial. Both quantities are positive. However, the created areas are not at equilibrium for their CO_2 net flux and thus we will monitor their status as a cohort of disturbed (i.e. transitioning) ecosystems since the time of their "creation". This is called the "book-keeping" approach.

To do so we introduce the vector notation for cohorts of transitioning ecosystems of different age classes τ:

$$\boldsymbol{\delta S}^+(g,\ b) = \boldsymbol{\delta S}^{+,\tau=0,\ldots,\infty}(g,\ b) = \left(\delta S^{+,\tau=0},\ \ldots,\ \delta S^{+,\tau},\ \ldots\right)(g,\ b) \tag{6}$$

where $\delta S^{+,\tau}(g,\ b)$ is the area of transitioning b over the geographic point g that was created τ years before t and $\boldsymbol{\delta S}^+(g,\ b)$ is the vector that describes all the values $\delta S^{+,\tau}(g,\ b)$ along the τ axis. As a consequence, we can further express the total created area of secondary ecosystems $\Delta S^+(g,\ b)$ at time t:

$$\Delta S^+(g,b) = \int_{\tau=0}^{t} \delta S^{+,\tau}(g,\ b). \tag{7}$$

The notation for cohorts is extended to all variables associated with the transitioning ecosystems, so that the cohort of net areal land-to-atmosphere CO_2 fluxes that corresponds to $\boldsymbol{\delta S}^+(g,\ b)$ is:

$$\boldsymbol{f}(g,\ b) = \boldsymbol{f}^{\tau=0,\ldots,\infty}(g,\ b) = \left(f^0,\ \ldots,\ f^\tau,\ \ldots\right)(g,\ b). \tag{8}$$

As a perturbation becomes old (i.e. as τ increases), a disturbed secondary ecosystem tends to become fully transitioned to a new state of the undisturbed equivalent ecosystem $(g,\ b)$. Note that some ecosystems (like croplands), because of continual

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anthropogenic perturbations, may never really reach this "undisturbed" state, but we can still define an hypothetical – idealized – undisturbed state. Thus, mathematically:

$$f^{\tau\to\infty}(g,b) \to f^*(g,b) \tag{9}$$

where f^* is the value of f at equilibrium. The superscript * will hereafter be used to describe the equilibrium of a variable relative to the LUC perturbation. It was discarded in the previous section for simplicity. Note that there is no reason for any f^τ to equal f^* before the termination of the transition.

Following the illustration of f^* given in the previous section, we can write that $f = \epsilon + \mathrm{hr} - \mathrm{npp} + w$ where ϵ, hr and npp are the same fluxes as in Sect. 2.1, and w is the CO_2 flux of decaying products (usually wood) formed at the time of the land-use change activity (with $w > 0$ and $w^* = 0$). Despite not being part of local CO_2 fluxes, we keep accounting for w into the net flux $f(g,\ b)$ because it is tied to the initial land-use perturbation at the point $(g,\ b)$. As a consequence, our formalism does not consider the geographic location of harvested wood, or food, products (e.g. displacement and/or trade).

The local net land-to-atmosphere CO_2 flux in this second experiment is expressed by:

$$F(g,\ b) = \underbrace{f_0^*(g,\ b)\left(S_0(g,\ b) - \Delta S^-(g,\ b)\right)}_{\text{undisturbed lands}} + \underbrace{\boldsymbol{f}_0(g,\ b) \bullet \boldsymbol{\delta S}^+(g,\ b)}_{\text{disturbed lands}} \tag{10}$$

where the operation $\bullet$ is the multiplication term-by-term (a scalar product between two orthogonal vectors) of the cohort of transitioning areas and the cohort of net areal CO_2 fluxes. The first term of Eq. (10) is the net CO_2 flux over undisturbed lands, while the second term is the net flux over disturbed (i.e. transitioning) lands. Because we made the hypothesis of a preindustrial equilibrium in the first experiment, f_0^* is also equal to zero, and thus the global land-to-atmosphere flux is given by:

$$\mathrm{NetFlux}_{\mathrm{LUC}} = \iint_{g,b} \boldsymbol{f}_0(g,\ b) \bullet \boldsymbol{\delta S}^+(g,\ b). \tag{11}$$

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Cohorts are mathematical representations of the physical temporality of the land-use perturbation. Since an ecosystem disturbed by land-use change needs a few decades to meet its new equilibrium, it is necessary to keep track of fluxes and stocks legated by previous perturbations to make accurate estimations of CO_2 fluxes. The so-called "legacy" of emissions from land-use change (Jones et al., 2010; Houghton, 2010) is the concrete illustration of this physical property. ELUC at one time t are partially due to the perturbation at t, but also due to all perturbations before that time t. This has been illustrated e.g. by Pongratz et al. (2009), and can be visualized on the right-hand panel of Fig. 2, where land-use activities are stopped after the year 2005 in the OSCAR v2 model (whereas legated emissions do not go to zero immediately after this date).

2.3 Historical simulation with land-use (Exp. 3: CCN + LUC perturbations)

Our reasoning applies at the level of each couple (g, b), but we will drop the (g, b) notation for clarity in the following, bringing it back only when necessary.

In this third experiment, we consider an historical simulation with both CCN and LUC perturbations. Note that it is the only experiment that is realistic, as the two previous ones ignored one of the two perturbations. The local net land-to-atmosphere flux is deduced from Eqs. (3) and (10) as:

$$F = \left(f_0^* + \Delta f^*\right)\left(S_0 - \Delta S^-\right) + \left(\boldsymbol{f}_0 + \boldsymbol{\Delta f}\right) \bullet \boldsymbol{\delta S}^+ . \tag{12}$$

We make the same assumption of preindustrial equilibrium than in previous sections (i.e. $f_0^* = 0$), and we integrate the flux F over all couples (g, b):

$$\begin{aligned} \mathrm{NetFlux}_{\mathrm{CCN+LUC}} &= \iint_{g,b} \Delta f^*\left(S_0 - \Delta S^-\right) + \left(\boldsymbol{f}_0 + \boldsymbol{\Delta f}\right) \bullet \boldsymbol{\delta S}^+ \\ &= \underbrace{\iint_{g,b} \Delta f^* S_0}_{\mathrm{NetFlux}_{\mathrm{CCN}}} + \underbrace{\iint_{g,b} \boldsymbol{f}_0 \bullet \boldsymbol{\delta S}^+}_{\mathrm{NetFlux}_{\mathrm{LUC}}} + \underbrace{\iint_{g,b} \Delta f^*\left(-\Delta S^-\right) + \boldsymbol{\Delta f} \bullet \boldsymbol{\delta S}^+}_{\mathrm{NetFlux}_{\mathrm{CCN\times LUC}}} . \end{aligned} \tag{13}$$

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In Eq. (13), one can identify the first two terms, corresponding to Eq. (4) in Sect. 2.1 and to Eq. (11) in Sect. 2.2, i.e. the fluxes due to the separate CCN and LUC perturbations, plus a term (noted $\text{NetFlux}_{\text{CCN}\times\text{LUC}}$) representing the interactions between the CCN and LUC perturbations. This term is zero in the absence of at least one of the two perturbations.

