Earth System Dynamics Manuscript

Earth system modeling with complex dynamic human societies: the copan:CORE World-Earth modeling framework

Point by point reply

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(Reviewers' comments cited in italics)

Summary

Based on our earlier final authors response on the discussion paper, we revised the manuscript thoroughly to address the issues raised, deviating only very slightly from the detailed plan we had outlined in the final authors response. We therefore mainly repeat the point by point reply from the final authors response and indicate in blue where we deviated from it.

Response to Brian J. Dermody (reviewer 1)

The authors present a modelling framework for a new generation of Earth System Models that they term World Earth Models (WEM). The paper presents their theoretical framework for capturing environmental, cultural and what they term, social metabolism processes in a linked model. They then provide details of the software package copan:CORE, which builds on their theoretical framework and is implemented in Python language.

It is this reviewers opinion a new generation of Earth System Models is urgently needed to capture complex dynamics between humans and the environment and this paper is an important first step in attempting to implement a modelling framework for a WEM.

We are happy that you share our opinion on the need for a new generation of models and thank you for your overall assessment of our attempt.

However, I would like to see more argumentation for the development of the theoretical framework they set out as well as clearer description of the model implementation, with consistency between the description of the theoretical framework and the model implementation framework. In addition, I suggest some structural changes to the paper.

We improved the MS in this respect by considering your specific suggestions below. Regarding the consistency between the description of the theoretical framework and the implementation framework, we are not completely sure where you find them inconsistent, so we checked carefully during the revision process that these two levels of description are more easily matched by the reader.

Paper Structure

I think the paper could benefit from a slight restructuring for sections 1–3. The introduction introduces many terms without explanation or explanation comes in section 2 and 3. One important example of this is the term social-metabolism. This is later defined along with the other theoretical framings of the Earth System: environment and culture. You should introduce this framing earlier.

We realize we might have misjudged the commonality of terms such as "social metabolism", which might, though well-established in some research communities, be unfamiliar to part of ESD's readership. We made sure to identify such terms by having the MS read again by a more traditional Earth System scientist and have accordingly given their definitions earlier.

So, I would recommend starting with a shorter introduction with section 1.1 outlining the current state of modelling earth system processes, the shortcomings of these approaches and the motivation for a new framework.

Then section 1.2 outline briefly, and in a language that users can follow (so if you introduce a new term such as social-metabolism, explain it), your theoretical framework, what problems it addresses and how it is implemented.

We agree that such a summary will allow the reader to get a faster general understanding of what will follow.

If we understand the following part of your comments correctly, you suggest to either remove the original section 2, which describes the guiding principles we suggest for World-Earth Models, or to include it in much shorter form in 1.1., or to merge it with the description of the theoretical modeling framework (which is originally section 3). Since you comment on parts of this original section 2 below, we assume you would agree that they should not be deleted completely. Because these principles constitute part of the motivation for particular choices we made in designing our framework, we believe that they need to stay included in some way, but may be shortened considerably. After giving this much thought, we have decided to reorder the first sections as follows, giving them significantly more structure than before:

- 1 Introduction and theoretical considerations
  - 1.1 Motivation
    - 1.1.1 State of the art
    - 1.1.2 Current gap in the Earth system modeling landscape
    - 1.1.3 World-Earth modeling: a novel approach to Earth system analysis of the Anthropocene
    - 1.1.4 Features of the copan:CORE modeling framework
  - 1.2 General characteristics of integrated World-Earth models
    - 1.2.1 Basic process taxa in World-Earth models
    - 1.2.2 Design principles for World-Earth models
    - 1.2.3 World-Earth models compared to existing modeling approaches of global change
- 2 The copan:CORE World-Earth modeling framework (originally section 3)

Then in section 2 outline the theoretical framework in more detail. Crucial here is to motivate your reasoning behind the choices you make. This is not always clear in the discussion manuscript (Theoretical reasoning behind framework).

We believe that by "theoretical framework" you refer to the software-independent level of description of our framework that originally forms section 3.1, "Abstract structure". We agree that its details might need a better motivation in terms of the reasoning presented in the earlier part of the MS. At the same time, we must make sure that this part can still serve as a concise reference to the main concepts used in our framework that is not cluttered by too much background information and motivation. We have therefore solved this by adding to the end of each subsections of this section a paragraph labelled "Rationale", giving the reasoning you rightly request. So, the beginning of the new section 2 now looks like this:

- 2 The copan:CORE World-Earth modeling framework
  - 2.1 Abstract structure
    - 2.1.1 Entities, processes, attributes

      …

      Rationale: …
    - 2.1.2 Entity types, process taxa, process types

…

Rationale: …

…

Since we moved the section on process taxa to the introduction (see above), the software design section (before 3.4) thus became 2.3.

Then section 3 outline how the model is implemented. It should be very clear how the theoretical framework links with the implementation framework. This is not currently clear to me yet. Figure 2 is helpful, but I would like to see then how that relates to model framework structure: i.e. a figure like figure 4 but then capturing what is shown in figure 2. Importantly, if you keep more consistency between the theoretical framework structure and the implementation structure, then readers and users will be more easily able to follow what you have done.

We agree that the original description of our reference implementation of the framework in the Python language (originally 3.5) was less complete than the theoretical description of the modeling framework's concepts (originally 3.1–3.3) and the language-independent description of the software design (originally 3.4), and hence the link between the theoretical concepts and the individual Python features we mention may not be sufficiently clear.

Still, we feel that we should not add much more detail to this lowest-level description of the software for several reasons. On the one hand, the current implementation in Python is mainly meant as a first reference implementation which readers may use to try out the framework but whose details might undergo significant changes and improvements in future releases and will probably be accompanied by more high-performance-oriented alternative implementations of the same framework in other languages, in particular C++ and potentially Julia, so that a detailed description as part of the MS will soon be outdated. On the other hand, more importantly, ESD is not a software journal and we believe that software implementation details are not important for the scientific understanding of the framework, its design and possible merit for scientific research.

In view of this situation and the length of the MS we therefore restructured the MS regarding the implementation description as follows. The original subsection 3.5, "Reference implementation in Python" became subsection 2.4 but only its original first paragraph and the first code example (Fig. 5) stayed in the main text, extended by a sentence saying that the most recent API documentation can be found online. The rest of the original 3.5 has been moved into the SI, the original Fig. 4 has been dropped because it conveyed no valuable additional information to the new Figs. 3 and 4.

To visualize the different elements of the software more clearly, we uses the freed space to improve Fig. 3 and added a new Fig. 4 as follows. Fig. 3, originally showing a class diagram only for entity-types, was completed to show all classes that correspond to the abstract concepts shown in Fig. 2, in an arrangement corresponding to Fig. 2. i.e., we added the classes "Culture", "Metabolism", and "Environment" to its left and the classes "Step", "Explicit", "ODE", "Implicit", "Event" etc. to its right. The new Fig. 4 shows in a simple way how several model components contribute mixin-classes to the entity type implementation classes of a composed model.

Theoretical reasoning behind framework

Page 4 Line 10: The planetary boundaries concept has come in for some criticism lately (Montoya et al. 2018). A model framework such as this can potentially explain how planetary boundaries emerge through cross-scale human-environment interactions. It would be good to explain shortly how such a model framework could illuminate how we can understand how global planetary boundaries link across scales, keeping in mind the criticisms of the concept.

We thank the referee for this helpful comment. We added a more detailed discussion of how World-Earth modeling can help to understand the properties of planetary boundaries as emergent properties of complex social-ecological systems on the global scale, reflecting also on different perspectives on the planetary boundaries concept.

Page 4 Line 25 "environmental and societal processes should be described on similar levels of complexity" – sounds good but why? And what does that mean in reality? A tree and a person is equivalent? A country and an ecosystem equivalent? If so, what is the theoretical grounds for that?

We aim to state here that in our opinion World-Earth models should contain balanced representations of social and biophysical components of the Earth system. They should neither be too biased towards very detailed biophysical processes (as current Earth system models already cover this terrain) or towards very detailed socio-economic processes (as current Integrated Assessment Models [IAMs] cover part of this terrain already). Still, concrete model design needs to follow the requirements of the research questions at hand. In the revised manuscript, we provided a more differentiated reasoning behind this guideline for WEMs.

Page 4 line 30–33, page 5 line 0–5 This seems all reasonable but why? And what is your grounding for these statements? In addition, there is a large body of work on applying agent-based models in the socio-cultural domain, which seems to have been ignored here. If you want to capture that, then you should demonstrate that you are aware of this literature and have considered it, including the many pitfalls of applying agent-based models to social systems. Also relates to the statement on Page 6, Line 13–15. There has been extensive work on formal modelling of socio-cultural processes. See Netlogo References for example: https://ccl.northwestern.edu/netlogo/references.shtml

We added an explicit explanation of why we think that agent-based (ABM) and network modelling approaches are a valuable addition to Earth system modelling and should, hence, be implementable in World-Earth models. We emphasized the point that while there is a rich literature on ABMs and formal modelling of socio-cultural processes, it has so far been weakly integrated with other Earth system processes in Earth system modelling. World-Earth models are intended to be designed as tools to enable this integration and coupling that is missing so far.

Page 5 line 9–10 Outline why it is important to capture tipping points. This should also be covered in the intro when discussing shortcomings of existing models.

We thank the referee for pointing out yet another missing explicit explanation for one of our suggested guidelines. We revised the text accordingly, highlighting that a major shortcoming of existing models in the Earth system domain (particularly IAMs) is their inability to represent social-economic or social-ecological or social tipping points.

Coupling or not?

It is not clear to me whether the copan:CORE framework is designed to couple to other models such as LPJ-Guess and IAMs that you mention or if it is a standalone model with different modules or both? I.e. can external models can be modules within the copan:CORE framework? I would encourage you to outline this in more detail and with more prominence in the paper as a lot of the community are interested in a framework for coupling existing models that can incorporate the kind of dynamics you set out to include.

This is a really important remark which also very much resonates with Mr. Lemmen's comments. We admit we should have discussed the coupling issue in much more detail and will do so in a new subsection 2.3.5, "Interoperability with other model software". To answer your question already here, at the moment it is essentially possible to include external model software by writing a short "wrapper component" that handles the exchange of state data, including any necessary regridding, and calls the external model's time-stepping function as long as the external model provides some interface that allows this (e.g. by implementing a BMI, see Mr. Lemmen's comments below). For IAMs that run in intertemporal optimization mode rather than time-forward simulation mode (via stepping or integration) this will probably not be possible since copan:CORE currently only supports time-forward simulation mode.

Model description

Generally, I find the model description too vague to know what can and can't be done with it. For instance, it is mentioned you can model resources flows and migration with it. How would this be implemented? Perhaps a few simple examples of specific model frameworks would help the reader understand what copan:CORE can and cant do. E.g. explain how would you use the framework to capture the relation between migration and drought or how tragedy of the commons scenarios emerges within a river catchment?

