

Review #1

This manuscript introduces a newly developed modelling framework `copan:LPJmL`, which can simulate a wide range of socio-ecological dynamics. This work makes an important contribution to addressing the conceptual and technical challenges in modelling intertwined human and nature processes. The overall structure of the manuscript is clearly presented. The three examples introduced well highlight this framework's flexibility and versatility.

Thank you very much for the extensive positive and constructive feedback. Below we provide a point-by-point response together with the implemented changes in the revised manuscript as well as explanations.

However, the manuscript could be improved by distributing the content more properly between the manuscript and the technical manual to enhance the ease of understanding for readers. In general, I would suggest leaving the conceptual content, modelling decisions/justifications, and model logic in the manuscript, while the technical specifications in the GitHub/Zenodo repo, so that readers can easily navigate from high-level conceptual description to implementation details. More suggestions follow here.

We agree on a better differentiation between conceptualization and API documentation. The API documentation clearly belongs to the software documentation/technical documentation in the software repositories (and hosted on the website `copanlpjml.pik-potsdam.de`) itself.

In the revision, we evaluated all described entities and removed technicalities specific to the Python programming language and the corresponding API documentation. We retained those that are essential for explaining the model structure in the paper, such as World, Cell and associated attributes as Input and Output.

1. `copan:LPJmL` is defined as a framework in the manuscript. It might be ambiguous to readers as a framework can mean different things, such as a conceptual framework, a model, a sub-model, or a wrapper for the existing `LPJmL` to interface with `copan:CORE`. It would be best to clarify what `copan:LPJmL` exactly is early in the text. This could also help readers know clearly what kind of contribution the manuscript is intended to stress.

Thank you, the term “framework” indeed requires clarification. We explicitly defined what a modelling framework is in the Introduction (L72-74) and highlighted that it extends the `copan:CORE` modelling framework by integrating the biophysical Earth system model (`LPJmL`) via a coupling interface as the ENV taxon. This clarification specifies its role as neither a stand-alone model nor a conceptual framework, but as a software and modelling framework enabling tightly coupled human–Earth system simulations with process-based and spatially-explicit detail.

2. Usually, readers are motivated to invest efforts in looking into technical details (e.g., code) only if the concepts are attractive and clearly presented. A class

diagram appears unable to serve as an efficient means of communication, as it normally provides neither conceptual simplicity for broad readers nor accurate technical details for developers. It would be best to replace the class diagram with a conceptual framework that illustrates the connections and information flow between model components.

The class diagram was replaced in the main text by a conceptual diagram illustrating model components, data flow, and feedbacks between LPJmL, copan:CORE entities, and above all the user-defined model

3. Accordingly, much of the technical description, especially the parts that mix narratives with variable names defined in the code, could be organised into a README.md/txt file in the code repo, leaving only the description of the conceptual idea and model logic (using text, pseudocode, or equations) in the paper. I saw the current code repo only has a minimal technical description in contrast with that in the manuscript. A proper redistribution of the content might be necessary.

We agree and will redistribute content accordingly. Code-specific descriptions, API-level details, and variable-level explanations will be moved to the software documentation (Read the Docs and GitHub repositories). The manuscript was revised and formulations such as “world.output” removed. Figures 3, 4 from the submitted manuscript have been moved to the appendix and Figures 6, 9 have been removed and replaced by Figure 4 (revised manuscript). We further reformulated L141-150 in the submitted manuscript to make it less technical. Several paragraphs in Section 2.3 have been adjusted accordingly or removed such as L152-162, 176-179 or 183-185 from the submitted manuscript.

4. The code shown in the figures seems to provide limited information about the model mechanism. If the code only serves as examples of the use of copan:LPJmL, the README file in the repo should be the best place.

The code snippets shown in the manuscript are intended solely as illustrative examples demonstrating the flexible interface and versatility that enables different modelling approaches. We see that this perspective is limited to Python developers and modellers and therefore was removed and replaced by a conceptual figure (Figure 4). Detailed model mechanisms belong to the respective model implementations (e.g. InSEEDS) and are documented in their dedicated repositories.

5. The manuscript could be improved by avoiding relying on Python syntax in the narrative. Although Python and object-oriented programming are widely used in research, using syntax-dependent expressions like “world.input[1]” might not be an ideal way to express the gist of copan:LPJmL.

We agree that Python-specific syntax in the narrative may obscure the conceptual structure of the coupling framework. We therefore revised the manuscript to remove implementation-dependent expressions (e.g. world.input[...]) from the main

text. The underlying functionality is now described using more general terms like "Cell is an attribute of World".