2.4 The four components of the net land-to-atmosphere flux

2.4.1 Equations

Following Eq. (10), the partition between undisturbed and disturbed lands in the local flux $F(g, b)$ of Eq. (12) can be expressed as:

$$F = \underbrace{\Delta f^{*}\left(S_0 - \Delta S^{-}\right)}_{\text{undisturbed lands}} + \underbrace{(\boldsymbol{f}_0 + \boldsymbol{\Delta f}) \bullet \boldsymbol{\delta S}^{+}}_{\text{disturbed lands}}. \tag{14}$$

In this equation there is no separation of the CCN and LUC perturbations over disturbed lands. For old "almost transitioned" ecosystems where the LUC perturbation is becoming negligible, the simulated net flux over disturbed lands is dominated by the CCN perturbation. To separate the two effects, we isolate in Eq. (14) the term representing the CCN perturbation that would occur in hypothetical fully transitioned ecosystems of the same area than the cohort: $\boldsymbol{\Delta f}^{*} \bullet \boldsymbol{\delta S}^{+} = \Delta f^{*}\, \Delta S^{+}$. Subtracting this term to the "disturbed lands" part of Eq. (14) and adding it to the "undisturbed lands" one leads to:

$$F = \underbrace{\Delta f^{*}\left(S_0 - \Delta S^{-} + \Delta S^{+}\right)}_{\text{CCN driven}} + \underbrace{(\boldsymbol{f}_0 + \boldsymbol{\Delta f} - \boldsymbol{\Delta f}^{*}) \bullet \boldsymbol{\delta S}^{+}}_{\text{LUC driven}}. \tag{15}$$

Now, the first term (left) of Eq. (15) is mainly driven by the CCN perturbation and the second term (right) is mainly driven by the LUC perturbation.

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In Eq. (15), the two main fluxes due to the separate CCN and LUC perturbations are present, but this time we conceptually split the coupling term $\mathrm{NetFlux}_{\mathrm{CCN}\times\mathrm{LUC}}$ of Eq. (13) into two sub-terms. This provides the four generic components of the net land-to-atmosphere CO_2 flux when both CCN and LUC perturbations occur. Figure 1 shows a conceptual diagram of the three experiments we used to break down the net land-to-atmosphere flux into these four components. To follow the formalism developed in previous sections, we propose the following notations and formulations:

$$\mathrm{NetFlux}_{\mathrm{CCN+LUC}} = \underbrace{\iint_{g,b} \boldsymbol{f}_0 \bullet \boldsymbol{\delta S}^+}_{\mathrm{ELUC}_0} + \underbrace{\iint_{g,b} (\boldsymbol{\Delta f} - \boldsymbol{\Delta f}^*) \bullet \boldsymbol{\delta S}^+}_{\Delta\mathrm{ELUC}}$$
$$+ \underbrace{\iint_{g,b} \Delta f^* S_0}_{\mathrm{LSNK}_0} + \underbrace{\iint_{g,b} \Delta f^* \left(-\Delta S^- + \Delta S^+\right)}_{\Delta\mathrm{LSNK}}. \quad (16)$$

ELUC_0 is the flux due to the LUC perturbation only (experiment 2) and LSNK_0 is the flux due to the CCN perturbation only (experiment 1). The two terms with the delta symbols are the two sub-fluxes due to the coupling of CCN and LUC perturbations. ΔELUC (resp. ΔLSNK) is named on the basis of its formulation that is analogous to the one of ELUC_0 (resp. LSNK_0).

Conceptually, ELUC_0 are *the emissions from land-use change that would have been observed if land-use change activities occurred under preindustrial climate, CO_2 and nitrogen conditions*. ΔELUC are *the extra-emissions from land-use change due to the CCN perturbation that has been affecting transitioning ecosystems* (e.g. CO_2- and N-fertilizations have made carbon stocks larger, and global warming has changed the rate of heterotrophic respiration). LSNK_0 is *the global land sink that would have been observed under preindustrial land-cover* (i.e. without LUC perturbation). ΔLSNK is *the altered land sink due to land-cover change* (i.e. due to changes in areas of the different

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ecosystems when compared to the preindustrial ones). This last term was called "amplification effect" by Gitz and Ciais (2003) and "loss of sink capacity" by Pongratz et al. (2009).

2.4.2 Simulation with OSCAR v2

Now we illustrate the magnitude of the four components of $\text{NetFlux}_{\text{CCN+LUC}}$ using a numerical model of the global carbon cycle, OSCAR v2. The simulation by OSCAR v2 of the four fluxes is shown in Fig. 2. The left-hand panel shows the results of the historical simulation and the right-hand panel the results when the CCN perturbation follows the RCP 8.5 scenario (Riahi et al., 2011) without LUC perturbation after the year 2005. The two main fluxes ELUC_0 and LSNK_0, due to the LUC and CCN perturbations separately, behave as expected over the historical period. ELUC_0 is positive because of deforestation being more important than afforestation or reforestation, although it declines since the beginning of the 1990s (Friedlingstein et al., 2010). LSNK_0 is a sink driven in OSCAR v2 mainly by CO_2-fertilization but also affected by climate variability. The legacy of ELUC_0 is negative few years after 2005 and it (slowly) tends toward zero when all transitioned ecosystems have recovered. Contrarily, LSNK_0 keep on increasing (in absolute value) under the RCP 8.5 CCN perturbation as CO_2 atmospheric concentration is also increasing. The stagnation of the sink after 2080 is due to the carbon-climate feedback on the terrestrial biosphere in OSCAR v2 (Gasser et al., 2013) with the negative effect of warming climate countering the positive effect of CO_2-fertilization, and thus reducing the land sink.

ΔELUC is the term of the net land-to-atmosphere flux that quantifies the impact of the CCN perturbation over the LUC perturbation. It is roughly proportional to ELUC_0, with a proportionality factor equal to the ratio of change in carbon areal density to preindustrial carbon areal density (i.e. $\Delta c^*/c_0^*$, see Sect. A2). In our simulation, the estimated value of ΔELUC is about +10 % that of ELUC_0 over the 1980–2000 period. However, the behavior of this term is not exactly similar to ELUC_0. Contrarily to ELUC_0, the legacy of ΔELUC after 2005 is positive. This result may be model-dependent, and it

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is explained in OSCAR v2 by the fact that the change in living biomass carbon density is faster than the change in soil carbon density (i.e. $\Delta c^*/c_0^*$ is greater in vegetation than in soils). Thus, the legacy of ΔELUC is driven by the increased emissions due to dead biomass after deforestation, while the legacy of $ELUC_0$ is driven by soil carbon accumulation due to biospheric regrowth (see also Houghton, 2010).

The last flux illustrated in Fig. 2 is the "amplification effect"/"altered sink capacity", ΔLSNK. We can see that it is positive, mainly because deforestation causes a loss of sink capacity compared to leaving in place pristine forests. ΔLSNK can be seen as the portion of $LSNK_0$ that is "not realized" because it is affected by land-cover change, thus the two fluxes are roughly proportional (with a proportionality factor equal to $\Delta S/S_0$, see Sect. A4). ΔLSNK has a temporal profile similar to $LSNK_0$. Indeed, ΔLSNK becomes significant after 1950 (i.e. when atmospheric CO_2 starts to increase significantly), and it is strongly affected by climate variability. When land-use activities are stopped (after 2005) it does not tend toward zero. ΔLSNK is about −15 % of $LSNK_0$ in the 1990s and later. Over the period 2005–2100, ΔLSNK increases as CO_2-fertilization strengthens the potential sink, and consequently the loss of potential sink. The causes of the stabilization after 2080 are exactly the same as for $LSNK_0$.