We were hoping the exemplary model described in the original Sec. 4 would suffice to answer this question. As described in the SI, it implements some resource flows via ODEs in its carbon cycle and economic production components, and has other ODEs implementing migration in its "wellbeing-driven migration" component. The bottom lines of the original Fig. 10 (now moved to the SI for space reasons) show a code example, how ODEs are specified in the Python reference implementation. Regarding the modeling of a possible relationship between migration and drought, a model component developer has many possibilities: she could "micro"-model individual migration decisions by giving her "Individual" entity-type mixin class a process of type "Event" that makes the individual move to a different "SocialSystem" at some regular or random time-points with some probability depending on some attribute of its current "Cell" of residence that represents the occurrence of a drought. Or she might choose a "macro"-modeling approach by giving the "Cell" mixin class a process of type "Explicit" that specifies an explicit equation which computes at each time point the emigration flow from this place as a function of some drought-related cell attributes. For tragedy-of-the-commons scenarios the model component developer might chose a game-theoretic modeling approach and give each "Cell" representing a catchment a process of type "Step" that represents discrete time-points at which all "Individual"s residing in the cell make water extraction decisions; the outcome of these decisions might by implemented by giving each "Cell" another process of type "Implicit" that encodes a system of implicit equations which represent the Nash equilibrium between these individual decisions. Implicit equations can also be used to model price equlibria. We have chosen the code examples in original Figs. 9 and 10 to show all available formal process types.

Specific Comments

Page 1 line 1–3. This is quite a vague opening sentence. I would drop it. Start with: we introduce.… (the abstract is already quite long)

We revised the opening sentence to give a clearer motivation of the paper, but decided to keep a motivating sentence in the beginning as a central part of what constitutes an abstract.

Page 1 line 5: Not clear what is meant by user roles. Can you be more explicit, especially since this is the abstract.

In shortening the abstract, we dropped the mentioning of user roles from it.

Page 1 Line 14: I wouldn't include social metabolism in the abstract. Not a widely know term.

In shortening the abstract, we also dropped the mentioning of social metabolism from it.

Page 3 line 30–35 Is this an agent-based model? From the abstract and introduction, I thought it was more than that. However, this concluding paragraph makes the reader think that you are going to introduce an ABM. If you view it as an ABM, fine. But then state that clearly in the abstract.

World-Earth models in our understanding contain agent-based process representation along with other modules that may be, e.g. grid-based. We now clarify this in the text.

Page 5 line 8 what is time forward integration?

We now define it like this: simulation of changes in system state over time consecutively in discrete time-steps (e.g. via difference equations or stochastic events) or at a continuum of time points (e.g. via ordinary differential equations), rather than solving equations that describe the whole time evolution at once as in intertemporal optimization.

Page 7 Figure 2. While I like this figure, it could be clearer. It's not clear to me how each of the elements relate. Is each level of the network equivalent to Cul, Met and Env and are they then equivalent to the network on the right? It could be simpler to just show the central image (entity types) in one figure in the new intro section 1.2, for example. I like the way you show the different modelling approaches but it isn't clear with the network image how they relate or how cul,met, env relate.

The original version of the Fig. is the result of a lot of discussions with colleagues. We found it important to make clear that there are these three different aspects of WEMs, process taxa, entity types, and modeling approaches, and that they are loosely related without having a simple one-to-one relationship. The thicker lines between "CUL" and "individuals", "MET" and "social systems", and "ENV" and "cells" indicate that we expect that most socio-cultural processes will be implemented at the level of individuals, most socio-metabolic processes at the level of social systems, and most environmental processes at the level of grid cells. The thinner lines however are meant to make clear that this is by no means necessary and that some socio-cultural processes (e.g. regular elections) might better be implemented at the level of social systems etc. The same holds for the relationship between entity types and modeling approaches. While agent-based model components will probably most often use the "individual" entity type, they might also use the "social system" entity type, e.g. for representing governments' decisions, etc.
We now make this clearer in the caption and have reduced the grey-level of those lines to be less prominent and not distract from the main point of the figure.

Section 3.1 is very clear.

Page 10 line 4-5 delete "maybe changing numbers and"

Here we disagree since we believe it is a notable feature that during a simulation, the number of, say, individuals may change.

Page 10 line 12 instead of following entity types, write entity types outlined in Section 3.2

OK.

Page 10 line 20: Give an example, such as countries to clarify

OK.

Page 11 line 4: human-designed, human-reproduced

OK.

Page 12 Line 6–30 Introduce this earlier in the manuscript. See my comments on structure

We agree and edited the introduction accordingly, see also our response on restructuring the sections above.

Page 16 Line 4: Examplary is not a word. It appears to be an obsolete form of exemplary which means "perfect".

We now use "example model" instead.

A couple of important references "in prep". Try to find pre-existing publications to support arguments in addition to these where possible.

The Donges et al., in prep., paper is now published as a discussion paper in Earth System Dynamics Discussions (currently in review, 2018). We updated the reference accordingly. Regarding the Otto et al., in prep., paper which is currently in review but not published online, we supported it by already published literature on the topic.

Page 22: Figure nested within references

We moved these to the SI as stated above.

Response to Carsten Lemmen (reviewer 2)

1 General comments

This manuscript by Donges and colleagues introduces the core technology and concept behind a new software tool called "copan", that should serve as "a framework for developing, composing and running World-Earth models". The authors motivate the development of such World Earth Models (WEM) that encompass dynamic descriptions of both the anthroposphere as well as the Earth System, they contrast WEM to integrated assessment and Earth System models, they describe the concepts of the developed software package pycopancore and they show simple example applications of the software.

The contribution is within the scope of the Special Issue "Social dynamics and planetary boundaries in Earth system..." in Earth System Dynamics, although the preferred outlet for this kind of technical model description could also be Geoscientific Model Development. The novelty of the approach is the complexity of a World model combined with a stylized version of an Earth model; the innovation is in the open framework and theoretical embedding of the World Earth Model approach.

The paper is overall well written, but suffers from resilience theory and technical jargon, which should be reduced to address a wider readership.

We thank you for this overall assessment and aimed at making the MS more accessible by reducing jargon, especially in the introduction, which has now been shortened in response to Mr. Dermody's comments, and by giving additional definitions where necessary.

Figures are appropriate but they are of mixed graphical quality and accessibility and should be improved on. Tables are appropriate throughout; code examples examples are useful but in need of better quality. The supplementary material is well presented and useful.

In the revision, we aimed at improving the (old and new) figures' and code examples' appearance.

The theory-laden motivation somewhat contrasts with the very technical model description. Reviewer one already remarked on the need for better embedding of these two major perspectives the manuscript assumes. I agree with that assessment, but for brevity I will concentrate in my detailed review below on other aspects of the manuscript. A major missing part is a description of how the presented copan:CORE framework fits into and operates with much of the existing coupling and model infrastructures in Earth and Social sciences; claims to interoperability, modularity and flexibility remain unsubstantiated.

We realize that this had to be improved, see our responses below.

I recommend that this paper is published after substantial revisions.

We thank the referee for his overall encouraging assessment.

Title, Abstract and related parts of Introduction

Title. There is an inconsistency in the spelling of "modelling" right in the title. Also, consider to spell out WEM as World Earth Model without hyphens; carefully consider lowercase/uppercase for "Model" in WEM. Nowhere in the paper the authors motivate the naming "copan:CORE"; please add a sentence on this naming and add to a table of abbreviations, if any of this is an acronym.

Thank you for pointing this out. We checked all our spelling again carefully. The hyphen in "World-Earth" has become somewhat of a standard spelling, so after reconsidering it, we decided to keep it. We explain the naming "copan:CORE"; "copan" is the name of PIK's flagship activity for studying coevolutionary pathways, all our models are named "copan:XYZ", and "CORE" refers to the modeling framework which will form the core of our working group's model portfolio.

p1 l1ff. That first sentence "Possible future trajectories of the Earth system in the Anthropocene are determined by the increasing entanglement of processes operating in the physical, chemical and biological systems of the planet, as well as in human societies, their cultures and economies" is very debatable. "Possible" is redundant, the choice of Anthropocene (capitalized) possibly politically motivated, the word "determined" raises concern of confusion with "deterministic" approaches and the conjunctions are not well placed. If I may rephrase this, the "Anthropocene (sic!) is characterized by close entanglement between the Earth system and its physical, chemical and biological processes and the World system with its economic, social, and cultural interactions." And certainly there is no need for eight (!) citations to entanglement in the Anthropocene; possibly, authors who argue for entanglement in the anthropocene (minuscule "a") should be cited instead.
p1 l3ff. Second sentence "Here, we introduce the copan:CORE open source software library that provides a framework for developing, composing and running World-Earth models..." This sentence should foremost and first emphasize that this publication introduces a new term and concept, namely that of a WEM, and second that it also provides a software library for modeling such WEM. Also the definition of WEM as "social-ecological co-evolution up to planetary scales" does not agree exactly with the later definitions given in the manuscript. Please elaborate in the abstract on your term WEM, on the theoretical embedding and reduce the room given to technicalities.

We thank the referee for these insightful remarks and carefully revised and shortened the abstract accordingly.

Introduction.

p2 l25ff Please provide a reference your historical examples. In the discussion of the "Tragedy of the Commons" it would not hurt to point to related works that make Ostrum's work operational in model simulations.

We added such references on historical examples and modelling studies operationalising Ostrom's framework.

p2 l34f I believe the term "planetary social-ecological system" needs more explanation. SES are usually understood as local in much of the literature, and as multiple instances that behave very different. Thus, also the implementation of SES mostly in agent-based models (as you mention yourself later in the introduction). Elaborate and contrast your "planetary" approach to the local SES. You might also consider to reduce usage of the term SES altogether in favor of your new term WEM to avoid this confusion.
p3l 7ff Congratulations on the choice of the term "World Earth Model". This is to date the best term I have yet heard to describe the type of model you've developed. I suggest to elaborate on how you come to this term, and to set it off from other terms including, but not limited to, SES and CHANS (Coupled Human and Natural Systems).

We revised the introduction to define and explain these terms and their interrelations and differences, while making sure that such elaborations do not take too much attention away from the actual aims of the paper.

Blueprinting World Earth Models

p3 l6ff Please use precise language, do not "outline guidelines" or "address leading research questions". Check entire manuscript for this type of bloated wording.

We revised the text to ensure a more concise and crisp language.

p3 l7ff For the definition of an Anthropocene you already need to say how it differs from the Holocene and other paleoclimatic stages. So the first half of question type 1 is circular. As for the second part "how might it alter the evolution", it is unclear what "it" refers to. Certainly the "Anthropocene" is not an actor (so it cannot alter) but a diagnostic term for the World-perturbed Earth. Please clarify.

Well spotted. We carefully revised and clarified this sentence and others relating to the notion of the Anthropocene.

p3 l8ff Avoid general valueing statements like "disastrous" or specify; check entire manuscript for further occurences of such type. Avoid jargon here and explain all domain-specific terms.

We very much agree and revised the text accordingly to avoid unnecessary jargon.

p3 l27 Here you use "framework" in the management sense, later you use (software) "framework" for the technical description.