6. It is fantastic to learn that copan:LPJmL can accommodate a range of modelling approaches. However, the three examples do not contain enough information about how this framework can achieve this. Developers or model users might not be clear about what efforts they should make to switch modelling approaches within copan:LPJmL. I would suggest describing the examples using an identical structure: for each example, including background information, concepts, model processes, model settings, and outcomes, while highlighting the role of copan:LPJmL and what model users should do. In addition, please cite the source code of each example in the text.

Thank you for this helpful suggestion. We restructured all example sections following a consistent template including: (i) Modelling approach, (ii) Model design, and (iii) Example simulation results. We also added citations of the corresponding source code of the repositories in the text.

7. Line 287, the citation "Schwarz et al." is not complete.

This is a paper under review that is closely linked to this one as it builds on copan:LPJmL and describes the InSEEDS model in detail. We corrected the citation with the current preprint version.

8. Line 370, ")" is missed in "(Chapter 3.1". In addition, I am not sure whether "section" or "chapter" is more accurate in the context. Please check the convention regarding the word choice of GMD.

Chapter was replaced by section and the closing parenthesis was added.

9. Please cite the sources of the figures and code if they are already publicly available elsewhere.

We added explicit citations for all figures and code where it is reasonable apart from the code and data availability statement.

Review #2

This article describes the coupling of the copan:CORE World-Earth model and the DGVM LPJmL, giving three examples of its use for agent-based, rule-based and LLM-based modelling. It's great to see this approach being developed further and the resulting copan:LPJmL framework has real promise for modelling the interactions of human and natural (land) systems, and doing so in ways that are distinct from established models. The easy availability of the framework is also important, and it should be useful to many.

While I think the article is strong, there are several points that either could or need to be strengthened in a revision. These include conceptual descriptions of some aspects of the approach, but also how some of the core functionalities are operationalized. I've highlighted these in the comments below.

We appreciate the reviewer's careful reading of the manuscript and the detailed and thoughtful comments provided. The feedback has been very helpful in identifying where conceptual clarity, interpretation, and applicability of the copan:LPJmL framework can be strengthened. Below, we respond point by point to the reviewer's comments and outlined how we revised the manuscript accordingly.

General comments

- The novel capabilities of the model are given in overview, but the conceptual details aren't always apparent. There's an emphasis on technical description (largely appropriate given the journal) but this isn't always convincingly linked back to the objectives. In particular more content on how (and which) social and decision processes can be modelled would be really useful. There are inevitably some parts that are unclear at the moment, but also I think some under-selling in that the authors leave more open questions about applicability than they need to. See specific comments below on these points.

We agree with this assessment and strengthened the conceptual framing by adding a paragraph in the discussion (L428-440) of the revised manuscript. In particular we linked the technical components of copan:LPJmL (entities, interfaces, and coupling mechanisms) to the classes of social and decision-making processes they are able to represent. We will expand the discussion of the three example applications to clarify how different decision paradigms are already illustrated.

- Resolution: The default resolution given here is fairly coarse for some of the processes (especially social) that the authors highlight as being important; things like social norms and networks, but also diverse vegetation growth within what are represented as single land holdings. Some more detail and justification of the implications of resolution, and how they can be accounted for in an applied model, is needed.

This is an important and well-taken observation. In the current implementation, the 0.5° grid and one agent per cell should be understood as representative of multiple real-world actors within a cell summarising their decision-making. This design choice was made primarily to demonstrate the breadth of modelling approaches that copan:LPJmL can accommodate, rather than to provide a direct representation of land-holding structures or fine-scale social networks. In the revised manuscript, we added a paragraph in section 2.2 (L135-143) for the implications the spatial resolution has for representing Individuals – multiple Individuals as well as representative individuals.

- [Figures: I'm not convinced how useful the figures comprising code \(or components, as in Fig. 2\) are. The code is already available, so it might be best to use more generic/descriptive representations here to give conceptual overviews and to provide more interpretation of model capabilities.](#)

Figure 2 has been replaced by a conceptual framework illustrating the model workflow of implementation, configuration and simulation of the model by defining copan:CORE entities, and the user-defined model. Further figures containing code have either been moved to the appendix (Fig. 3, 4) or removed (6, 9). The latter have been replaced by Figure 4 to show modelling possibilities in the framework for social-ecological processes and feedback representations.