3 Three possible definitions of ELUC and LSNK

In this section, we consider both CCN and LUC perturbations. Irrespective of the chosen definition of ELUC and LSNK, mass conservation implies that the sum of the two fluxes must be equal to the net land-to-atmosphere flux: NetFlux = ELUC + LSNK. NetFlux is defined globally by the difference between fossil fuel emissions and ocean uptake of anthropogenic CO_2 plus atmospheric CO_2 growth rate (e.g. Canadell et al., 2007; Le Quéré et al., 2012) Thus, using one definition for one of the two fluxes implies a non-ambiguous definition for the other, and users must take care of not using two inconsistent definitions for ELUC and LSNK.

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3.1 Definition 1: simulations with/without land-use

A first choice (called definition 1, and noted def 1) underpinning the calculation of ELUC and LSNK with terrestrial ecosystem models is to compare the simulated land-to-atmosphere flux of two model experiments: one done with LUC and exogenous CCN conditions, and another done without LUC and the same CCN conditions. Then, ELUC is the difference between the first simulation and the second one, and LSNK is necessarily equal to the result of the second simulation (because of the mass conservation constraint). The local flux calculated by the first model experiment is given by Eq. (13) while the one calculated by the second experiment is given by Eq. (4). Hence:

$$\begin{aligned}\mathrm{ELUC}_{\mathrm{def\ 1}} &= \mathrm{NetFlux}_{\mathrm{CCN+LUC}} - \mathrm{NetFlux}_{\mathrm{CCN}} \\ &= \mathrm{NetFlux}_{\mathrm{LUC}} + \mathrm{NetFlux}_{\mathrm{CCN\times LUC}} \\ &= \iint_{g,b} -\Delta f^{*}\,\Delta S^{-} + (\boldsymbol{f}_0 + \boldsymbol{\Delta f}) \bullet \boldsymbol{\delta S}^{+}\end{aligned} \tag{17}$$

and

$$\begin{aligned}\mathrm{LSNK}_{\mathrm{def\ 1}} &= \mathrm{NetFlux}_{\mathrm{CCN+LUC}} - \mathrm{ELUC}_{\mathrm{def\ 1}} \\ &= \mathrm{NetFlux}_{\mathrm{CCN}} \\ &= \iint_{g,b} \Delta f^{*}\,S_0.\end{aligned} \tag{18}$$

The choice of definition 1 is usually (although implicitly) made with ecosystem models that do not include explicit land-use cohorts (e.g. McGuire et al., 2001; Piao et al., 2009; Pongratz et al., 2009). With def 1, the flux due to the cross-interactions between CCN and LUC is fully accounted for as part of "emissions from land-use change" (i.e. in the ELUC term).

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3.2 Definition 2: disturbed/undisturbed lands

3.2.1 General definition 2

A second definition for ELUC and LSNK (definition 2, def 2) is suggested by Eq. (10), and subsequently by Eq. (14). One can consider that ELUC is the net land-to-atmosphere flux over disturbed lands, and that consequently LSNK is the net flux over undisturbed lands. The resulting definitions are:

$$\begin{aligned} \mathrm{ELUC}_{\mathrm{def\,2}} &= \mathrm{NetFlux}_{\mathrm{disturbed}} \\ &= \iint_{g,b} (\boldsymbol{f}_0 + \boldsymbol{\Delta f}) \bullet \boldsymbol{\delta S}^+ \end{aligned} \tag{19}$$

and

$$\begin{aligned} \mathrm{LSNK}_{\mathrm{def\,2}} &= \mathrm{NetFlux}_{\mathrm{undisturbed}} \\ &= \iint_{g,b} \Delta f^* \left(S_0 - \Delta S^-\right). \end{aligned} \tag{20}$$

The few vegetation models that have an explicit treatment of cohorts usually use this definition (e.g. Shevliakova et al., 2009). It is important to note that this definition is the only one that corresponds to what is observable with direct measurements. Assuming that we know if a land is primary or secondary – which is feasible thanks to satellite land-cover observations and land-use historical data – the local measurements with e.g. flux towers will provide data consistent with this definition. However, this raises the issue of choosing a reference land-cover S_0 that should depend on the scope of the study. For instance, considering European forests of the 18th century as primary forests, and thus neglecting previous land-use activities, seems a reasonable approximation if the study focuses on the industrial era, i.e. a period when land-use is mostly driven by Americas (North and then South). Contrarily, studies on preindustrial

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land-use (e.g. Kaplan et al., 2010) may prefer to define S_0 with only natural biomes (e.g. potential vegetation) in order to seize all human-induced impacts on the terrestrial biosphere.

3.2.2 Truncated definition 2

The main drawback of implementing definition 2 in a spatially explicit ecosystem model is that it requires to keep track of very old age classes of the cohort (which are almost transitioned) in each grid point, making it demanding in computing time for almost no improvement in the precision of the simulation. To avoid this, one solution is to arbitrarily define an age class τ_{lim} after which the cohorts are considered "transitioned" and are then reallocated to the "undisturbed" group of ecosystems. In IPCC guidelines (Paustian et al., 2006) the default value of τ_{lim} is 20 yr. Using this truncated approach, we give a variation of definition 2 (noted def 2, τ_{lim}) of ELUC and LSNK, with a variable parameter that defines the last disturbed age class τ_{lim} considered in the accouting of the ELUC term, which gives:

$$\mathrm{ELUC}_{\mathrm{def\,2},\tau_{\mathrm{lim}}} = \iint_{g,b} \left(\boldsymbol{f}_0^{\tau\leq\tau_{\mathrm{lim}}} + \boldsymbol{\Delta f}^{\tau\leq\tau_{\mathrm{lim}}}\right) \bullet \boldsymbol{\delta S}^{+,\tau\leq\tau_{\mathrm{lim}}} \tag{21}$$

and

$$\mathrm{LSNK}_{\mathrm{def\,2},\tau_{\mathrm{lim}}} = \iint_{g,b} \Delta f^{*}\left(S_0 - \Delta S^{-}\right) + \left(\boldsymbol{f}_0^{\tau>\tau_{\mathrm{lim}}} + \boldsymbol{\Delta f}^{\tau>\tau_{\mathrm{lim}}}\right) \bullet \boldsymbol{\delta S}^{+,\tau>\tau_{\mathrm{lim}}}. \tag{22}$$

The general definition 2 given in Eqs. (19) and (20) is verified in Eqs. (21) and (22) for $\tau_{\mathrm{lim}} = \infty$ (i.e. $\mathrm{ELUC}_{\mathrm{def\,2}} = \mathrm{ELUC}_{\mathrm{def\,2},\tau_{\mathrm{lim}}=\infty}$). It is clear that the setting of τ_{lim} is crucial in the truncated definition 2. If τ_{lim} is too small, disturbed lands will be considered transitioned too early (the ELUC flux will be "underestimated"). However, there are no rigorous mathematical conclusions regarding the consequences of a choice of τ_{lim},

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since the behavior of the cohorts is model-dependent. We illustrate the effect of choosing different values of τ_{lim} in Fig. 4 and discuss it in Sect. 3.4.2, using the OSCAR v2 model.