You are right, this was an unsensible choice of term here. We rephrased this sentence, avoiding the word "framework". We now reserve the word "framework" for its software meaning in the MS.

Then you both consider Netlogo as well as copan:CORE frameworks, but both are very different things. I would prefer to term NetLogo a modeling platform.

We agree since NetLogo provides a graphical interface and other features typical of a modeling platform.

The term "framework" is a difficult one, please try to use it consistently in only one sense (and explain that sense by giving your definition of a framework) throughout the paper.

We added a short definition of "modeling framework" similar to the one of "software framework" that can, e.g., be found on Wikipedia.

p3 l27 The "high degree of modularity and flexibility and coupling capabilities" is not substantiated. While there is some software modularity and role modularity (see my later comment), there is no effort made towards coupling capabilities in a more general sense (there is a statement later on interoperability with LPJml, see my comment below). There is also no elaboration of what you mean by flexibility.

We agree that our discussion of these aspects needs to be improved. We added text to support flexibility in both the introduction and the section on software design; by "flexibility" we mainly mean the possibility to use various combinations of modeling approaches and levels of aggregation (i.e., on the individual, cell, social system, or global level), so that one might combine an ABM of a labour market at the micro-level (i.e., individuals) with a system of ODEs modeling a carbon cycle on the cell level (photosynthesis) and global level (ocean-athmosphere diffusion) and a system of implicit and explicit equations representing a multisector economy with perfect factor markets on the social system (e.g. country) level.

p4 l14ff I don't see how the stylized biophysical description in the WEM can help answer this question. Would we not need a "whole" WEM where both the Earth System and the Socio-cultural system are described process-detailed (ref your Fig 1)?

The simple example WEM described in original Sec. 5 is not meant to be a candidate for a meaningful WEM that could be used to answer real research questions. It is given only to illustrate the features of the modeling framework that this MS is about. If a user of copan:CORE deems it necessary to represent certain processes in more detail than others to be able to answer some specific research question, she can develop a model component that does just that or that acts as a wrapper around an existing external model software implementing these processes (see our comments on coupling in the response to Mr. Dermody and below). Although this is not too relevant here, we however personally believe that the specific question we gave as an example of a research question, namely "How does climate change feed back on complex social structures and their dynamics?", *can* be studied to some extent by a model that has only a stylized biosphere. E.g., changes in global mean temperature can lead to economic damages and increased average mortality, which in turn can lead to changes in demographic structure and economic processes and eventually to changes in social coherence. This is not saying that we already have all the necessary model components or even the theoretical or empirical means to formulate these model components, but that if one had these then a stylized biosphere component might well suffice to perform useful studies.

p4 l25ff You argue that environmental and societal processes should be described on a similar level complexity, yet in Figure 1 you argue for a stylized description of the biophysical world. Please explain better or resolve this conflict between text and figure.

This is a valid point, we carefully revised the text in original Section 2 and Figure 1 to resolve this apparent inconsistency.

As for your list of five characteristics of WEM, I suggest to give each item a short title. You might want to consult our modeling framework paper (see references, we had to argue for biological models on par with physical oceanography models and called this "equitability"). Others could be "nonlinearity" and "aggregation".

We agree with this suggestion and added summary titles to the WEM characteristics, referencing also to your recent modeling framework paper in the same special issue.

copan:CORE WEM framework

p6 l22ff Your modularity is achieved through object-oriented programming. This is not enough to justify modularity as an eminent feature of your software. This is mere good software practice. Object-oriented programming then does not per se allow interoperability and dynamics coupling to other models, as you claim.

We believe this is a misunderstanding caused by sloppy wording in the original MS. Of course we do not claim that object-oriented programming automatically leads to either modularity or interoperability. We made sure in the revision that it becomes clearer that the high degree of modularity is the result of very specific design choices (which we found to be easier by following an object-oriented software design pattern rather than, e.g., a functional programming one), such as using multiple inheritance to allow different model components to use the same entities and attributes.

To this end, much more (like coupling frameworks, data exchange standards, computational bridging infrastructures) are needed, all of which are absent from the manuscript. Please elaborate *on the specific coupling solution to LPJml and to IMAGE to substantiate your interoperability claim.*

As already hinted at in our response to Mr. Dermody, interoperability with LPJmL, IMAGE etc. follows from the flexibility to basically use any Python code whatsoever in a model components' process implementation methods, including any calls to external software in order to exchange data or call stepper functions etc.

p8 l14ff Consider making this list of process-types identical to the one found in figure 2

Perhaps another misunderstanding. There is no list of process types in Fig. 2 but a list of modeling approaches. While there are some one-to-one relationships between the latter and the former, e.g. the modeling approach of using ODEs is supported by providing a process type "ODE" implementing a system of ODEs, other modeling approaches will require several formal process types, e.g. the ABM and adaptive network approaches will typically require a combination of processes of the formal process types "event", "step", and "explicit". We included a similar clarification into the revised manuscript.

p9 l16ff It should also be the role of the "master" model to ensure interoperability with other modeling frameworks, of which you make no mention.

We agree that both the "*base* model component" (implementing the most basic entity-types and relationships every copan:CORE model *must* have) and the "master *data* model" (a repository of entity-types and attributes model component developers *may* use) should aim at supporting as much interoperability with other models as possible. copan:CORE's metadata model already contains fields for referencing entries in common variable catalogues such as the *CF Conventions Standard Names* for climate-related quantities or the *World Bank's CETS* list of socio-economic indicators. We realize this should be extended by fields for referencing, e.g., the *CSDMS Standard Names*. We will check whether we missed any further important catalogues and add them if required.

A prominent framework that you should reach out to is the CSDMS BMI (basic model interface) idea. Your master component could implement that BMI/CMI and thus make all user-contributed models also interoperable. We have, e.g., done this with the FABM (Framework for Adaptive Biogeochemistry) for ESMF interoperability. If you don't want to add a BMI (to CSDMS, OpenMI or ESMF, or other frameworks) please add a section outlining your plans to do so or your reservations against doing so.

This is a really very helpful hint, indeed we were sadly unaware of the existence of this initiative. In the next release of pycopancore we will aim at providing a generic wrapper component that allows wrapping external models that implement the BMI into copan:CORE model components, and will also think of how to implement the BMI ourselves in the base model component so that any copan:CORE model can run in a "passive" mode governed by an external coupler that calls its BMI. We added a corresponding paragraph in the revised MS.

*p13 l 3ff The term "modular" is in your context the software modularity typically found in modern software architecture. This is *not* an emanating feature of copan:CORE. There is modularity beyond software modules in other frameworks and I would encourage you to rethink modularity in that broader sense.*

What we mean by modularity in the MS is (i) the division of the program *code* into packages representing "model components" that can be developed by independent "model component developers" and still use the same set of entity-types and attributes, "models" that can be composed from these components by "model composers", and "scripts" that "model end users" can use to perform specific studies, and (ii) the division of each entity-type's processes into contributions coming from different model components via multiple inheritance. We will try to identify further forms of modularity that copan:CORE does or should provide.

p16 l 4 A section on performance is missing (e.g. at end of section 3). Many thousands of cells, individuals or other entities might have to be simulated with this framework. What is your approach to ensuring that integrations of differential equations (exemplary for one of your process-types) is efficiently handled for large numbers of entities? Is there consideration for optimization (you already mention communication with MPI and JSON) for high-performance computing architectures? What tradeoffs to performance do you expect by using "slow" packages like sympy? Did you perform any scaling experiments?

We totally agree that performance is eventually a very important aspect for the production version of any software. With the current paper, the copan:CORE framework described therein, and its reference implementation in Python, pycopancore, our main aim is however a slightly different one than providing a performance-optimized production software. Such a performance-oriented production implementation of the copan:CORE framework, cppcopancore, is currently under development and its performance will be tested and documented thoroughly in a separate paper. For the revision – also in the interest of space – we therefore limited our comments on performance to a sentence stating this and giving running times for the illustrative example.

Figures

Overall, the figures are of mixed quality and style. A more consistent layout, style, coloring and fonts across all figures would make the paper more pleasing to the eye and also more readable. Please spend some efforts towards this goal. Especially Figs 1 and 2 are very clear and could serve as a template.

We agree and worked on the figures to achieve a larger degree of stylistic consistency and aesthetics, taking Fig. 1 and 2 as prototypes.

fig 1 The white box could contain text, such as "none"

OK. We added this "none" to clarify the figure.

fig 2 For consistency with text, use "process type", not "modelling approach"

Please see our response above.

fig 3 This entity–relationship diagram in UML style is only understandable to a small fraction of readers. Please explain the notation used in the diagram (for example by giving an example of the cell–person relationship). I do not at all understand the circular relationships for entities with themselves, especially for the SocialSystem entity. Please clarify. This figure does not need color, in fact, color distracts here.

OK. Still, because we extended the figure to have a clear correspondence to Fig. 2, we kept some background shading colors to make this clear.

fig 4 This "spaghetti" diagram is not helpful. Please create an entirely new graph. Rearrange the information, e.g., choose a UML style for consistency with fig 3. Avoid crossing lines, strange coloured shapes without obvious semantics, use typewriter font consistently for code parts. Make graphical markers (colors, line widths, boxes) easily accessible by adding a legend instead of explanation in caption.

OK, see also our response to Mr. Dermody.

fig 5 see comments for code figures later

OK.

fig 6 Change colours entirely to be consistent with figure 2 (CUL, MET, ENV). Don't use background color. Change layout to something visually appealing; currently the table structure suggest as semantic for rows and columns that is not evident.

OK. As suggested, we removed background color except the three colors that reference to *CUL, MET, ENV.* All other background color was replaced by hashing so that different entity types can still be distinguished.

fig 7 Table layout conveys meaning, but could be highlighted (columns are scenario (is that what you call "runs" in the caption?, rows are taxa). Avoid mixing colour semantics with those of previous figures. Avoid mixing color semantics between panels: How to top and middle row colors align? If they do, don't add two legends but use only one. Explain why for CUL/ENV there are only four quantities shown, but for MET there is an ensemble (each four) of three quantities shown. Upper left: where is the blue line (I guess hidden behind the grey one ...)? Find a way to display lines that are on top of each other without hiding any (also upper right figure). Possibly add events on time axis, especially for understanding middle right panel events with sudden transitions from fossils to biomass.

We tried a version in which all lines in the two top panels used the color we used earlier for the CUL taxon, and similarly for the other panels, distinguishing different variables within the same panel by different dash patterns. However, that did not work in the middle right panel since the dash patterns removed too many features of the ragged lines and were not well distinguishable. We therefore retained the original color scheme and instead explained its rationale in the text.

figs 5,8-10 Try improved syntax colouring and choose different font. Fixed width is important, but better use a smaller width. Consider light grey for comments, for example. A light (cream) background might help to set the code apart from the title, which is barely visible (and which uses inconsistent font with main text).

OK.

Technical comments

p7 l 10 There is no such thing as "sharp criteria". Criteria alone is sufficient.

