RC1: 'Comment on egusphere-2025-2202', Anonymous Referee #1, 12 Aug 2025

Replies to **Reviewer 1:**

- **General comment 1: This study introduces a new land allocation tool to produce spatially explicit datasets consistent with different states of the LSC planetary boundary. The conceptual framework is enticingly simple and forms a novel contribution. Using the PB framework, the authors construct unique scenarios which provide a much-needed contribution to the currently limited diversity of LULCC scenarios in the literature. However, the simplicity of the approach is not supported with sufficient discussion about its potential limitations. In particular, the manuscript would benefit from further discussion about the land use allocation algorithm employed which omits key factors known to influence LULCC, including land productivity, land use and conversion costs, and socioeconomic factors. Including these factors could result in significantly different patterns of LULCC than those simulated here and add further layers of uncertainty not explored.**

  Response: We thank the reviewer for their generally positive review and agree that the discussion is currently lacking a limitations section. In the revised manuscript, we will include a new limitations subsection that explicitly synthesizes the main points raised by the reviewer. In line with the reviewer remarks, we will stress that socioeconomic factors driving LULCC are vast, ranging from existing transport infrastructure that limits accessibility, to policy and legislation frameworks, as well as national and international demand for produced commodities. LUCATOO deliberately abstracts from these complex socio-economic drivers by applying a simplified and spatially uniform LULCC allocation scheme. This abstraction is intentional and motivated by the objective of generating internally consistent, spatially explicit land-use configurations that meet predefined planetary boundary–related constraints, thereby enabling controlled experiments on biophysical Earth system responses. These limitations will be explicitly discussed, and we will emphasize that the resulting scenarios should be interpreted as stylized, boundary-consistent land-system states rather than plausible future trajectories.

Representing socio-economic drivers and producing realistic future LULCC projections lies beyond the scope of the present study and of this initial version of LUCATOO.

- **Specific comment 1 (L47): While forest loss is a prominent example, it might be worth highlighting that the impacts of LULCC are not just limited to forests but can affect a diverse range of ecosystems. For example: peatland drainage resulting in carbon emissions, soil carbon loss due to overgrazing of semi-natural grasslands. Additionally, LULCC impacts aren't necessarily binary (e.g. forest vs. no forest) but can exist on a continuum based on different levels of land use intensity. While this study focuses on absolute deforestation and afforestation, it's important to note the complexity of forest degradation more generally.**

  Response: We fully agree with the reviewer that the sole focus on forest ecosystems is not enough to highlight the diverse and severe impacts of LULCC. In this study, we focus exclusively on forest biomes, following the current definition of the planetary boundary for land system change (PB-LSC), which is the prime motivation for the development of our tool. Steffen et al. 2015 justify the focus on forest biomes in the following way: *"the control variable has been changed from the amount of cropland to the amount of forest cover remaining, as the three major forest biomes—tropical, temperate and boreal—play a stronger role in land surface–climate coupling than other biomes".* To address the reviewer's concern, we will revise the Introduction to clearly state that the definition of LULCC adopted in this paper is tailored to PB-LSC and therefore focuses exclusively on forest transformation. In addition, we will add a dedicated paragraph to the Discussion that explicitly acknowledges the resulting limitations. In this section, we will clarify that LUCATOO is tailored to the current PB-LSC definition and thus excludes changes in other ecologically and climatically important land systems such as savannas, grasslands, or wetlands, a conceptual limitation inherited from the PB-LSC framework rather than a modeling choice specific to LUCATOO. In our manuscript, we will note that future versions of the tool could be adapted to include additional land systems. Furthermore, we will include that by omitting more nuanced forms of forest degradation such as selective logging, fragmentation, or understory thinning

LUCATOO likely underestimates the full spectrum of anthropogenic pressures on forest ecosystems and their Earth system impacts.

- **Specific comment 2 (L50-54): A little more background about how the 50% and 85% boundaries were chosen would be useful. It's not clear how the third sentence of that paragraph leads on from the previous two. Where are we currently with respect to these boundaries? I think there needs to be more justification for setting a lower boundary for temperate forests or at least a discussion of the limitations of this assumption. The original source (Steffen et al. 2015) states "this is a provisional boundary only" – are there no recent updates? This lower boundary is justified in Steffen et al. by referencing Snyder et al 2004. However, I find this claim is not at all clear just from that paper - the climate impacts of removing temperate forests seems comparable to other biomes.**

  Response: The current definition of PB-LSC is still based on provisional estimates, a shortcoming that we had already acknowledged in the original manuscript (ln 50). We do agree with the reviewer that the rationale behind the placement of the 50% and 85% boundaries needs to be stated in the paper. In our revised manuscript, we will elaborate on the rationale behind the different boundary values assigned to the major forest biomes. Specifically, we will explain that the stricter precaution applied to tropical and boreal forests reflects their strong and distinct climate feedbacks (moisture provision, albedo feedback). This shortcoming builds one of the major incentives of the study and LUCATOOv1: to be able to selectively deforest and reforest and quantify the impacts on affected Earth system processes (Fig 1).