3.3 Definition 3: LUC/CCN perturbations

The third definition we propose (definition 3, def 3) is based on Eq. (15) which separates the LUC and CCN perturbations:

$$\mathrm{ELUC}_{\text{def 3}} = \mathrm{NetFlux}_{\text{LUC driven}} = \iint_{g,b} (\boldsymbol{f}_0 + \boldsymbol{\Delta f} - \boldsymbol{\Delta f}^*) \bullet \boldsymbol{\delta S}^+ \tag{23}$$

and

$$\mathrm{LSNK}_{\text{def 3}} = \mathrm{NetFlux}_{\text{CCN driven}} = \iint_{g,b} \Delta f^* \left(S_0 - \Delta S^- + \Delta S^+\right). \tag{24}$$

The separation of the two perturbations implied by def 3 is conceptual. Book-keeping models usually use this definition because they are developed to look at the "difference to the equilibrium" for every kind of land-use activity. However, a model such as the one developed by Houghton et al. (1983) even updated for recent evaluations of ELUC (Friedlingstein et al., 2010; Le Quéré et al., 2012) is not fully coupled with the CCN perturbation. Indeed, if the parameters of such models are calibrated on observed stocks and fluxes in e.g. the 1970s, then the simulated ELUC will always be nudged to the CCN perturbation of the 1970s (e.g. increased C stocks when compared to preindustrial) even for emissions calculated at others dates like 1850 or 2050. A solution would be to use a time-dependent calibration of the book-keeping model (e.g. updated every decade) in order to update the parameters that are changing because of the CCN

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perturbation. The only fully coupled book-keeping model we know of this far, that uses def 3 for calculating emissions from land-use change, is the one developed by Gasser et al. (2013).

3.4 Comparing the three definitions of ELUC

3.4.1 Equations

To compare the three definitions introduced above, we use the formal names for fluxes given in Sect. 2.4. Thus, based on Eqs. (17) to (24), and using the notation of Eq. (16), we can write the three definitions as:

$$\begin{aligned} \mathrm{ELUC}_{\mathrm{def\,1}} &= \mathrm{ELUC}_0 + \Delta\mathrm{ELUC} + \Delta\mathrm{LSNK} \\ \mathrm{ELUC}_{\mathrm{def\,2}} &= \mathrm{ELUC}_0 + \Delta\mathrm{ELUC} + \boldsymbol{LSNK}_0^{\tau<\infty} + \boldsymbol{\Delta LSNK}^{\tau<\infty} \\ \mathrm{ELUC}_{\mathrm{def\,3}} &= \mathrm{ELUC}_0 + \Delta\mathrm{ELUC}. \end{aligned} \quad (25)$$

We previously explained that, for an historical simulation and at global scale, ELUC_0, ΔELUC and ΔLSNK are all positive (emissions of CO_2 to the atmosphere) while LSNK_0 is negative (sink of atmospheric CO_2). In absolute values, ΔLSNK must be inferior to LSNK_0 because the loss of sink capacity cannot be superior to the total sink capacity. Thus, $\mathrm{LSNK}_0 + \Delta\mathrm{LSNK}$ is necessarily of the sign of LSNK_0 (i.e. negative in present days). Finally, using Eq. (25) we can order the three definitions of ELUC as follows:

$$\mathrm{ELUC}_{\mathrm{def\,2}} < \mathrm{ELUC}_{\mathrm{def\,3}} < \mathrm{ELUC}_{\mathrm{def\,1}}. \quad (26)$$

This inequality is valid only when comparing the results of different simulations of one model, with all parameters being the same. Consequently, comparison between ELUC calculated by different models should be done only if a single definition of land-use change emissions has been agreed upon, to avoid definition-related biases when trying to assess and understand differences between models. With this formalism, the truncated definition 2 (with τ_{lim} finite) is:

$$\mathrm{ELUC}_{\mathrm{def\,2},\tau_{\mathrm{lim}}} = \boldsymbol{ELUC}_0^{\tau\le\tau_{\mathrm{lim}}} + \boldsymbol{\Delta ELUC}^{\tau\le\tau_{\mathrm{lim}}} + \boldsymbol{LSNK}_0^{\tau\le\tau_{\mathrm{lim}}} + \boldsymbol{\Delta LSNK}^{\tau\le\tau_{\mathrm{lim}}}. \quad (27)$$

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It is impossible to draw general conclusion so as to include this definition in the comparison of Eq. (26) because of the opposite mathematical relation (in an historical simulation where $LSNK_0$ is negative) between the two terms:

$$\boldsymbol{ELUC}_0^{\tau\leq\tau_{\text{lim}}} + \boldsymbol{\Delta ELUC}^{\tau\leq\tau_{\text{lim}}} < \boldsymbol{ELUC}_0^{\tau<\infty} + \boldsymbol{\Delta ELUC}^{\tau<\infty}$$
$$\boldsymbol{LSNK}_0^{\tau\leq\tau_{\text{lim}}} + \boldsymbol{\Delta LSNK}^{\tau\leq\tau_{\text{lim}}} > \boldsymbol{LSNK}_0^{\tau<\infty} + \boldsymbol{\Delta LSNK}^{\tau<\infty}. \quad (28)$$

Let us now consider an idealized simulation where historical land-use activities are stopped at a given time t_0 while others anthropogenic forcings (such as fossil fuel emissions) are not. We then look at the value of ELUC with our different definitions a long time after the LUC perturbation stopped. The values of $ELUC_0$ and ΔELUC must both tend toward zero (Eqs. 9 and 16) as time since the last perturbation increases (i.e. the age of the younger non-zero element of the cohort increases), which gives:

$$\text{ELUC}_{\text{def 1}}(t \gg t_0) \simeq \Delta\text{LSNK}$$
$$\text{ELUC}_{\text{def 2}}(t \gg t_0) \simeq \boldsymbol{LSNK}_0^{\tau<\infty} + \boldsymbol{\Delta LSNK}^{\tau<\infty}$$
$$\text{ELUC}_{\text{def 3}}(t \gg t_0) \simeq 0. \quad (29)$$

That result is interesting because it shows that only the third definition allows ELUC to be zero a long time after the end of the LUC perturbation. Oppositely, when using definitions 1 or 2, if there has been a LUC perturbation at one time, there will always be emissions from land-use change calculated by the model. In the case of the truncated definition 2 (def 2, τ_{lim}), ELUC also tends toward zero for this simulation but with a discontinuity at $t = \tau_{\text{lim}} + t_0$, when ELUC drops from the value of the (small) net flux of the τ_{lim}-th element of the cohort to a value of exactly zero (and because all elements of the cohort younger than τ_{lim} years are equal to zero as land-use activities have stopped).