Although we do not agree here, we removed the "sharp" anyway.

p14 l14 The link to pycopancore (http://github.com/pik- 15 copan/pycopancore) does not work yet (so make sure it does work on publication day)

OK. The following link now works since May 2018: https://github.com/pik-copan/pycopancore . The online publication as open access code was delayed due to institutional legal checks that were pending.

p14 l29ff and Figure 5 Use a consistent form for presenting code, do not alternate between text and figure.

OK.

p16 l 4 Examplary => Exemplary

OK.

p16 l 9 "not intended to be a serious representation". A representation cannot be serious. I suggest "is intended to be a toy representation". BTW, what is the "real" world anyway :=)

OK.

p17 l3ff Avoid double parentheses throughout this paragraph and manuscript.

OK.

Earth system ~~modelling~~ modeling with complex dynamic human societies: the copan:CORE World-Earth modeling framework

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Abstract. ~~Possible future trajectories of the Earth system~~

Analysis of Earth system dynamics in the Anthropocene ~~are determined by the increasing entanglement~~ requires to explicitly take into account the increasing magnitude of processes operating in human societies, their cultures, economies and technosphere and their growing entanglement with those in the physical, chemical and biological systems of the planet. This work (i) introduces design principles for constructing World-Earth models (WEM), i.e., ~~as well as in human societies, their cultures and economies.Here, we introduce~~ models of social-ecological co-evolution on up to planetary scales, and (ii) presents the copan:CORE open source software library that provides a ~~framework~~ simulation modeling framework for developing, composing and running ~~World-Earth models, i.e., models of social-ecological co-evolution up to planetary scales. It~~ such WEMs based on the proposed principles. copan:CORE is an object-oriented software package ~~written in Pythondesigned for different user roles. It allows model end users to run parallel simulations with already available and tested models. Furthermore, model composers are enabled to easily implement new models by plugging together a broad range of model components , such as opinion formation on social networks, generic carbon cycle dynamics, or simple vegetation growth. For the sake of a modular structure, each provided component specifies a~~ currently implemented in Python. It provides components of meaningful yet minimal ~~collection~~ collections of closely related processes ~~. These processes can be formulated in terms of various process types, such as ordinary differential equations, explicit or implicit functions, as well as steps or events of deterministic or stochastic fashion. In addition to the already included variety of different components in copan:CORE, model developers can extend the framework~~ in the Earth System that can be plugged together in order to compose and run WEMs. Developers can supplement the already existing model components with additional components that are based on elementary entity types, ~~i.e.~~e.g., grid cells, ~~individuals and social systems, or the~~ or fundamental process taxa~~environment, social metabolism, and culture. To showcase~~

~~possible usage we present an exemplary World-Earth model that combines a variety of model components and interactions thereof. As the frameworkallows a simple activation and deactivation of certain components and related processes, users can test for their specific effects on modeling results and evaluate model robustness in a controlled way. Hence,~~ , e.g., environment or culture. To illustrate the capabilities of the framework, this paper presents a WEM example implemented in copan:CORE ~~allows developing process-based models of global change and sustainable development in planetary social-ecological systems and thus fosters a better understanding of crucial mechanisms governing the co-evolutionary dynamics between societies and the natural environment~~that combines a variety of model components and interactions thereof. Due to its modular structure, the simulation modeling framework enhances the development and application of ~~stylized~~ integrated models in Earth system science but also climatology, economics, ecology, or sociology, and allows combining them for interdisciplinary studies~~at the interface between different areas of expertise.~~ .

1 Introduction and theoretical considerations

In the Anthropocene, ~~the future trajectory of the Earth system~~ Earth system dynamics is equally governed by two kinds of internal processes ~~(Crutzen, 2002; Steffen et al., 2007; Lewis and Maslin, 2015; Waters et al., 2016; Steffen et al., 2018)~~: those operating in the physical, chemical, and biological systems of the planet and those occurring in its human societies, their cultures and economies ~~(Schellnhuber, 1998, 1999)~~(Schellnhuber, 1998, 1999; Crutzen, 2002; Steffen et al., 2018). The history of global change is the history of the increasing planetary-scale entanglement ~~of~~ and strengthening of feedbacks between these two domains ~~(Lenton and Watson, 2011; Lenton et al., 2016b; Gaffney and Steffen, 2017)~~(Lenton and Watson, 2011). Earth system analysis of the Anthropocene requires to close the loop by integrating the dynamics of complex human societies into integrated *whole* Earth system models (Verburg et al., 2016; Donges et al., 2017a, b). These are referred to as World-Earth models (WEMs) in this article that capture the coevolving dynamics of the social (the *World* of human societies) and natural (the biogeophysical *Earth*) spheres of the Earth system on up to global scales. World-Earth modeling builds upon the work done in the fields of social-ecological systems (Berkes et al., 2000; Folke, 2006) and coupled human and natural systems (Liu et al., 2007) research. However, it emphasizes the study of planetary scale interactions between human societies and parts of the Earth's climate system such as atmosphere, ocean and the biosphere, instead of more local and regional scale interactions with natural resources that these fields have focussed on in the past (Donges et al., 2018).

The contribution of this paper is twofold: First, following a more detailed motivation (Sect. 1.1), general theoretical considerations and design principles for a novel class of integrated WEMs are discussed (Sect. 1.1). Second, a concrete software design for the copan:CORE World-Earth modeling framework and its reference implementation in the programming language Python are developed and described (Sect. 2), including a study of a WEM example (Sect. 3). Finally, Sect. 4 concludes the paper.

1.1 Motivation

1.1.1 State of the art

Computer simulation models are pivotal tools for gaining scientific understanding and providing policy advice for addressing global change challenges such as anthropogenic climate change or rapid degradation of biosphere integrity and their interactions (Rockström et al., 2009; Steffen et al., 2015). At present, two large ~~modelling~~ modeling enterprises considering the larger Earth system in the Anthropocene are mature (van Vuuren et al., 2016): (i) Biophysical “Earth system models” (ESMs) derived from and built around a core of atmosphere-ocean general circulation models that are evaluated using storyline-based socioeconomic scenarios to study anthropogenic climate change and its impacts on human societies (e.g., representative concentration pathways, RCPs) (Stocker et al., 2013). (ii) Socio-economic Integrated Assessment Models ~~built for the evaluation of policy pathways and options that~~ (IAMs) are operated using storyline-based ~~environmental~~ socio-economic baseline scenarios (e.g., shared socio-economic pathways, SSPs, Edenhofer et al. (2014)) and evaluate technology and policy options for mitigation and adaption leading to different emission pathways. There is a growing number of intersections, couplings and exchanges between the biophysical and socio-economic components of these two model classes for more comprehensive consistency ~~(van Vuuren et al., 2012; Foley et al., 2016)~~(van Vuuren et al., 2012; Foley et al., 2016; Dermody et al., 2018; Robinson et al., 2018)
.

~~However, such~~

1.1.2 Current gap in the Earth system modeling landscape

However, the existing scientific assessment models of global change ~~do to a large degree not include~~ include only to a limited degree – if at all – dynamic representations of the socio-cultural dimensions of human societies ~~(Donges et al., 2018) and the diverse actors, their agencies and complex dynamics networks connecting them that together constitute social structure (Verburg et al., 2016~~
~~. Such dimensions are at most~~ (Fig. 1), i.e. the diverse political and economic actors, the factors influencing their decisions and behavior, their interdependencies constituting social network structures and institutions (Verburg et al., 2016; Donges et al., 2017a, b) as well as the broader technosphere they created (Haff, 2012, 2014). In IAMs, these socio-cultural dimensions are partly represented by different socio-economic scenarios (e.g., SSPs)~~that act~~, providing the bases for different emision pathways. These are in turn used in ESMs as external forcing, constraints and boundary conditions to the ~~modelled~~ modeled Earth system dynamics. ~~There are, however,~~ However, a dynamic representation would be needed to explore how changes in the global environment influence these socio-cultural factors and vice versa.

There are large differences in beliefs, norms, ~~and political preferences~~ economic interests, and political ideologies of various social groups, ~~as well as in~~ and their metabolic profiles, which are related to their access and use of energy and resources ~~(Fischer-Kowalski, 1997; Otto et al., in review)~~(Fischer-Kowalski, 1997; Otto et al., in review; Lenton et al., 2016a; Lenton and L
. Historical examples show that ~~economic interests, beliefs and political preferences of various social groups might be contradictory and sometimes~~ these differences might lead to rapid social changes, revolutions and sometimes also devastating conflicts~~and wars~~, wars and collapse (Betts, 2017; Cumming and Peterson, 2017). In other cases, the inability to establish effective social

institutions controlling resource access might lead to unsustainable resource use and resource degradation~~, a process described as the tragedy of the commons (Ostrom, 1990).~~ (see the discussion around the tragedy of the commons, Ostrom, 1990; Jager et al., 2000; J . Climate change is the paradigmatic example of a global commons ~~which~~ that needs global institutional arrangements for the usage of the atmosphere as a deposit for greenhouse gas emissions if ~~devastating~~ substantial environmental and social damages are to be avoided in the future ~~(Schellnhuber et al., 2016b; Otto et al., 2017)~~(Edenhofer et al., 2015; Schellnhuber et al., 2016b; Otto et al., .

In order to explore the risks, dangers and opportunities for sustainable development~~within this planetary social-ecological system in the Anthropocene~~, it is important to understand how biophysical, ~~socio-metabolic~~ socio-economic and socio-cultural processes influence each other (Donges et al., 2018), how institutional and other social processes function, and which tipping elements can emerge out of the interrelations of the subsystems (Lenton et al., 2008; Kriegler et al., 2009; Cai et al., 2016; Kopp et al., 2016). ~~The objective is to explore from a~~ To address these questions, the interactions of social systems and the natural Earth system can be regarded as part of a planetary social-ecological system (SES) or World-Earth system, extending the notion of SES beyond its common usage to describe systems on local scales (Berkes et al., 2000; Folke, 2006). This dynamical systems perspective ~~under what~~ allows to explore under which preconditions the maintenance of planetary boundaries (Rockström et al., 2009; Steffen et al., 2015), i.e., a Holocene-like state of the ~~Anthropocene~~natural Earth System, can be reconciled with human ~~material objectives (i.e., development) to produce a tolerable (i.e., ethically defensible)~~ development to produce an ethically defensible trajectory of the whole Earth system (i.e., sustainable development) (Raworth, 2012; Steffen et al., 2018).