- [The discussion would also benefit from substantially more reflection on applicability and interpretation. Some of this could perhaps deal with flexibility in the model to represent more things or to represent them differently. Even the authors seem unconvinced at times about this!](#)

We agree and will revise the Discussion accordingly. We expanded the Discussion to more clearly reflect on the applicability of the copan:LPJmL framework. In particular, we now discuss the types of research questions the framework is well suited to address (e.g., social-ecological feedbacks, land-use transitions, and adaptive management) (L428-430), highlight the flexibility to represent different modelling paradigms and decision processes (L430-437), and frame the identified limitations more explicitly as modelling trade-offs rather than shortcomings (L468-470).

[Specific comments](#)

[Lines 21-22: 'Committee, 1986' – incomplete reference?](#)

We completed this reference in the revised manuscript.

[Lines 28-29: It might be worth stating how you see WEM relating to social-ecological systems modelling](#)

We added a short clarification explaining that World-Earth Models are a specific strand of social-ecological systems (SES) modelling and relate to, and extend, SES modelling by

explicitly focusing on coevolutionary feedbacks between human and Earth system processes at larger scales (L29-31 in the revised manuscript).

Lines 83-84: Repeated 'detailed'

We revised the wording to avoid repetition.

Line 88: the reference 'Schwarz et al.' doesn't have a year

We added the missing year in the revised manuscript.

Line 109: It's a bit unclear what 'the framework' is.

The term "framework" requires clarification. We explicitly defined what a modelling framework is in the Introduction (L72-74) of the revised manuscript and added an explanation for a similar request by reviewer 1.

Line 110: Clarify the 'aforementioned taxonomy' by writing out the terms again?

The corresponding taxonomy terms have been stated and explained explicitly already in L73ff. of the submitted manuscript.

Line 113: Is the word 'entities' being used in the same sense throughout the description? It seems imprecise in its meaning.

We agree and clarified the use of the term "entity" by the methodological realisation within copan:LPJmL (L191-193). Further Information is provided in the original copan:CORE publication by Donges et al., 2020.

Lines 115-116: Is the Group entity distinct from the social institutions mentioned previously?

We clarified the distinction and relationship between Groups as entities without a location and a looser connection than Social Systems. (L119-120). Social Institutions can either be modelled as both, depending on the context.

Lines 126-127: It would be useful to have here a description or link to one, of what the various agricultural management practices can be.

This is stated in Table 1 and was referenced here in the revised manuscript.

Lines 129-130: Some text already at this point on how this resolution aligns with the objectives of the model would be helpful.

We added a paragraph explaining how the chosen resolution supports the intended modelling objectives (L135-143) as explained above.

Figure 2: I'm particularly unsure how helpful this Figure is. There are lots of terms in there that aren't (and can't easily be) interpreted, so add little value. This might be better in SI with full explanations, and a simpler version here with normal language explanations.

Answered above. We replaced the figure by a conceptual one that shows the copan:LPJmL workflow.

Line 164: 'Serves as a' or 'provides a' alternatively.

We revised the wording accordingly.

Line 170: 'are only sent...'

We revised the sentence for clarity.

Lines 195-199: It would be useful to have less technical (more conceptual) summaries above this point to establish that these things can be modelled meaningfully, beyond the technical capacity of the model. But even at that technical level, it's not clear to me how decisions and interactions can/should be modelled at this resolution.

We agree but we added a clarification for this when writing about the resolution. (L135-143)

Lines 205-206: Are land use and agricultural management given as examples of social processes, or ENV interactions & feedbacks? The following list about the CUL taxon does I think need to be justified and explained better.

Thank you for pointing out this ambiguity. In the revised manuscript, we will added the sentence *We here provide a platform to include and explicitly represent these social processes of different actors and their interactions that influence environmental dynamics, for example through land-use and agricultural management decisions that affect the inputs to the ENV component and its feedback to the CUL taxon.*

Table 1: The 'Key variables' for Land Use seem questionable – what is included in 'land systems'?

We adjusted the wording and added a short explanation and differentiation for the CFTs where it was applicable.

Table 2: Should the vegetation row include PFTs?

Thanks for pointing this out. We added short texts where the corresponding output is available per PFT, meaning PFT-specific values.

Lines 256-257: I think it would be very worthwhile to describe how this can be extended.

The neighbourhood can either be extended or complemented by non-local networks on national or world level networks, depending on the context where Individuals are communicating. We added a short sentence in L265-266.

Figure 5: legend – why ‘following’ Fig 8? (or, why in this order). Also are crop yields and soil carbon the only things observed by the farmer types, and are they known perfectly?