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3.4.2 Simulation with OSCAR v2

The OSCAR v2 model is used, forced by prescribed land cover changes and forestry since preindustrial for the LUC perturbation, and climate and CO_2 effects (but no nitrogen) for the CCN perturbation. See Appendix B for references of data. The model code was written to be tractable with the calculation of ELUC and LSNK fluxes under the three different definitions. Figure 3 displays ELUC calculated using def 1, def 2 and def 3, as well as two examples of the truncated definition 2 (def 2, τ_{lim}) with different τ_{lim} values being set to 20 and 40 yr. The left-hand panel displays the simulated value from 1900 to 2005, for an historical simulation that starts in 1700. First, we observe that the simulation results shown in Fig. 3 fulfill the established inequality (Eq. 26), and that the difference between def 3 and def 2, or between def 1 and def 3, can be up to about 20 % during the 1980s and the 1990s. This result highlights the importance of the choice of the definition to quantify land-use-related emissions and compare different model estimates. In the previous section, we explained why the value of ELUC calculated under def 2, τ_{lim} is variable when compared to the values simulated under the other definitions. Up to 1950, both $\text{ELUC}_{\text{def 2},\tau_{\text{lim}}}$ curves (τ_{lim} equal to 20 and 40 yr) are below the curves generated with the other three definitions; but after that date, $\text{ELUC}_{\text{def 2},\tau_{\text{lim}}}$ can be either above or below the $\text{ELUC}_{\text{def 2}}$ curve. Another interesting result here is that def 3 is the less affected by climate variability. $\text{ELUC}_{\text{def 2}}$ is more variable during the represented period than $\text{ELUC}_{\text{def 1}}$, which itself varies more than $\text{ELUC}_{\text{def 3}}$. Equation (16) bring insights on the causes of this behavior: definitions 1 and 2 are functions of the LSNK_0 and ΔLSNK terms that are mainly driven by the CCN perturbation, as explained in Sect. 2.3, and are consequently affected by climate variability. By contrast, under definition 3, the only term affected by the CCN perturbation is ΔELUC (and even then, the formulation $\Delta f - \Delta f^*$ in Eq. (23) is expected to act as a "buffer" of the variability because the perturbation Δf and the transitioned state Δf^* are both affected by the variability in a similar way).

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The right-hand panel of Fig. 3 shows the simulated ELUC from the different definitions between 2005 and 2100, in the idealized case where land-use activities would stop after 2005 but atmospheric CO_2 and subsequent climate change follow the RCP 8.5 scenario. This part of the simulation illustrates the consequences of adopting different ELUC definitions. First, about the "legacy" of land-use change, the stop of land-use activity after 2005 does not imply that ELUC become immediately equal to zero, as explained in Sect. 2.3. Second, the very different behaviors of the three definitions during the period 2005–2100 are good illustrations of Eq. (29). While ELUC from def 3 tends slowly toward zero as theory predicts, emissions following def 1 and def 2 clearly diverge from zero when $t \gg 2005$. This is due to the continuing CCN perturbation in the RCP 8.5 CO_2 and climate change scenario. Here, ELUC from def 1 remain positive and increase with time after 2005 because this definition includes the loss of potential sink due to past deforestation (ΔLSNK), and this lost potential sink is also increasing (due to CO_2-fertilization, despite its attenuation by carbon-climate feedbacks). Oppositely, ELUC from def 2 are negative for $t > 2005$ (and increase in absolute value with time) because def 2 includes the net effect of the CCN perturbation ($LSNK_0$ + ΔLSNK) over lands that have been disturbed at any previous time. In other words, def 2 takes into account the "land sink" that occurs above previously disturbed lands that have almost "recovered" from the LUC perturbation. Finally, the emissions defined by def 2, τ_{lim} behave as explained in the previous section: they drop to zero at the year $t = 2005 + \tau_{lim}$.

For a better discussion on the implications of using a truncated definition 2, Fig. 4 provides a comparison of def 2, τ_{lim} for different values of τ_{lim}, at different times of the simulation: in 1850, 1990, 2005 and 2025. On the four subplots, $ELUC_{def\,2,\tau_{lim}}$ tends toward $ELUC_{def\,2}$, by construction (see Eqs. 19 to 22). $ELUC_{def\,2,\tau_{lim}}$ is not a monotonic function of τ_{lim}. For instance, in 1990 and 2005, it decreases as τ_{lim} increases for $\tau_{lim} > 100$ yr, but it increases with τ_{lim} in the range 50 to 100 yr. In 1850, however, $ELUC_{def\,2,\tau_{lim}}$ is generally increasing with τ_{lim}. Emissions calculated with def 2, τ_{lim} appears to be close to that of def 2, but not always. In 2005, $ELUC_{def\,2,\tau_{lim}}$ is even superior

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to $ELUC_{def\,3}$ for small values of τ_{lim} (< 20 yr). Therefore, since it seems that the behavior of the truncated second definition is highly model-dependent, we cannot recommend any "best" value of τ_{lim} and great care must be taken when comparing ELUC estimates from models that use this definition.

4 Discussion

We see two limitations to this theoretical framework. First, natural climate variability affects the hypothesis of a preindustrial equilibrium. For clarity, we decided to write down equations without accounting for this variability. However, we could break down the flux f into a mean and a variable terms which average value is equal to zero: $f = \langle f \rangle + \dot{f}$ with $\int \dot{f} = 0$. In this case, the mathematical demonstrations of Sect. 2 are still valid for the mean term $\langle f \rangle$. Practically, so as to avoid biases due to climate variability affecting ecosystem fluxes in models, the four component fluxes of the CCN and LUC perturbations should be estimated either on average over a long enough time period (e.g. 10 yr) or as cumulative fluxes. Note that the biases will only appear for the experiment with LUC perturbation at preindustrial times (where a reference preindustrial CCN perturbation has to be defined, but cannot because of climate variability).

The second limitation is the migration of vegetation induced by CO_2 and climate changes. This phenomenon can be seen as a natural (yet indirectly human-induced) land-use change. A first option to include it in the framework is to consider three perturbations: CCN, direct anthropogenic LUC and indirect anthropogenic LUC (i.e. migration). However, adding a third perturbation implies to run more experiments so as to separate more component fluxes of the net land-to-atmosphere flux. Another option, that avoids supplementary simulations, is to include the migration as part of the CCN perturbation. To do so, at each time step and over each grid cell, all natural biomes b have to be aggregated into one "mean" biome before applying our framework. In that way, the migration of natural biomes finally appears in the net areal flux Δf^* (the CCN perturbation) but not in the area changes δS (the LUC perturbation) that is limited to

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transitions from natural to anthropogenic biomes (and conversely) and to transitions between anthropogenic biomes.

5 Conclusions

By looking at the mathematical structure and properties of the net land-to-atmosphere CO_2 flux this study provides a theoretical framework so as to distinguish its different constitutive components. Rather than defining two component fluxes (as one would expect since the net flux is the result of two perturbations: CCN and LUC), we show that considering four components of the net flux is mathematically exact. Using those four components, we demonstrate that different modeling definitions of emissions from land-use change (ELUC) can be chosen, mainly depending on the way a model is built. We can draw three conclusions from this work:

- Choosing a definition for ELUC (or having a definition imposed by a model's structure) implies a complementary definition for the land sink (LSNK). This is critical for studies that look at the global carbon budget since choosing two inconsistent definitions may lead to missing – or accounting for multiple times – some terms of the net land-to-atmosphere flux that are due to the coupled interaction between CCN and LUC perturbations. We suggest that might explain a part of the "residual" flux of the global carbon budget estimated by Le Quéré et al. (2009) where they use estimates of ELUC through book-keeping (def 3) and estimates of LSNK through modeling without explicit representation of land-use (def 1).