1.1.3 World-Earth modeling: a novel approach to Earth system analysis of the Anthropocene

To this end, the case has been made that substantial efforts are required to advance ~~*whole* Earth system models, referred to as World-Earth models (WEMs) in this article, that capture the coevolving dynamics of the social (the *World* of human societies) and natural (the biogeophysical *Earth*) spheres of the Earth system on planetary scales (Verburg et al., 2016; Donges et al., 2017a, b; Mülle~~ the development of integrated World-Earth system models (Verburg et al., 2016; Donges et al., 2017a, b). The need for developing such next generation social-ecological models has been recognized in several subdisciplines of global change science dealing with socio-hydrology (Di Baldassarre et al., 2017; Keys and Wang-Erlandsson, 2018), land-use dynamics ~~(Arneth et al., 2014; **?**)~~ (Arneth et al., 2014; Robinson et al., 2018), and the ~~globalised~~ globalized food-water-climate nexus (Dermody et al., 2018). While in recent years there has been some progress in developing stylized ~~(also referred to as conceptual)models of this type in recent years (Kellie-Smith and Cox, 2011; Motesharrei et al., 2014; Garrett, 2015; Wiedermann et al., 2015; Heck et al., 2016; Barfuss et a~~ models that combine socio-cultural with economic and natural dynamics (e.g. Janssen and De Vries (1998); Kellie-Smith and Cox (2011); ( ), advanced and process-detailed WEMs are not yet available for studying the deeper past and the longer-term Anthropocene future of this coupled system.

A number of new developments make it attractive to re-visit the challenge of building such WEMs now. Due to the huge progress in computing, comprehensive Earth system ~~modelling~~ modeling is advancing fast. And with the ubiquity of computers and digital communication for simulation and data acquisition in daily life (Otto et al., 2015), efforts to model social systems are increased and become more concrete. Recent advances for example in complex systems theory, computational social sciences,

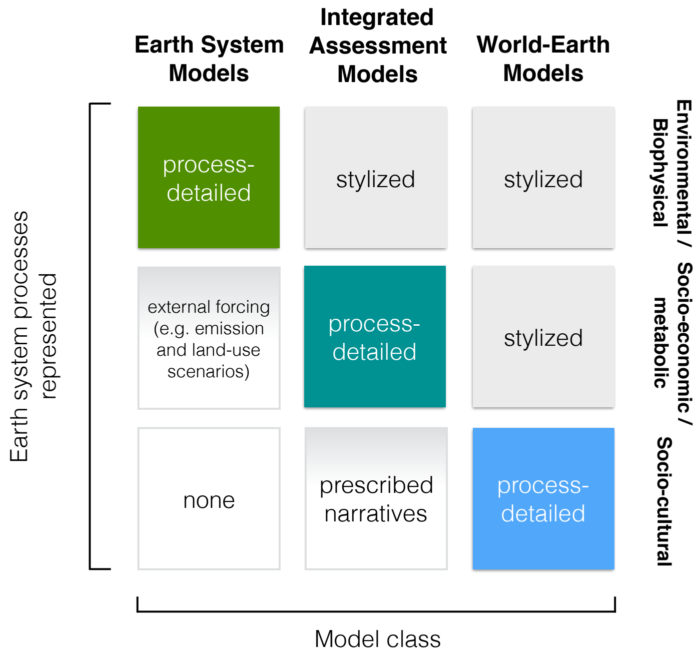

Figure 1. World-Earth models (WEMs) in the space of model classes used for scientific analysis of global change. It is shown to what degree current Earth system models, integrated assessment models and WEMs cover environmental/biophysical, socio-economic/metabolic, and socio-cultural processes, respectively.

social simulation and social-ecological systems ~~modelling~~modeling (Farmer and Foley, 2009; Farmer et al., 2015; Helbing et al., 2012; Müller-Hansen et al., 2017) make it feasible to include some important macroscopic dynamics of human societies regarding among others the formation of institutions, values, and preferences, and various processes of decision-making into a model of the whole Earth system, i.e., the physical Earth including its socially organised and mentally reflexive humans. Furthermore, new methodological approaches are developing fast that allow representing crucial aspects of social systems, such as adaptive complex networks (Gross and Blasius, 2008; Snijders et al., 2010). Finally, initiatives such as *Future Earth* (Future Earth, 2014) and the *Earth League* (Rockström et al. (2014), www.the-earth-league.org) provide a ~~framework~~ basis for inter- and trans-disciplinary research that could support such an ambitious modeling program. ~~This would allow qualitative and quantitative numerical exploration of the universe of possible trajectories in the Anthropocene, their accessibility and their preconditions.~~

1.1.4 Features of the copan:CORE modeling framework

~~While there~~ There is a wealth of software frameworks ~~for modelling~~ and platforms for modeling complex social dynamics using agent-based and network approaches (Kravari and Bassiliades, 2015)~~, for example~~. However, platforms like *Netlogo* (Wilensky and Rand, 2015), *Repast* (North et al., 2013) ~~or~~ and *Cormas* (Bousquet et al., 1998) ~~, these~~ tend to focus on applications to rather local systems and none of them is specialized for an Earth system analysis context. ~~Accordingly, we have designed the~~ In turn, WEMs need to be able to combine physics-based descriptions of climate dynamics on spatial grids with agent-based components for simulating socio-cultural processes.

The *copan:CORE World-Earth modeling framework* presented in this paper ~~to allow for a high degree of modularity and flexibility and~~ is a code-based (rather than graphical) simulation modeling framework with a clear focus on Earth system models with complex human societies. It was developed within the flagship project 'copan – coevolutionary pathways' and will form the core of its further model development, which explains the naming. Similar to the common definition of 'software framework', we define a '(simulation) modeling framework' as a tool that provides a standard way to build and run simulation models.

We have designed copan:CORE to meet the special requirements for model development in the context of Earth system analysis: First, the framework's modular organization combines processes into model components. Different components can implement different, sometimes disputed, assumptions about human behavior and social dynamics from theories developed within different fields or schools of thought. This allows for comparison studies in which one component is replaced by a different component modeling the same part of reality in a different way and exploring how the diverging assumptions influence the model outcomes. All components can be developed and maintained by different model developers and flexibly composed into tailor-made models used for particular studies by again different researchers. Second, our framework provides coupling capabilities to preexisting biophysical Earth system and economic integrated assessment models and thus helps to benefit from the knowledge of the detailed processes embedded in these models.

~~Following the introduction, this article is structured as follows. Sect. 1.1 outlines general design principles for and required properties of WEMs.Sect. 2 presents the conceptual and object-oriented software design of~~ Finally, copan:CORE facilitates the integration of different types of modeling techniques. It permits for example to combine agent-based models (e.g., of a labor market at the micro-level of individuals) with systems of ordinary differential equations (modeling for example a carbon cycle). Similarly, systems of implicit and explicit equations (e.g., representing a multi-sector economy) can be combined with Markov jump processes (for example representing economic and environmental shocks).

These features distinguish the copan:CORE ~~World-Earth modeling framework and its reference implementation in the programming language Python. Furthermore, an exemplary WEM is introduced and the resulting World-Earth dynamics are briefly discussed (Sect. 3). Sect. 4 concludes~~modeling framework from existing modeling frameworks and platforms. Before we continue with a more detailed description of the modeling framework, we go back to the underlying design principles of WEMs that guided the development of copan:CORE.

2 ~~Towards blueprinting World-Earth models~~

1.1 General characteristics of integrated World-Earth models

In this section, we ~~outline guidelines~~ discuss general characteristics and design principles for the construction of the novel class of WEMs ~~and also discuss their required properties for addressing leading~~ that constrain their properties for to allow for addressing research questions of the following type: ~~(1)~~

1. In which respects is Earth system dynamics in the Anthropocene different from previous paleoclimatic states of the Earth (note that the definition of the Anthropocene is stratigraphic [Waters et al. (2016)], not dynamic), and how might ~~it~~ current human societies and the broader technosphere (Haff, 2012, 2014; Donges et al., 2017a) they created alter the future evolution of the Earth system and its main components (Steffen et al., 2018)? ~~(2)~~

2. What are the social, economic and environmental ~~conditions~~ preconditions for sustainable development towards and within a "safe and just" operating space for humankind, i.e., for a trajectory of the Earth system that eventually neither violates precautionary planetary boundaries nor acceptable social foundations (Rockström et al., 2009; Steffen et al., 2015; Raworth, 2012)? ~~(3) Are there possibly disastrous~~

3. Are there cascading interactions between ~~potential~~ climatic (e.g., continental ice sheets or major biomes such as the Amazon rain forest) and potential social tipping elements (e.g., ~~public opinion formation and~~ in attitudes towards climate change or eco-migration) and how can they be avoided ~~(Schellnhuber et al., 2016a)? (4)~~ (Schellnhuber et al., 2016a; Steffen et al., 20 ?

4. How does climate change feed back on complex social structures and their dynamics? ~~(5)~~

5. How do societal transformations affect the natural Earth system?

~~**World-Earth models (WEMs) in the space of model classes used for scientific analysis of global change.** It is shown to what degree current Earth system models, integrated assessment models and WEMs cover biophysical, socio-metabolic/economic, and socio-cultural processes, respectively.~~

1.1.1 Basic process taxa in World-Earth models

~~We think that such a research program, which aims at~~ Based on the companion article by Donges et al. (2018), we classify processes occurring in the World-Earth system into three major taxa that represent the natural and societal spheres of the Earth system as well as their overlap (Fig. 2). We give only a rough definition and abstain from defining a finer, hierarchical taxonomy, being aware that gaining consensus among different disciplines on such a taxonomy would be unlikely, and thus leaving the assignment of individual processes and attributes to either taxon to the respective model component developers:

Environment (ENV; environmental, biophysical and natural processes) The 'environment' process taxon is meant to contain biophysical or "natural" processes from material subsystems of the Earth system that are not or only insignificantly shaped or designed by human societies (e.g., atmosphere-ocean diffusion, growth of unmanaged vegetation, and maybe the decay of former waste dumps).

Metabolism (MET; socio-metabolic and economic processes) The 'metabolism' process taxon is meant to contain socio-metabolic and economic processes from material subsystems that are designed or significantly shaped by human societies (e.g., harvesting, afforestation, greenhouse gas emissions, waste dumping, land-use change, infrastructure building). Social metabolism refers to the material flows in human societies and the way societies organize their exchanges of energy and materials with nature (Fischer-Kowalski, 1997; Martinez-Alier, 2009).

Culture (CUL; socio-cultural processes) The 'culture' process taxon is meant to contain socio-cultural processes from *immaterial* subsystems (e.g., opinion adoption, social learning, voting, policy-making) that are described in models in a way abstracted from their material basis. Culture in its broadest definition refers to everything what people do, think and posses as members of society (Bierstedt, 1963, p. 129).

1.1.2 Design principles for World-Earth models

The research program investigating the dynamics and resilience of the ~~planetary social-ecological~~ World-Earth system in the Anthropocene ~~,~~ should be built upon recent advances in the theory and ~~modelling~~ modeling of complex adaptive systems. It needs to take into account the agency of heterogeneous social actors and global-scale adaptive networks carrying and connecting social, economic and ecological processes that shape social-ecological ~~coevolution~~co-evolution (Verburg et al., 2016; Donges et al., 2017a, b).

