General comments

This manuscript provides a well-structured framework with which the authors go on to quantify different LUC emission components and explain how they can be isolated formally. This is an extremely welcome contribution to the scientific community and helps to clarify the confusion about different definitions of what is to be counted towards “LUC emissions”. A question that has been addressed differently by different research “sub-communities” (DGVM modelers, book-keeping modelers, satellite data users) and, as the authors demonstrate, may (partly) explain differences in their results.

The formalism in the present paper (thereafter referred to as GC13) is presented in a simplified and understandable form. However, in one aspect (as I try to demonstrate below) the simplification ignores what (fossil fuel emissions vs. land use change) causes what part of the land-atmosphere C flux. This inconsistency leads to an over-estimation of the land use change (LUC) C flux when assessed from the CCN+LUC and the CCN-only experiments (“CCN” used in the meaning of GC13). A more rigorous separation of different fluxes can solve this problem and can also serve to accommodate other flux components within the formalism introduced by GC13 that have been defined in previous publications (LUC fertilisation feedback flux, replaced sinks/sources). In general, a strengthening of such references to and comparisons with previously published Strassmann et al. (2008); Pongratz et al. (2009); Stocker et al. (2011) flux component definitions could - in my view - even further improve this important paper. In particular, the paper by Strassmann et al. (2008) already provides a formalistic framework to quantify LUC flux components.

I’ll start with arguing why I suggest to separate the CCN perturbation into a part caused by FF emissions and a part caused by LUC. The CO₂ increase since pre-industrial times is partly caused by LUC. In other words, today’s CO₂ levels would not be as high as they are, if there was no LUC and consequently, the C sink flux into the biosphere (in models usually resulting from higher CO₂) would not be as strong. This feedback has been termed, e.g. by Strassmann et al. (2008), as land use-climate/fertilisation feedback. As demonstrated by Pongratz et al. (2009) and Stocker et al. (2011), this flux is indeed important and compensated for about 35%-48% of ELUC₀. In other publications, ELUC₀ has been termed “book-keeping flux” Strassmann et al. (2008), or “primary emissions” Stocker et al. (2011). I would argue that when asking “What flux is due to anthropogenic LUC”, then one should compare worlds with and without LUC (but with fossil fuel (FF) emissions in both cases). The inconsistency arises because the world without LUC (GC13 experimental setup 1: CCN, no LUC) comes with a prescribed CO₂ from observations which contains the effect of actual historical LUC.

Clearly, a hypothetical world without LUC but with the effect of FF emissions can only be simulated when feeding a coupled model (ocean+atmosphere+biosphere system) with emissions. In the setup as presented here, the LNSK₀ flux is over-estimated and consequently the sum of the remaining terms in Eq. (16) as well. In the following, I am trying to formally demonstrate this.

Consider a unit land area which is fully converted from natural to agricultural land at time t = 0. In a world with LUC, the C storage on (now agricultural) land is $C_{agr}^{*}$ (the star denoting equilibrium). Note that the superscripts denote what drivers to environmental change (CO₂, climate, etc) are acting in the two worlds. In a world that has not been affected by LUC, but is affected by higher CO₂ levels due to FF emissions, the unit C storage consequently is $C_{nat}^{*}$. The cumulative emissions caused by the LUC disturbance can be quantified as

$$\Delta C^* = C_{nat}^{*} - C_{agr}^{*}$$  (1)

Both terms on the right-hand-side can be expressed as the sum of the preindustrial equilibrium
storage plus the cumulative sink/source flux due to the indirect effects of FF emissions (and LUC).

\[ C_\text{nat}^\star = C_0^\star \text{nat} + \int_0^\infty f_t^\text{FF} \, dt = C_0^\star \text{nat} + \Delta C_\text{nat}^\star \]  \hspace{1cm} (2)

\[ C_\text{agr}^\star + LUC^\star = C_0^\star \text{agr} + \int_0^\infty f_t^\text{FF} + f_t^LUC \, dt = C_0^\star \text{agr} + \Delta C_\text{agr}^\star + \Delta C_\text{agr}^\star + \Delta C_\text{agr}^\star \]  \hspace{1cm} (3)

Combining above equations and re-arranging the terms illustrates different fluxes:

\[ \Delta C_\text{agr}^\star = C_0^\star \text{nat} - C_0^\star \text{agr} - \Delta A + \Delta C_\text{nat}^\star - \Delta C_\text{agr}^\star - \Delta C_\text{agr}^\star + \Delta C_\text{agr}^\star \]  \hspace{1cm} (4)

By not discriminating the CCN perturbation that is due to FF from what is due to LUC, the emissions due to LUC are quantified as

\[ \Delta C_\text{agr}^\star = C_\text{agr}^\star \text{FF+LUC} - C_\text{agr}^\star \text{FF+LUC} \]  \hspace{1cm} (5)

Expanding the components as above yields

\[ \Delta C_\text{agr}^\star = C_0^\star \text{nat} - C_0^\star \text{agr} + \Delta C_\text{nat}^\star - \Delta C_\text{agr}^\star - \Delta C_\text{agr}^\star + \Delta C_\text{agr}^\star \]  \hspace{1cm} (6)

The right-most term does not appear in Equation 4. For a historical simulation, it will be positive, the flux \( \Delta C_\text{agr}^\star \) derived from Equation 6 will thus be higher than in Equation 4 where the CCN perturbations caused by LUC and FF are rigorously separated. This issue is common to all quantifications of LUC emissions that rely on uncoupled DGVMs with prescribed observational CO\(_2\). The present paper could make a strong additional point by demonstrating this using the formalism they introduced.