- There is only one modeling definition that is comparable to what can be directly measured: the second definition (def 2) based on the undisturbed/disturbed status of lands. However, since calculating the ELUC flux based on this definition requires important computing memory and time, one might approximate it with the truncated definition 2 (def 2, τ_{lim}) based on a deliberately limited size of the cohort of transitioning ecosystems. Here, we suggest that the parameter τ_{lim} should

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be as high as possible, or at least carefully evaluated for each transition and/or ecosystem so as to keep a maximum of information about the cohorts.

- The different possibilities of definition increase the discrepancy between ELUC estimates made through modeling. In the OSCAR v2 model used for illustration here, the difference between two definitions can be of about 20 %. Since this adds up to the three uncertainties related to data (on area transitions, carbon areal densities and emission dynamics) and to the variability linked to the structure of the models, we highly recommend to compare modeling results which definition of ELUC is the same. For model intercomparison, it is even better to assess the values of the four component fluxes of the net land-to-atmosphere CO_2 flux, which is feasible thanks to the three simulations describe in Sect. 2 of this paper: one with Carbon-Climate-Nitrogen perturbation only, one with Land-Use Change perturbation only, and one with both perturbations. The mass conservation constraint gives the fourth and last flux.

Appendix A

Detailed formulations of the four constitutive fluxes

A1 Uncoupled land-use change emissions ($ELUC_0$)

Now, we consider a normalized transition from $(g,\ b_1)$ to $(g,\ b_2)$, i.e. $\delta S = 1$, that happens at time t_0 with no CCN perturbation (like in Sect. 2.2). The successive values of the τ-th element of the cohort (i.e. f_0^τ) taken at $t = t_0 + \tau$ can be written as being the total carbon stock per area unit ($\hat{c}$, expressed in $gC\,m^{-2}$) that is to be emitted during the whole transition (i.e. through all the years of the transition) multiplied by a time-dependent rate of emission that represent the dynamics of this emission (r, expressed in yr^{-1}). We can write:

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$$f_0^{\tau}(t_0+\tau) = \hat{c}_0\, r_0(\tau) \quad \text{(A1)}$$

with the following condition on f_0^{τ} and thus on the function r_0:

$$\int_{\tau} f_0^{\tau}(t_0+\tau) = \hat{c}_0 \Leftrightarrow \int_{t} r_0(t) = 1. \quad \text{(A2)}$$

In this formulation, for a normalized transition, the exact value of $\hat{c}_0$ is the difference in carbon density between the primary ecosystem and the secondary "transitioned" ecosystem (i.e. $\hat{c}_0 = c_0^*(g,\ b_1) - c_0^*(g,\ b_2)$). Indeed, the total integrated over time CO_2 flux induced by a transition from $(g,\ b_1)$ to $(g,\ b_2)$ only depends on the local carbon densities of b_1 and b_2 at the point g, because of mass conservation constraint. That flux is positive, causing net CO_2 emission (resp. negative, causing a net sink of atmospheric CO_2), if the primary ecosystem holds more (resp. less) carbon per area unit than the secondary ecosystem. By way of consequence, land-use activities like forestry, modeled as transitions from $(g,\ b_1)$ to itself, are carbon neutral when integrated over a long enough period (i.e. $\hat{c}_0 = c_0^*(g,\ b_1) - c_0^*(g,\ b_1) = 0$).

The function r_0 is a normalized Impulse Response Function (IRF) for the normalized transition from b_1 to b_2 over g. Thus, if we know the impulse response function at each point g for each transition $b_1 \rightarrow b_2$ noted $r_0(t;\ g,\ b_1,\ b_2)$, if we know the local carbon densities $c_0^*(g,\ b)$ and the history of land-use change transitions $\delta S(t;\ g,\ b_1,\ b_2) > 0$, the emissions from land-use change $ELUC_0$ (under preindustrial conditions) can be expressed at all times t by the following convolution:

$$ELUC_0(t) = \int_{t'=0}^{t} \iiint_{g,b_1,b_2} \left[c_0^*(g,\ b_1) - c_0^*(g,\ b_2)\right] r_0(t-t';\ g,\ b_1,\ b_2)\, \delta S(t';\ g,\ b_1,\ b_2). \quad \text{(A3)}$$

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A2 Extra land-use change emissions (ΔELUC)

Including the CCN perturbation to the experiment of Sect. A1, so as to obtain new impulse response functions, requires adding perturbation terms (with prefix Δ) to the variable $\hat{c}$ and the function r. Consequently, the net land-to-atmosphere areal flux of CO_2 due to the LUC perturbation in presence of the CCN perturbation, at time $t = t_0 + \tau$, is given by:

$$\begin{aligned} f^\tau(t_0 + \tau) &= (\hat{c}_0 + \Delta\hat{c})\,(r_0(\tau) + \Delta r(\tau)) \\ &= \underbrace{\hat{c}_0\, r_0(\tau)}_{f_0^\tau} + \underbrace{\Delta\hat{c}\, r_0(\tau) + \hat{c}_0\, \Delta r(\tau) + \Delta\hat{c}\, \Delta r(\tau)}_{\Delta f^\tau}. \end{aligned} \tag{A4}$$

The term $\Delta\hat{c}$ represents the change in carbon stocks that is to be emitted over the whole transition period. It can be, for instance, an increase in vegetation biomass due to CO_2- and N-fertilization, or a decrease in soil carbon due to the accelerating rate of heterotrophic respiration induced by global warming. The Δr term is the change in the dynamics of emission (i.e. the change in emission rate). However, the same constraint as in Eq. (A2) must be applied so that we have this new condition about the impulse response function r:

$$\int_\tau f^\tau(t_0 + \tau) = \hat{c}_0 + \Delta\hat{c} \Leftrightarrow \int_t r_0(t) + \Delta r(t) = 1. \tag{A5}$$

Since the constraint of Eq. (A2) is still valid, we have:

$$\int_t r_0(t) = 1 \Leftrightarrow \int_t \Delta r(t) = 0. \tag{A6}$$

This equation shows that if the emission rate with CCN perturbation is superior to the emission rate at preindustrial times at the beginning of a transition (i.e. $\Delta r(t) > 0$ for

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"small" values of t; because of increase in heterotrophic respiration rate, for instance) then it will be inferior to the preindustrial rate at the end of the transition (i.e. $\Delta r(t) < 0$ for "great" values of t).

Finally, following Eqs. (A3) and (A4), we can give the expression of ΔELUC that is the sum of three convolutions:

$$\begin{aligned}\Delta\mathrm{ELUC}(t) = &\int_{t'=0}^{t} \iiint_{g,b_1,b_2} \left[\Delta c^*(t';\, g,\, b_1) - \Delta c^*(t';\, g,\, b_2)\right] r_0(t-t';\, g,\, b_1,\, b_2)\, \delta S(t';\, g,\, b_1,\, b_2) \\ &+ \int_{t'=0}^{t} \iiint_{g,b_1,b_2} \left[c_0^*(t';g,b_1) - c_0^*(t';\, g,\, b_2)\right] \Delta r(t-t';g,\, b_1,\, b_2)\, \delta S(t';\, g,\, b_1,\, b_2) \\ &+ \int_{t'=0}^{t} \iiint_{g,b_1,b_2} \left[\Delta c^*(t';\, g,\, b_1) - \Delta c^*(t';\, g,\, b_2)\right] \Delta r(t-t';\, g,\, b_1,\, b_2)\, \delta S(t';\, g,\, b_1,\, b_2)\,. \qquad \text{(A7)}\end{aligned}$$

Note that the two last terms, where the perturbation of the impulse function Δr appears, are expected to be negligible because they are equal to zero if integrated over a long enough period of time, as shown by Eq. (A6). Thus, when developing simple models, ΔELUC might be approximated by the first term only, driven by the changes in carbon areal densities.