Modeling approaches for investigating social-ecological or coupled human and natural system dynamics have already been developed. However, they usually focus on local or small-scale human-nature interactions (Schlüter et al., 2012). Therefore, ~~we need to scale up such approaches~~ such approaches need to be scaled up to the planetary scale and incorporate insights from macro-level and global modeling exercises. Accordingly, we propose that the development of WEMs of the type discussed in this paper should be guided by aiming for the following properties:

1. **Balanced process representation** Environmental and societal processes should be described on similar levels of complexity (e.g., in terms of the number of state variables representing the two spheres and three process taxa [see above], Fig. 2) to do justice to the dominant role of human societies in Anthropocene Earth system dynamics and to allow for balanced model design and analysis (in contrast to ESMs and many IAMs which are not balanced in that respect). One implication of this ~~guideline~~ principle is that WEMs should have the ability to reflect a similar number of planetary boundaries and social foundations, respectively. The ~~modelled~~ modeled subsystems and processes can be further structured into biophysical, socio-metabolic and socio-cultural taxa (Donges et al., 2018) (see ~~Sect. 2 definitions~~above). First generation WEMs may be well-advised to choose to focus on the novelty of integrating process-detailed representations of socio-cultural dynamics with other biophysical and socio-metabolic Earth system processes, while maintaining more stylized representations of the latter two classes (Fig. 1).

2. **Heterogeneity, agency and complex social structures** WEMs should allow for representations of the dynamics of the diverse agents and the complex social structure connecting them that constitute human societies, using the tools of agent-based and adaptive network ~~modelling~~modeling (Müller-Hansen et al., 2017). ~~Accordingly, such models should~~ The rationale behind this design principle is the observation that the social sphere is networked on multiple layers and regarding multiple phenomena (knowledge, trade, institutions, preferences etc.) and that increasing density of such interacting network structures is one of the defining characteristics of the Anthropocene (Steffen et al., 2007; Gaffney and Steffen, 20 . While there is a rich literature on modeling various aspects of socio-cultural dynamics (e.g. Castellano et al. (2009); Snijders et al. (2), this work so far remains mostly disconnected from Earth system modeling. Accordingly, WEMs should be able to describe decision processes of representative samples of individual humans, social groups or classes, and collective agents such as firms, households or governments. This includes the representation of diverse objectives, constraints, and decision rules, differentiating for example by the agent's social class and function and taking the actual and perceived decision options of different agent types into account. ~~They should reflect the observation that the social sphere is networked on multiple layers and regarding multiple phenomena (knowledge, trade, institutions, preferences etc.).~~

3. **Feedbacks and co-evolution** WEMs should incorporate as dynamic processes the feedbacks of collective social processes on biogeophysical Earth system components and vice versa. ~~This feature~~ The rationale behind this principle is that the strengthening of such feedbacks, e.g. the feedback loop consisting of anthropogenic greenhouse gas emissions driving climate change acting back on human societies through increasingly frequent extreme events, is one of the key characteristics of the Anthropocene. Moreover, the ability to simulate feedbacks is central to a social-ecological and complex adaptive systems approach to Earth system analysis. Capturing these feedbacks enables them to produce paths in ~~coevolution~~ co-evolution space (Schellnhuber, 1998, 1999) through time-forward integration of all entities and networks allowing for deterministic and stochastic dynamics. Here, time-forward integration refers to simulation of changes in system state over time consecutively in discrete time-steps (e.g. via difference equations or stochastic events) or at a continuum of time points (e.g. via ordinary or stochastic differential equations), rather than solving equations that describe the whole time evolution at once as in inter-temporal optimization.

4. **Nonlinearity and tipping dynamics** WEMs should be able to capture ~~nonlinear dynamics. This feature~~ the nonlinear dynamics that is a prerequisite for modeling climatic (Lenton et al., 2008) and social tipping ~~elements (Kopp et al., 2016)~~ dynamics (Kopp et al., 2016; Milkoreit et al., 2018) and their interactions (Kriegler et al., 2009) that are not or only partially captured in ESMs and IAMs. This feature is important because the impacts of these critical dynamics are decisive for future trajectories of the Earth system in the Anthropocene, e.g. separating stabilized Earth states that allow for sustainable development from hothouse Earth states of self-amplifying global warming (Steffen et al., 2018).

5. **Systematic exploration of state and parameter spaces** WEMs should allow for a comprehensive evaluation of state and parameter spaces to explore the universe of accessible system trajectories and to enable rigorous analyses of uncertainties and model robustness. Hence, they emphasize neither storylines nor ~~optimisations~~ optimizations but focus on the exploration of the space of dynamic possibilities. This ~~feature allows for WEM~~ principle allows for crucial Anthropocene

Earth system dynamics to be investigated with state-of-the-art methods from complex systems theory, e.g., for measuring different ~~flavors of resilience~~aspects of stability and resilience of whole Earth system states (Menck et al., 2013; van Kan et al., 2016; Donges and Barfuss, 2017) and for ~~establishing hierarchies of planetary boundariesand~~ understanding and quantifying planetary boundaries, safe operating spaces ~~in models~~and their manageability and reachability as emergent system properties across scales (Heitzig et al., 2016; Kittel et al., 2017).

1.1.3 World-Earth models compared to existing modeling approaches of global change

It is instructive to compare WEMs to the two existing classes of global change models in terms of to what degree they represent biophysical, socio-metabolic/economic and socio-cultural subsystems and processes in the ~~planetary social-ecological~~ World-Earth system (Fig. 1). Earth System Models ~~(ESMs)~~ focus on the process-detailed description of biogeophysical dynamics (e.g., atmosphere-ocean fluid dynamics or biogeochemistry), while socio-metabolic processes (e.g., economic growth, greenhouse gas emissions and land use) are incorporated via external forcing and socio-cultural processes (e.g., public opinion formation, political and institutional dynamics) are only considered through different scenarios regarding the development of exogenous socio-metabolic drivers. Integrated Assessment Models ~~(IAMs)~~ contain a stylized description of biophysical dynamics, are process-detailed in the socio-metabolic/economic domains and are driven by narratives in the socio-cultural domain. In turn, WEMs should include all three domains equally. However, the focus of current and near-future developments in World-Earth modeling should lie on the development of a detailed description of socio-cultural processes because they are the ones where the least work has been done so far in formal modeling.

2 The copan:CORE World-Earth ~~modelling~~ modeling framework

In this section, we present the World-Earth ~~modelling~~ modeling framework copan:CORE that was designed following the ~~blueprinting guidelines outlined~~ principles given above (Sect. 1.1). We describe our framework on three levels, starting with the abstract level independent of any software (Sects. ~~2.1 , 2.2, and~~ 2.1 and 2.2, also using Sect. 1.1.1), then describing the software design independent of any programming language (Sect. 2.3), and finally presenting details of our reference implementation in the Python language (Sect. 2.4).

In summary, copan:CORE enables a flexible model design around standard components and model setups that allows investigation of a broad set of case studies and research questions (Fig. 2). ~~This~~ Its flexibility and role-based modularization ~~via multiple-inheritance is achieved through~~ are realized within an object-oriented ~~programming. For example, these features allow for~~ software design and support flexible scripting by end users and interoperability and dynamic coupling with existing models ~~(~~– e.g., the terrestrial vegetation model *LPJmL* working on the cell level (Bondeau et al., 2007) ~~,~~ or other Earth system models or integrated assessment models based on time-forward integration (rather than intertemporal optimization) such as *IMAGE* (van Vuuren et al.)~~) as well as for flexible scripting by end users~~. On the level of model infrastructure, a careful documentation ~~, an automated test framework and git versioning allow for~~ and software versioning via the ‘git’ versioning system aim to support collaborative and structured development in large teams using copan:CORE.

2.1 Abstract structure

This section describes the abstract structure of models that can be developed with copan:CORE and gives rationales for our design choices, many of which are based on experiences very similar to those reported in Robinson et al. (2018), in particular regarding the iterative process of scientific modeling and the need for open code, a common language, and a high level of consistency without losing flexibility.

2.1.1 Entities, processes, attributes

A model composed with copan:CORE describes a certain part of the World-Earth system as consisting of a potentially large set (that may change over model time) of sufficiently well-distinguishable *entities* ("things that are", e.g., a spot on the Earth's surface, the European Union [EU], yourself)~~that~~. Entities are involved in a number of sufficiently well-distinguishable *processes* ("things that happen", e.g., vegetation growth, economic production, opinion formation)~~which~~. Processes in turn affect one or more *attributes* ("how things are", e.g., the spot's harvestable biomass, the EU's gross product, your opinion on fossil fuels, the atmosphere-ocean diffusion coefficient). During a model run, entities may come into existence (individuals may be born, social systems may merge into larger ones or fractionate), cease to exist (individuals may die, social systems may collapse), or may even be "reactivated" (e.g., an occupied country may regain independence).

Rationale. While for some aspects of reality an ontological distinction between entities, attributes of entities, and processes might be ambiguous, it corresponds very well to both the distinction of nouns, adjectives, and verbs in natural languages, and to the concepts of objects, object attributes, and methods in object-oriented programming.

2.1.2 ~~Entity-types~~Entity types, process taxa, ~~process-types~~process types

copan:CORE classifies entities by ~~*entity-types*~~*entity types* ("kinds of things that are", e.g., spatial grid cell, social system, individual), and allows to group (some or all) processes into *process taxa* (e.g., natural, socio-metabolic, cultural). Each process and each attribute *belongs to* either a certain ~~entity-type~~ entity type or a certain process taxon. We deliberately do not specify ~~sharp~~ criteria for deciding where processes belong since this is in part a question of style and academic discipline and there will inevitably be examples where this choice appears to be quite arbitrary and will affect only the model's description, implementation, and maybe its running time, but not its results. ~~When talking about processes, people from very different backgrounds widely use a subject-verb-object sentence structure even when the subject is not a conscious being and the described action is not deliberate (e.g., "the oceans take up carbon from the atmosphere"). copan:CORE therefore allows modelers to treat some processes as if they were "done by" a certain entity (the "subject" of the process) "to" itself and/or certain other entities (the "objects" of the process). Other processes for which there appears to be no natural candidate entity to serve as the "subject" can be treated as if they are happening "inside" or "on" some larger entity that contains or otherwise supports all actually involved entities. In both cases, the process is treated as belonging to some entity-type. Still other processes such as multilateral trade may best be treated as not belonging to a single entity and can thus be modeled as belonging to some process taxon.~~