- **Specific comment 3 (L167-169): Why were continents chosen as the regional boundaries? That seems somewhat arbitrary. Wouldn't ecologically relevant boundaries such as ecoregions be more appropriate? Or national boundaries given the importance of domestic policies.**

  Response: We follow the original control variable definition from Steffen et al. (2015) who state: *"In particular, we focus on those land-system changes that can influence the climate in regions beyond the region where the land-system change occurred."* This line of argumentation builds the premise for analyzing LULCC on a continental

scale. We thank the reviewer for this important comment, as it links to one of the novelties and strengths of our approach: with the introduction of LUCATOO, the scientific community is given a tool at hand to adjust LULCC on a chosen spatial level. We have already explored this possibility and adjusted LULCC on the level of IPCC reference regions (see *Appendix C: IPCC reference region level*). Moreover, we conducted first test runs to operate LUCATOO on the national level but the spatial resolution of the underlying LPJmL model (0,5°x0,5°) constitutes a challenge for such finer granularity.

- **Specific comment 4 (L197): Uniform intensification is rather unrealistic. LULCC is influenced by a range of factors including land productivity and costs, national and international demand for commodities, and proximity to existing managed lands. This leads to complex LULCC patterns which are rarely spatially uniform, particularly on continental scales. A discussion on the limitations of this assumption is needed.**

  Response: Yes, as already stated above, we fully agree that the patterns of anthropogenic action driving LULCC are far more complex than the uniform intensification featured in LUCATOO. See above comment on the to be added limitation subsection in the discussion which we extend to include a paragraph on the limitations of performing a uniform intensification.

- **Specific comment 5 (L215): Figure 5. The notation used in the figure could be improved. It's not clear whether i, m, p etc. are parameters, variables or sets. For example, using the key in the top right corner, I would translate "i < LU_scn" as "subset of scenario dataset is less than scenario dataset" – while I can guess the intended meaning with the help of the caption, it's perhaps a bit unconventional. Maybe it would be clearer with something like Si < SLU_scn where S is the LSC boundary variable. "m = i*fac.re[m]" and similar is particularly difficult to parse – is this representing the transformation of subset i into subset m? In which case, perhaps this could be written as "m = fre(i)" where fre() is the reduction function?**

  Response: This is an important critique. In the revised manuscript, we will improve the notation in Fig. 5 to make the logic of the allocation procedure more transparent

and conventional. Specifically, we will revise the symbols to clearly distinguish between land-system state variables, subsets of land-cover fractions, and transformation steps, and we will avoid relational notation that could be misread.

- **Specific comment 6 (L226-230): Some background information on previous assessments would fit well in the introduction (see comment for L50-54).**
  Response: We will include and discuss the following references in the introduction: Richardson et al. (2023), more detailed and biome-specific results of their findings. Tobian et al. (2024), who show that temperate forests are more resilient to future climate change than boreal and tropical forest biomes in the LPJmL model. This study found boreal dieback under severe climate change and changes in the PFT distribution of the tropical forest biome (shift from evergreen to deciduous tree types).

- **Specific comment 7 (L255): Figure 6. Higher resolution image needed. It's interesting that each scenario shows either reforestation (planetary boundary) or deforestation (risk and strong transgression) in all biomes but not a mixture of both. Why is that? Given that different biomes in different continents are at or below the planetary boundaries (Table 1), shouldn't result in a more heterogenous response? Also, the uniform application of the intensity factors within each biome is very apparent here. I think there needs to be discussion whether this is realistic, given that observed LULCC is spatially (and temporally) heterogeneous.**
  Response: The reason for this uniform change is the 'prohibiting deforestation' flag, which (turned on for the datasets shown in Fig 6). Currently, the flag is described in line 191 and 239 of the manuscript. This flag protects cells from being subject to deforestation (that includes both the intensification and expansion operations) if their current value is above the boundary threshold. In other words, if the scenario is focused on forest restoration (as it is the case with scenario (I) - Planetary Boundary), deforestation will not occur if the regional biome value is above the PB-LSC threshold. We will highlight the flag in the caption of Fig 6. Regarding the uniform application, see our comment to "Specific comment 4 (L197)(RC1)".

- **Specific comment 8 (L265-267): It's not clear how this has been demonstrated. You have produced maps consistent with the PB-LSC boundary but there was no further analysis of how other PBs are affected under this scenario. Or is this referencing Richardson et al. 2023 (as it appears so further down)?**
  Response: It is correct that we have not demonstrated this. We fully agree with the reviewer that the current phrasing "can help to" is not strong enough to highlight that this paper can enable future research to stress-test the boundary value placements. This section will be largely rewritten to better align with the improved introduction.