A3 Potential land sink capacity (LSNK_0)

The formulation of LSNK_0 immediately comes from Eq. (4) in Sect. 2.1:

$$\mathrm{LSNK}_0(t) = \iint_{g,b} \Delta f^*(t;\, g,\, b)\, S_0(g,\, b) \qquad \text{(A8)}$$

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and we can link the net CO_2 flux Δf^* with the change in areal carbon density Δc^*, in the undisturbed ecosystem (g, b), with the following equation:

$$\Delta c^*(t; g, b) = \int_{t'=0}^{t} -\Delta f^*(t'; g, b). \tag{A9}$$

A4 Altered land sink capacity (ΔLSNK)

Based on Eqs. (7) and (16), we can precise the formulation of ΔLSNK which is, despite being (partly) due to land-use change activities, very different from the one of $ELUC_0$ and ΔELUC:

$$\Delta LSNK(t) = \iiint_{g,b_1,b_2} [\Delta f^*(t; g, b_2) - \Delta f^*(t; g, b_1)] \int_{t'=0}^{t} \delta S(t'; g, b_1, b_2). \tag{A10}$$

The sign of ΔLSNK for a given transition depends only on the sign of the difference $\Delta f^*(g, b_1) - \Delta f^*(g, b_2)$. Thus, land-cover change from an ecosystem of high sink capacity to an ecosystem of low sink capacity induces less carbon removal in the future (i.e. negative sink, i.e. emission). In OSCAR v1 (Gitz and Ciais, 2003) and v2 (Gasser et al., 2013, and this study), most high sink capacity ecosystems are high carbon density ecosystems (e.g. forests), thus deforestation induces both CO_2 emissions ($ELUC_0$ and ΔELUC) and a significant loss of potential sink (ΔLSNK); thence the other name of "amplification effect". Note that if reforestation dominated land-use changes, not only would CO_2 removal occur (i.e. negative $ELUC_0$ and ΔELUC) but there would be a gain of potential sink (i.e. negative ΔLSNK as well).

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A5 Cumulative fluxes

Here, we express the values of the four fluxes integrated over time, on the basis of all previous equations in Appendix A:

$$\int_{t=0}^{\infty} \mathrm{ELUC}_0(t) = \iiint_{g,b_1,b_2} \left[c_0^*(g,\ b_1) - c_0^*(g,\ b_2)\right] \int_{t=0}^{\infty} \delta S\,(t;\ g,\ b_1,\ b_2) \tag{A11}$$

$$\int_{t=0}^{\infty} \Delta\mathrm{ELUC}(t) = \iiint_{g,b_1,b_2} \int_{t=0}^{\infty} \delta S\,(t;\ g,\ b_1,\ b_2) \int_{t'=0}^{t} \left[\Delta f^*(t';\ g,\ b_2) - \Delta f^*(t';\ g,\ b_1)\right] \tag{A12}$$

$$\int_{t=0}^{\infty} \mathrm{LSNK}_0(t) = \iint_{g,b} S_0(g,\ b) \int_{t=0}^{\infty} \Delta f^*(t;\ g,\ b) \tag{A13}$$

$$\int_{t=0}^{\infty} \Delta\mathrm{LSNK}(t) = \iiint_{g,b_1,b_2} \int_{t=0}^{\infty} \left[\Delta f^*(t;\ g,\ b_2) - \Delta f^*(t;\ g,\ b_1)\right] \int_{t'=0}^{t} \delta S\,(t';\ g,\ b_1, b_2). \tag{A14}$$

Note that the expression of cumulative ΔELUC is obtained thanks to Eqs. (A6), (A7) and (A9); and that the expressions of the two coupling terms (cumulative ΔELUC and ΔLSNK) are symmetrical.

Appendix B

OSCAR v2 model and drivers

OSCAR v2 is a compact coupled carbon cycle and climate model. The terrestrial biosphere is treated in an aggregated manner and regionalized following the nine regions

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defined by Houghton (1999). In each region, three biomes (forests, grasslands and croplands) are described by a three-box model, where net primary productivity is affected by CO_2-fertilization through a logarithmic function and by local climate change through a linear function, and heterotrophic respiration rate is affected by local climate change through an exponential function. All parameters are calibrated on more complex and spatialized model. Detailed equations as well as parameters values are given by Gasser et al. (2013).

The LUC perturbation is prescribed as area transitions (land-use change) and as harvested biomass (forestry). From 1700 to 1980, the dataset used is the one by Houghton and Hackler (2001); from 1990 to 2100 it is the one developed by Hurtt et al. (2011). We use a linear transition between the two datasets from 1981 to 1989. The CCN perturbation is, here, limited to atmospheric CO_2 and land surface temperature changes. CO_2 concentrations are prescribed according to Mauna-Loa measurements from 1959 to 2010 (NOAA-ESRL, 2012), and to the CMIP5/RCP database before and after that period (IIASA, 2012). Land surface temperatures are from the CRU+NCEP dataset (Viovy, 2012) from 1901 to 2010, and are supposed to be equal to the average 1901–1920 value before that. The temperatures for the projection under RCP 8.5 come from the climate response implemented within the OSCAR v2 model.

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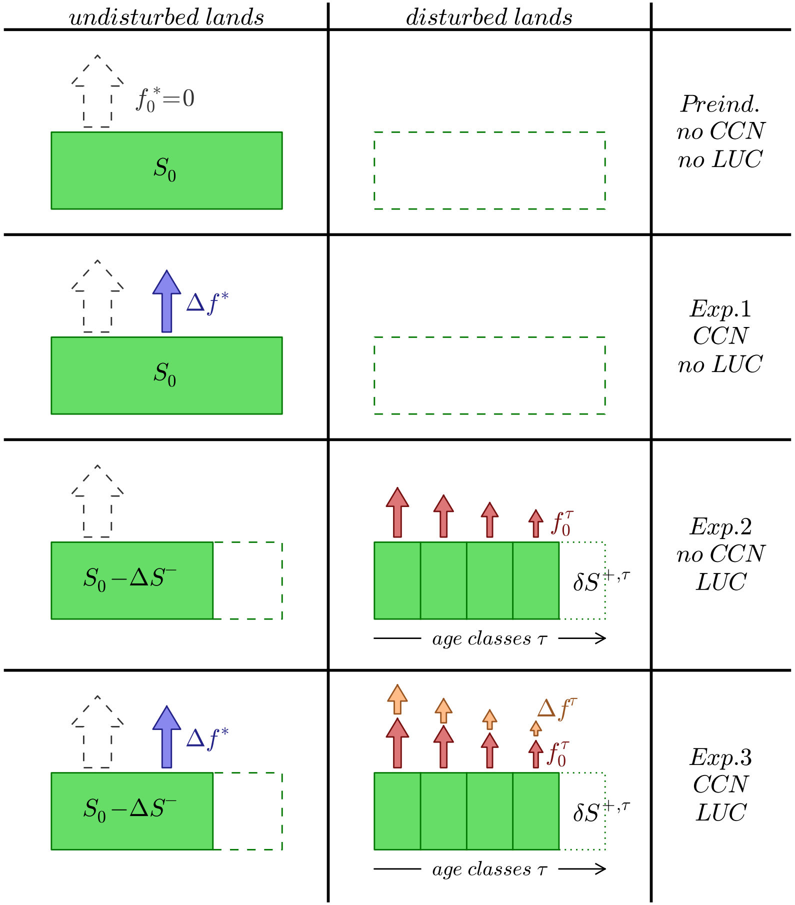

Fig. 1. Conceptual diagram of the three experiments described in Sect. 2. See text for notations and mathematical development of the framework used to break down the net land-to-atmosphere CO_2 flux.