The additional term in equation 6 is \( \Delta C_\text{agr}^\star \text{LUC} \) and represents a flux caused by LUC-induced changes in CO\(_2\) (and climate, N-deposition, etc.), it is thus something like the LUC fertilisation feedback. I have tried to write above equations in the form introduced by GC13, but made some changes. Similar as above, I will use a superscript denoting the sort of environmental condition the fluxes are affected by; and subscripts for the type of land where the flux is occurring. E.g., \( f_0^\text{nat} \) is flux on natural land that (would) occur under preindustrial conditions, while \( \Delta f_\text{nat} \) is change of that flux in response to higher CO\(_2\) altered climate, etc. caused by FF and LUC. The \( F \)s are thus the sum over all biological units \( b \), instead of the \( b \)-specific flux as in GC13 (see their Equation 5). I found this notation very helpful to intuitively understand to define different flux components (see below).

Following a more rigorous separation of the CCN perturbation by its causes (FF vs. LUC), the total flux due to LUC can - as above - be quantified as the difference between the flux in a world where only the FF perturbation is acting, and a world where the FF perturbation and LUC, including its (indirect) effects on CO\(_2\)/climate, are acting.

\[ F_\text{LUC} = F_{\text{FF+LUC}}^\star - F_{\text{FF}} \]  \hspace{1cm} (7)

The flux in the FF-only world is

\[ F_{\text{FF}} = \Delta f_\text{nat} A_0 \]  \hspace{1cm} (8)

while the (total) flux in the FF+LUC world is

\[ F_{\text{FF+LUC}} = \Delta f_\text{nat} \left( A_0 - \Delta A \right) + \left( f_0^\text{FF+LUC} + \Delta f_\text{nat} A_0 \right) \cdot \delta S^+ \]  \hspace{1cm} (9)
With $\Delta f^{FF+LUC} = \Delta f^{FF} + \Delta f^{LUC}$ the flux due to land use change $F_{LUC}$ becomes

$$F_{LUC} = \Delta f_{LUC}^{nat} A_0 - \Delta f_{FF}^{nat} A^- - \Delta f_{LUC}^{nat} A^-$$  \hspace{1cm} (10)

$$+ f^0 \cdot \delta^+$$  \hspace{1cm} (11)

$$+ \Delta f^{FF} \cdot \delta S^+ + \Delta f^{LUC} \cdot \delta S^+$$  \hspace{1cm} (12)

By not discriminating what part of the CCN perturbation is due to LUC and what due to FF, the authors write for the CCN only simulation:

$$F_{CCN} = \Delta f_{FF+LUC}^{nat} A_0 = \Delta f_{FF}^{nat} A_0 + \Delta f_{LUC}^{nat} A_0$$  \hspace{1cm} (13)

In that sense the flux due to LUC, quantified as $F'_{LUC} = F^{FF+LUC} - F_{CCN}$ becomes

$$F'_{LUC} = - \Delta f_{FF}^{nat} A^- - \Delta f_{LUC}^{nat} A^-$$  \hspace{1cm} (14)

$$+ f^0 \cdot \delta^+$$  \hspace{1cm} (15)

$$+ \Delta f^{FF} \cdot \delta S^+ + \Delta f^{LUC} \cdot \delta S^+$$  \hspace{1cm} (16)

The difference between the two quantifications is $F_{LUC} - F'_{LUC} = \Delta f_{LUC}^{nat} A_0$, analogous to $\Delta C_{nat}^{LUC}$ in Eq.6.

**Specific comments**

- I was puzzled by whether $\Delta S^+$ and $\Delta S^-$ were equal. Obviously they are not, because fluxes are presented for each geographic location and type (biological unit/PFT). I personally would prefer to see fluxes presented for the integral (sum) over all bs (see GC13, Eq. 5), but differentiated between two types of land: natural and agricultural. I find such a distinction helpful because it makes evident that fluxes ($\Delta f^{FF+LUC}$) are different on natural and agricultural land, and that this difference defines the “replaced sources/sinks flux” ($F_{RSS}$).

- An integral over $b$ would imply that $b$ is a “continuous dimension”, but it’s not. Distinguishing between natural and agricultural lands, or by PFTs, or biomes, always leads to discretisations. Thus, presenting sums instead of integrals would make more sense. But, as mentioned above, I would suggest to reduce $b$ to natural and agricultural land and always present the sum explicitly written out to make the difference in associated fluxes ($\Delta f^{FF+LUC}$) evident.

- page 191, line 9: “... without any LUC perturbation after the year 2005”: I assume it means without any further change (land distribution is “frozen”) rather than returning immediately to zero land use areas? However, then I don’t understand why ELUC$_0$ is negative after 2005 AD. Can you clarify?

**References**