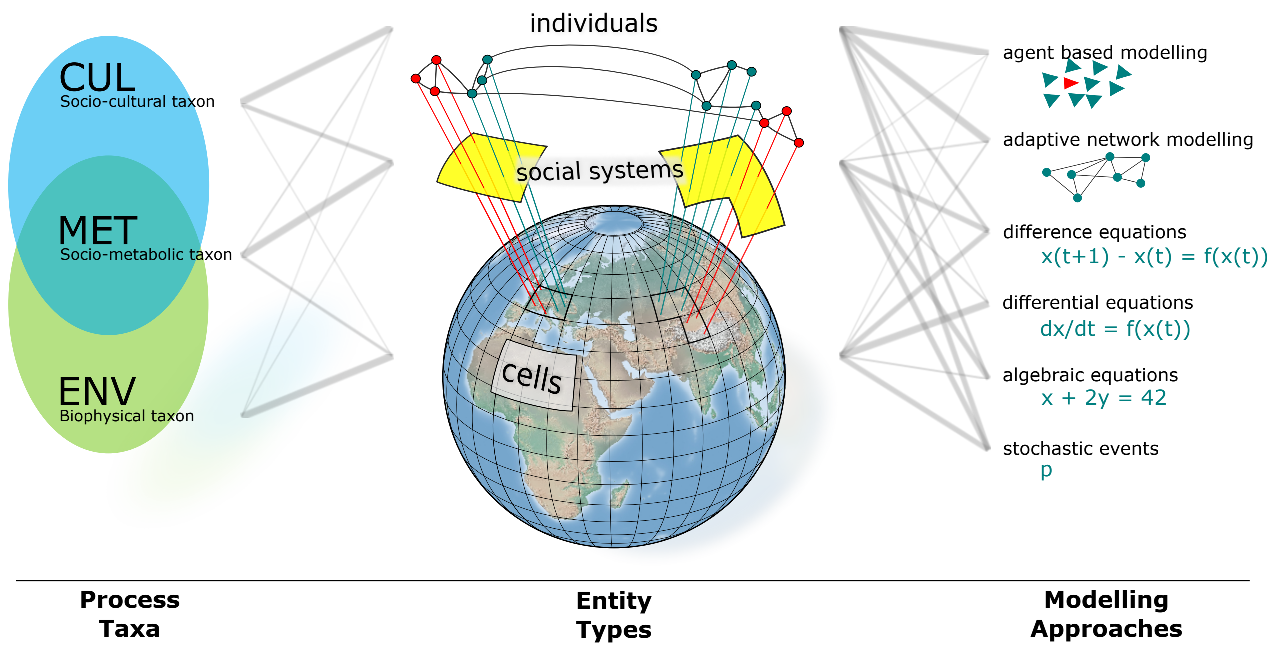

Figure 2. ~~**Overview of copan:CORE modelling framework.**~~ **Overview of copan:CORE modeling framework.** The entities in copan:CORE models are classified by ~~*entity-types*~~ *entity types* (e.g., grid cell, social system, individual~~). Processes are grouped into *process taxa* (cultural~~, ~~metabolic, environmental~~see middle column). Each process belongs to either a certain ~~entity-type~~ entity type or a certain ~~process taxon~~*process taxon* (left column). Processes are further distinguished by ~~their~~ formal ~~*process-type*,~~ process types (see text for a list) which ~~allows~~ allow for various different ~~modeling approaches~~*modeling approaches* (right column). Entity types, process taxa and process types can be freely combined with each other (grey lines). Thick ~~black~~ grey lines indicate which combinations are most common.

Similarly, attributes may be modeled as belonging to some ~~entity-type~~ entity type (e.g., 'total population' might be modeled as an attribute of the 'social system' ~~entity-type~~entity type) or to some process taxon (e.g., 'atmosphere-ocean diffusion coefficient' might be modeled as an attribute of the 'environment' process taxon). We suggest to model most quantities as ~~entity-type~~ entity type attributes and model only those quantities as process taxon attributes which represent global constants.

Independently of where processes belong to, they are also distinguished by their formal ~~*process-type*~~*process type*, corresponding to different mathematical modeling and simulation/solving techniques:

- continuous dynamics given by ordinary differential equations,
- (quasi-)instantaneous reactions given by algebraic equations (e.g., for describing economic equilibria),
- steps in discrete time (e.g., for processes aggregated at annual level or for coupling with external, time-step-based models or model components), or

– events happening at irregular or random time points (e.g., for agent-based and adaptive network components or externally generated extreme events).

the latter two potentially have probabilistic effects~~(later~~. Later versions will also include support for stochastic differential equations or other forms of time-continuous noise, currently noise can only be modeled via time-discretized steps~~)~~. Similarly, attributes have ~~*data-types*~~*data types* (mostly physical or socio-economic simple quantities of various *dimensions* and *units,* but also more complex ~~data-types~~ data types such as references or networks).

Fig. 2 summarizes our basic process taxa and ~~entity-types~~entity types, their typical connections, and the corresponding typical modeling approaches (which in turn are related but not equal to certain formal process types, not shown in the figure). Sects. 2.2 and 1.1.1 ~~will~~ describe them in detail.

Rationale. When talking about processes, people from very different backgrounds widely use a subject-verb-object sentence structure even when the subject is not a conscious being and the described action is not deliberate (e.g., "the oceans take up carbon from the atmosphere"). copan:CORE therefore allows modelers to treat some processes as if they were "done by" a certain entity (the "subject" of the process) "to" itself and/or certain other entities (the "objects" of the process). Other processes for which there appears to be no natural candidate entity to serve as the "subject" can be treated as if they are happening "inside" or "on" some larger entity that contains or otherwise supports all actually involved entities. In both cases, the process is treated as belonging to some entity type. Still other processes such as multilateral trade may best be treated as not belonging to a single entity and can thus be modeled as belonging to some process taxon.

A twofold classification of processes according to both ownership and formal process type is necessary since there is no one-to-one relationship between the two, as the grey lines in Fig. 2 indicate. E.g., processes from all three taxa may be represented by ODEs or via stochastic events, and all shown entity types can own regular time stepped processes.

2.1.3 Modularization, model components, user roles

copan:CORE aims at supporting a plug-and-play approach to ~~modelling~~ modeling and a corresponding division of labour between several user groups (or *roles*) by dividing the overall model-based research workflow into several tasks~~:~~

– ~~If there is already a model that fits your research question, use that one in your study (role: model end user).~~

– ~~If not, decide what model components the question at hand needs.~~

– ~~If all components exist, compose a new model from them (role: model composer).~~

– ~~If not, design and implement missing model components (role: model component developer). If some required entity attributes are not yet in the master data model (Sect. 2.1.4), add them to your component. Suggest well-tested entity attributes, entity-types, or model components to be included in the copan:CORE community's master data model or master component repository (modeling board memberswill then review them).~~

. As a consequence, we formally distinguish between model components and (composed) models.

A *model component* specifies (i) a meaningful collection of processes that belong so closely together that it would not make much sense to include some of them without the others into a model (e.g., plants' photosynthesis and respiration), (ii) the entity attributes that those processes deal with, referring to attributes listed in the master data model whenever possible, (iii) which existing (or, if really necessary, additional) ~~entity-types~~ entity types and process taxa these processes and attributes belong to. A *model* specifies (i) which model components to use, (ii) if necessary, which components are allowed to overrule parts of which other components (iii) if necessary, any *attribute identities*, i.e., whether some generally distinct attributes should be considered to be the same thing in this model (e.g., in a complex model, the attribute 'harvestable biomass' used by an 'energy sector' component as input may need to be distinguished from the attribute 'total vegetation' governed by a 'vegetation dynamics' component, but a simple model that has no 'land use' component that governs their relationship may want to identify the two).

The suggested workflow is then this:

- If there is already a model that fits your research question, use that one in your study (role: *model end user*).
- If not, decide what model components the question at hand needs.
  - If all components exist, compose a new model from them (role: *model composer*).
  - If not, design and implement missing model components (role: *model component developer*). If some required entity attributes are not yet in the master data model (Sect. 2.1.4), add them to your component. Suggest well-tested entity attributes, entity types, or model components to be included in the copan:CORE community's master data model or master component repository (*modeling board members* will then review them).

Rationale. Although in smaller teams, one and the same person may act in all of the above roles, the proposed role concept helps structuring the code occurring in a model-based analysis into parts needed and maintained by different roles, a prerequisite for collaborative modeling, especially across several teams.

The additional concept of model components (in addition to entity types and taxa) is necessary since processes which belong together from a logical point of view and are hence likely to be modeled by the same person or team may still most naturally be seen as being owned by different entity types, and at the same time developers from several teams may be needed to model all the processes of some entity type.

2.1.4 Master data model and master component repository

The *master data model* defines entity types, process taxa, attributes, and physical dimensions and units which the modeling board members deem (i) likely to occur in many different models or model components and (ii) sufficiently well-defined and well-named (in particular, specific enough to avoid most ambiguities but avoiding a too discipline-specific language). Users are free to define additional attributes in their components but are encouraged to use those from the master data model or suggest new attributes for it.

The *master component repository* contains model components which the modeling board members deem likely to be useful for many different models, sufficiently mature and well-tested, and indecomposable into more suitable smaller components. Users are free to distribute additional components not yet in the repository.

Rationale. Poorly harmonized data models are a major obstacle for comparing or coupling simulation models. Still, a perfectly strict harmonization policy that would require the prior approval of every new attribute or component would inhibit fast prototyping and agile development. This is why the above two catalogs and the corresponding role were introduced.

2.1.5 All attributes are treated as variables with metadata

Although many models make an explicit distinction between "endogenous" and "exogenous" variables and "parameters", our modular approach requires us to treat all relevant ~~entity-type~~ entity type or process taxon attributes a priori in the same way, calling them *variables* whether or not they turn out to be constant during a model run or are used for a bifurcation analysis in a study. ~~This is because a quantity that one model component uses as an exogenous parameter that will not be changed by this component will often be an endogenous variable of another component, and it is not known to a model component developer which of the quantities she deals with will turn out to be endogenous variables or exogenous parameters of a model or study that uses this component.~~

A variable's specification contains *metadata* such as a common language label and description, possibly including references to external metadata catalogs such as the Climate and Forecast Conventions' Standard Names (CF Standard Names, 2018) for climate-related quantities or the World Bank's CETS list of socio-economic indicators (World Bank CETS codes, 2017), a mathematical symbol, its level of measurement or scale of measure (ratio, interval, ordinal, or nominal), its physical or socio-economic dimension and default unit (if possible following some established standard), its default (constant or initial) value and range of possible values.

Rationale. The common treatment of variables and parameters is necessary because a quantity that one model component uses as an exogenous parameter that will not be changed by this component will often be an endogenous variable of another component, and it is not known to a model component developer which of the quantities she deals with will turn out to be endogenous variables or exogenous parameters of a model or study that uses this component. Well-specified metadata are essential for collaborative modeling to avoid hard-to-detect mistakes involving different units or deviating definitions.

2.2 Basic ~~entity-types~~entity types

We try to keep the number of explicitly considered ~~entity-types~~ entity types manageably small and thus choose to model some relevant things that occur in the real world not as separate entities but rather as attributes of other entities. As a rule of thumb (with the exception of the ~~entity-type~~ entity type 'world'), only things that can occur in potentially large, a priori unknown, and maybe changing numbers and display a relevant degree of heterogeneity for which a purely statistical description seems inadequate will be modeled as entities. In contrast, things that typically occur only once for each entity of some type (e.g., an individual's bank account) or which are numerous but can sufficiently well described statistically are modeled as attributes of the latter ~~entity-type~~entity type.