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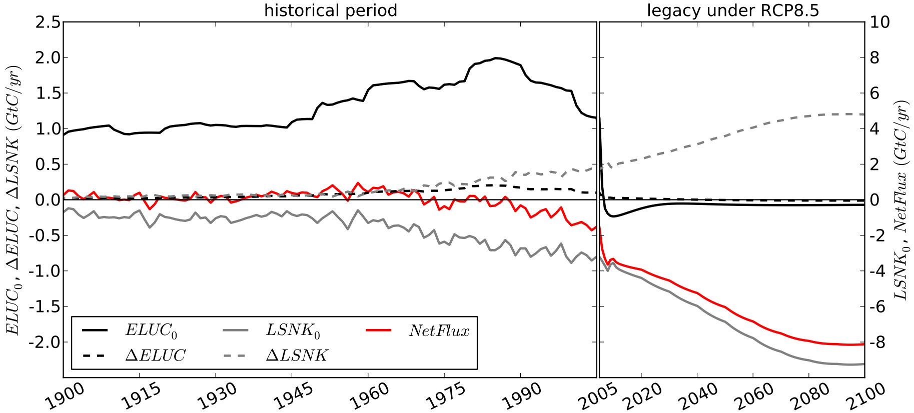

Fig. 2. The four component fluxes of the net land-to-atmosphere CO_2 flux simulated by OSCAR v2. Left panel shows results of the simulation over the last century (1900–2005) and right panel shows the simulated fluxes when the LUC perturbation is stopped in 2005 but the CCN perturbation follows the RCP 8.5 scenario. $ELUC_0$ is the term driven only by the LUC perturbation (plain black line) and ΔELUC is the term due to the effect of the CCN perturbation over the LUC perturbation (dashed black line). Conversely, $LSNK_0$ is the term driven only by the CCN perturbation (plain grey line) and ΔLSNK is the term due to the effect of the LUC perturbation over the CCN perturbation (dashed grey line). The net land-to-atmosphere flux is the sum of the four components (red line). Note that the scale for $LSNK_0$ and NetFlux is a fourth of the scale for the three other fluxes.

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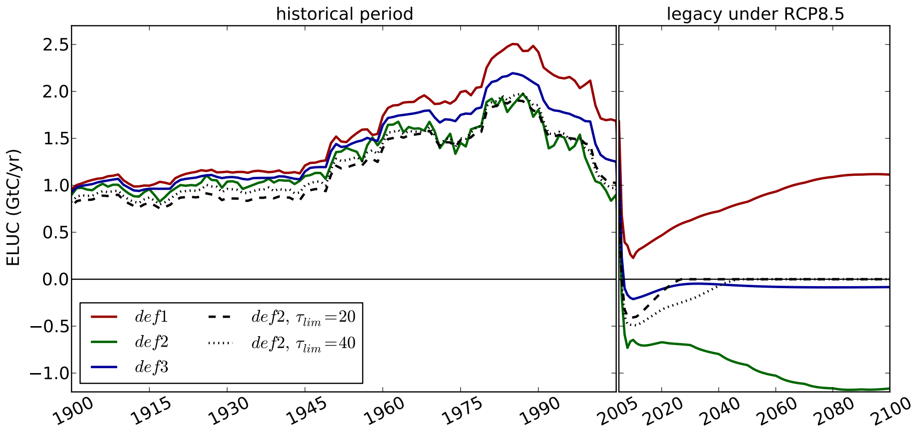

Fig. 3. Illustration with the OSCAR v2 model of the three proposed definitions of ELUC. The three plain lines correspond to the three definitions: first definition is based on the difference between a simulation with land-use and another without land-use (def 1, red line); second definition is based on the distinction between disturbed and undisturbed lands (def 2, green line); third definition is based on the distinction between LUC and CCN perturbations (def 3, blue line). Two examples of the truncated definition 2 (see text) are given, with τ_{lim} being 20 yr (dashed line) and 40 yr (dotted line). Left panel shows the results for an historical simulation, while right panel shows a simulation where land-use activities cease after the year 2005 but atmospheric CO_2 and global warming follow the RCP 8.5 scenario.

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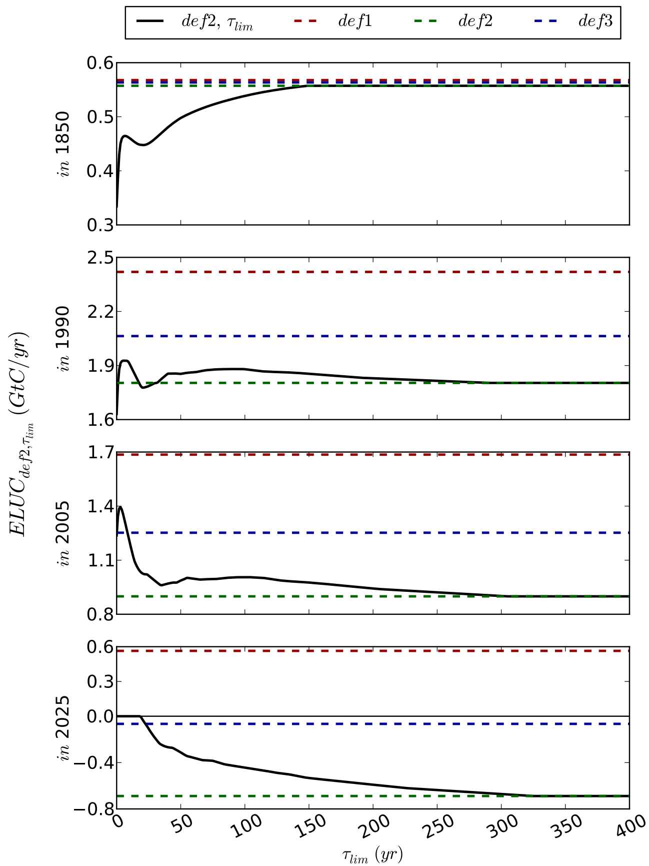

Fig. 4. Value of ELUC defined following the truncated second definition (def 2, τ_{lim}) as a function of the last element of the cohort considered to be disturbed (τ_{lim}), at four different years of the simulation with OSCAR v2. The value of this definition (black line) is compared to the three main definitions (dashed horizontal lines of the same color as in Fig. 3).

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