We changed statement to “highlighted in Fig. 1”. And yes, crop yields and soil carbon are the only two things observed and known “perfectly by” farmer agents in the inSEEDS model. We added this paragraph in the revised manuscript *In this realisation farming performance is measured using the average crop yield and soil carbon content at different points in time. It is assumed that farmers perfectly observe both variables in order to enable a preferably deterministic behaviour for analysis purposes only.*

Lines 266-267: As in previous comment, it seems unnecessarily unrealistic for farmer agents to know these things perfectly in the modelled world, and not to know about other constraints or outcomes. Explain/extend

We explained this with the paragraph from the last comment.

Line 273: Can the decision-making process be varied? Explain/extend

We added a short statement that the decision-making process can be replaced by other theories which is discussed in the discussion - linking back to the reply on the first comment of reviewer 2.

Lines 288-289: Anything you can say about how they can do this would be really interesting here.

We added an additional sentence that by using copan:CORE we can use entities, networks and components that have been designed for that purpose.

Lines 291-292: This is a very underwhelming end to the example! Surely you can – and need to – argue that they can at least generate some sort of new insight?

We agree and revised the concluding paragraph of the example to better articulate what kinds of scientific insights such models can generate, such as on coevolutionary dynamics of adaptive management dynamics under climate change (L305-308).

Figure 8 legend: This description seems quite distinct from real-world decisions, and more of a forward-looking optimisation. I’m not sure how much or easily this can be varied to represent alternative ways of making decisions, but it seems important that it can be.

It does not necessarily need to be a decision-making process, it’s a rule-based approach that has been reimplemented and endogenized on the base of copan:LPJmL. The purpose is to demonstrate the framework’s versatility; it can be used to substitute input

data generation that requires scenario specific data generation (Minoli et al. 2019, 2022) otherwise.

Figure 9: It's hard to see the value of this figure.

We see the point, that this figure is very technical and does not show the value of the simple interface copan:LPJmL provides for these kind of studies. We removed it and replace it by the conceptual figure

Line 381-382: It's good that the reasoning is provided as this can change the decision. Is this checked by a human user?

Yes, we will clarify the role of human oversight and how LLM outputs are interpreted within the modelling context. However, given that this is a simple proof-of-concept implementation, we did not systematically analyse the sensitivity of the LLM-Model in this application.

Line 424 on: I would prefer more reflection than a description followed by 'shortcomings'. The model of course can't do everything, so the framing here seems overly-negative, but then interpretation of what the model actually can do is largely missing.

In line with the above suggestion, we agree and revised the discussion. In the revised manuscript we expanded the Discussion to provide a clearer reflection on the applicability of the copan:LPJmL framework. In particular, we now discuss the types of research questions the framework is well suited to address (e.g., social-ecological feedbacks, land-use transitions, and adaptive management), highlight its flexibility to represent different decision-making paradigms and social processes across organisational levels, and frame the identified limitations more explicitly as modelling trade-offs. We also added guidance on how simulation results should be interpreted in the context of both behavioural assumptions and biophysical model responses.

Summary and Outlook: This is quite repetitive of the first part of the discussion; I think you could save space here and cover more ground overall, especially guiding the reader in what the technical capabilities of the model can be used for.

We thank the reviewer for this suggestion. In the revised manuscript we shortened this section to reduce repetition with the Discussion and added clearer guidance on the potential applications of the framework. In particular, we now emphasize that copan:LPJmL enables the exploration of social-ecological feedbacks between decision-making processes and biophysical dynamics.

Bibliography:

- Donges, J. F., Heitzig, J., Barfuss, W., Wiedermann, M., Kassel, J. A., Kittel, T., ... & Lucht, W. (2020). Earth system modeling with endogenous and dynamic human societies: the copan: CORE open World–Earth modeling framework. *Earth System Dynamics*, 11(2), 395-413. <https://doi.org/10.5194/esd-11-395-2020>
- Minoli, S., Müller, C., Elliott, J., Ruane, A. C., Jägermeyr, J., Zabel, F., ... & Pugh, T. A. (2019). Global response patterns of major rainfed crops to adaptation by maintaining current growing periods and irrigation. *Earth's Future*, 7(12), 1464-1480. <https://doi.org/10.1029/2018EF001130>
- Minoli, S., Jägermeyr, J., Asseng, S., Urfels, A., & Müller, C. (2022). Global crop yields can be lifted by timely adaptation of growing periods to climate change. *Nature Communications*, 13(1), 7079. <https://doi.org/10.1038/s41467-022-34411-5>