- **Specific comment 9 (L289): What did Drüke et al. 2024 find?**
  Response: We will elaborate the important findings by Drüke et al. (2024) who thoroughly examined how the land system change scenarios derived from LUCATOO would affect the Earth system in the long run. They found that a further violation causes a considerable loss of carbon from vegetation and raises global temperatures and aridity.

- **Specific comment 10 (L295-298 and L306): This is an important point of discussion that should be expanded on (also see previous comment).**
  Response: We will expand the relevant parts of the manuscript to more explicitly address the applicability and limitations of the approach across spatial scales. In particular, we will add a clear reference to Section C of the Appendix, where the application of LUCATOO at the level of IPCC reference regions is demonstrated.For more detail refer to answer to Specific comment 3 (L167-169)(RC1).

- **Specific comment 11 (L310-321): As previously commented, the reallocation of CFTs based purely on area is an important limitation here. A more detailed allocation tool would consider other factors such as potential yields, land suitability and production costs as well as trade-offs between agricultural expansion and intensification. Similarly, afforestation could be prioritised based on preservation of ecosystem services such as biodiversity and carbon storage. On a more fundamental level, it's also not clear whether the scenarios presented here are internally consistent – for example, is the amount of deforestation in the strong transgression scenario even feasible given**

socioeconomic constraints? How much demand growth (food, timber etc.) would be required to cause this much deforestation?

Response: We thank the reviewer for this constructive comment. We fully agree that CFT reallocation purely based on area is a strong simplification (see the now added section on limitations as a response to your earlier comment). A future iteration of LUCATOO could incorporate socioeconomic constraints such as potential yields, production costs, and trade-offs between agricultural expansion and intensification. Prioritizing reforestation based on ecosystem service provision (e.g. biodiversity, carbon storage, or hydrological regulation) is an interesting option as this would allow for more realistic or policy-relevant land-use patterns and will subsequently be included in the discussion part. Regarding the internal consistency, please refer to our reply to General comment 1(RC1) "we will emphasize that the resulting scenarios should be interpreted as stylized, boundary-consistent land-system states rather than plausible future trajectories".

- **Specific comment 12 (L329): "cannot be adjusted or modified to depict specific anthropogenic pressure levels" – to the contrary, many land system models work explicitly with "anthropogenic pressure levels", although these can be expressed in different ways (e.g. demand for commodities, marginal utility of ecosystem services). Prominent examples include the major IAMs (IMAGE, REMIND-MAgPIE etc.) and other frameworks such as LandSyMM. While these haven't extensively explored the PB framework, there's no reason why PB-oriented scenarios couldn't be constructed within these models.**

  Response: This is an important clarification, and we agree with the reviewer that many IAMs explicitly represent anthropogenic pressures and, in principle, could be used to construct scenarios relevant to the PB framework. Our original statement was not intended to suggest that such models are incapable of representing anthropogenic pressure per se. Rather, following the PB-LSC definition, anthropogenic pressure is expressed specifically in terms of remaining biome-specific forest extent relative to PNV, enforced at regional scales. Systematically varying such constraints within IAMs typically requires substantial model-specific modifications, additional assumptions, and iterative tuning of socio-economic drivers.

To clarify this distinction and avoid misinterpretation, we will revise the manuscript text accordingly. In particular, we will replace the original sentence with the following formulation: “Currently available LULCC scenario products are generally not designed to directly align with the definition of PB-LSC, nor to systematically vary land-system pressure as defined by biome-specific remaining forest extent relative to potential natural vegetation at regional scales. While such configurations could in principle be constructed within existing land-system and integrated assessment models, doing so typically requires substantial model-specific adaptations, additional assumptions, and iterative tuning of socio-economic drivers.”

We will further clarify that, while LUCATOO is limited in its representation of socio-economic complexity, it provides direct and transparent control over the land-system state required to study the Earth system impacts of varying transgression levels of PB-LSC.

- **Technical corrections 1: (L65) Replace “allocation models” with “land use models”**

  Response: Will be corrected accordingly.

- **Technical corrections 2: (L90) “The following _” section?**

  Response: Will be corrected accordingly.

- **Technical corrections 3: (L260-264) Too repetitive and non-specific, particularly “bridge the conceptual gap of an adjustable depiction”**

  Response: We will shorten the paragraph and make it more concise. It will read: *“Being easily extendable and reproducible, LUCATOO is a versatile tool that ensures the consistent and spatially explicit mapping of different PB-LSC statuses while maintaining the flexibility to be employed for various applications outside the PB framework context.”*