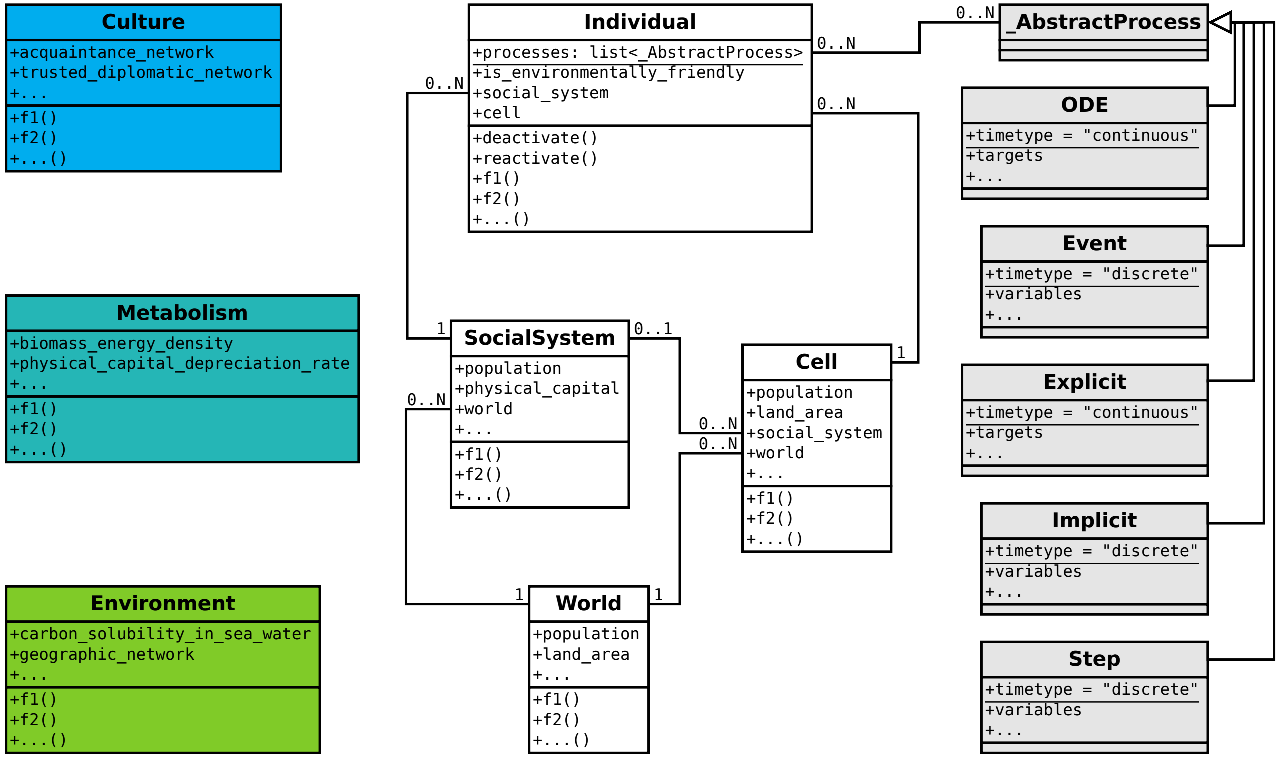

Figure 3. Basic relationships between entities in the copan:CORE framework. This ~~entity-relationship~~ UML class diagram shows the most important entity types and relationships, and a selection of entities' attributes, as implemented in the 'base' model component of the *pycopancore* reference implementation. 'f1()' and 'f2()' are placeholders for process implementation methods belonging to that taxon or entity type. The underlined attributes 'processes' (present in all taxa and entity types though shown only once here) and 'timetype' are class-level attributes.

Although further ~~entity-types~~ entity types (e.g., 'household', 'firm', 'social group', 'policy', or 'river catchment'~~, the latter being central in socio-hydrology (Di Baldassarre et al., 2017) and important for the water planetary boundary (Steffen et al., 2015)~~) will eventually be included into the master data model, at this point the copan:CORE ~~*base*~~ *'base' model component* only provides the ~~following entity-types that~~ entity types which all models must contain, described in this section, in addition to an overall ~~entity-type~~ entity type 'world' that may serve as an anchor point for relations between entities (see also Fig. 3).

2.2.1 Cells

An entity of type 'cell' represents a small spatial region used for discretising the spatial aspect of processes and attributes which are actually continuously distributed in space. They may be of a more or less regular shape and arrangement, e.g., represent a latitude-longitude-regular or an icosahedral grid or an irregular triangulation adapted to topography. Since they have no real-world meaning beyond their use for discretization, cells are not meant to be used as agents in agent-based model components. Geographical regions with real-world meaning should instead be modeled via the type ‘social system’.

2.2.2 Social systems

An entity of type ‘social system’ is meant to represent what is sometimes simply called a ‘society’, i.e. ~~g. , Wikipedia defines ‘society’ as~~ “an economic, social, industrial or cultural infrastructure” (Wikipedia, 2017) such as a megacity, country, or the EU. We understand a social system as a ~~humanly-designed and humanly-reproduced~~ human-designed and human-reproduced structure including the flows of energy, material, financial and other resources that are used to satisfy human needs and desires, influenced by the accessibility and usage of technology and infrastructure ~~(Otto et al., in review)~~(Fischer-Kowalski, 1997; Otto et al., in review) . Equally importantly, social systems include social institutions such as informal systems of norms~~and~~ , values and beliefs, and formally codified written laws and regulations, governance and organizational structures (Williamson, 1998). In our framework, norms, values and beliefs may be described in macroscopic terms on the social system level but may also be described microscopically on the level of individuals (Sect. 2.2.3).

Social systems in this sense typically have a considerable size (e.g., a sovereign nation state such as the United States of America, a federal state or country such as Scotland, an urban area such as the Greater Tokyo Area, or an economically very closely integrated world region such as the EU), controlling a well-defined territory (represented by a set of cells) and encompassing all the socio-metabolic and cultural processes occurring within that territory. Social systems are not meant to represent a single social group, class, or stratum, for which different ~~entity-types~~ entity types should be used (e.g., a generic ~~entity-type~~ entity type ‘social group’). To allow for a consistent aggregation of socio-metabolic quantities and modeling of hierarchical political decision-making, the social systems in a model are either all disjoint (e.g., representing twelve world regions as in some integrated assessment models, or all sovereign countries), or form a nested hierarchy with no nontrivial overlaps (e.g., representing a three-level hierarchy of world regions, countries, and urban areas). As the attributes of social systems will often correspond to data assembled by official statistics, we encourage to use a set of social systems that is compatible to the standard classification ISO 3166-1/2 when representing real-world social systems.

Social systems may act as agents in agent-based model components but an alternative choice would be to use ‘individuals’ like their ‘head of government’ or ‘social groups’ like a ‘ruling elite’ as agents.

2.2.3 Individuals

Entities of type ‘individual’ represent individual human beings. These entities will typically act as agents in agent-based model components, although also entities of other types (e.g., the potential types ‘household’, ‘firm’, or ’social group’) may do so. In contrast to certain economic modeling approaches that use “representative” consumers, an entity of type ‘individual’ in copan:CORE is not usually meant to represent a whole class of similar individuals (e.g., all the actual individuals of a certain profession) but just one specific individual. Still, the set of all ‘individuals’ contained in a model will typically be interpreted as being a representative *sample* of all real-world people, and consequently each individual carries a quantity ‘represented population’ as an attribute to be used in statistical aggregations, e.g., within a social system.

2.3 ~~**Basic process taxa**~~

2.2.1 **Relationships between entity types and process taxa**

~~Based on Donges et al. (2018), we classify processes into three major taxa . We give only a rough definition and abstain from defining a finer, hierarchical taxonomy, being aware that gaining consensus among different disciplines on such a taxonomy would be unlikely, and thus leaving the assignment of individual processes and attributes to either taxon to the respective model component developers:~~ Although there is no one-to-one correspondence between process taxa and entity types, some combinations are expected to occur more often than others, as indicated by the thicker gray connections in Fig. 2.

2.2.2 ~~**Environment**~~

~~The 'environment' process taxon is meant to contain biophysical or "natural" processes from material subsystems of the Earth system that are not or only insignificantly shaped or designed by human societies (e.g., atmosphere-ocean diffusion, growth of unmanaged vegetation, and maybe the decay of former waste dumps). We expect these processes~~ We expect processes from the *environmental (ENV)* process taxon to deal primarily with the ~~entity-types~~ entity types 'cell' (for local processes such as terrestrial vegetation dynamics described with spatial resolution) and 'world' (for global processes described without spatial resolution, e.g., the greenhouse effect) and sometimes 'social system' (for mesoscopic processes described at the level of a social system's territory, e.g., the environment diffusion and decomposition of industrial wastes).

2.2.3 ~~**Metabolism**~~

~~The 'metabolism' process taxon is meant to contain socio-metabolic and economic processes from material subsystems that are designed or significantly shaped by human societies (e.g., harvesting, afforestation, greenhouse gas emissions, waste dumping, land-use change, infrastructure building). Social metabolism refers to the material flows in human societies and the way societies organize their exchanges of energy and materials with nature (Fischer-Kowalski, 1997; Martinez-Alier, 2009). We expect these processes~~ *Socio-metabolic (MET)* processes are expected to deal primarily with the ~~entity-types~~ entity types 'social system' (e.g., for processes described at national or urban level), 'cell' (for local socio-metabolic processes described with additional spatial resolution for easier coupling to natural processes) and 'world' (for global socio-metabolic processes such as international trade), and only rarely with the ~~entity-type~~ entity type 'individual' (e.g., for micro-economic model components such as consumption, investment or the job market).

2.2.4 ~~**Culture**~~

~~The 'culture' process taxon is meant to contain socio-cultural processes from~~ Finally, processes from the ~~*immaterial*~~*socio-cultural (CUL)* ~~subsystems (e.g., opinion adoption, social learning, voting, policy-making)that are described in models in a way abstracted from their material basis. Culture in its broadest definition refers to everything what people do, think and posses as members of society (Bierstedt, 1963, p. 129). We expect these processes~~ taxon are expected to deal primarily with the

~~entity-types~~ entity types ‘individual’ (for “micro”-level descriptions) and ‘social system’ (for “macro”-level descriptions), and rarely ‘world’ (for international processes such as diplomacy or treaties).

2.3 Software design

This section describes the programming language-independent parts of how the above abstract structure is realized as computer software. As they correspond closely with the role-based and entity-centric view of the abstract framework, *modularization* and *object-orientation* are our main design principles. All parts of the software are organized in packages, subpackages, modules, and classes. The only exception are those parts of the software that are written by model end-users to perform actual studies, which will typically be in the form of *scripts* following a mainly imperative programming style that uses the classes provided by the framework. Fig. 4 summarizes the main aspects of this design which are described in detail in the following.

2.3.1 Object-oriented representation

~~Entity-types~~ Entity types and process taxa are represented by *classes* (‘Cell’, ‘SocialSystem’, ‘Culture’, . . .), individual entities by *instances* (objects) of the respective ~~entity-type~~ entity type class, and process taxon classes have exactly one instance. While ~~entity-type~~ entity type and process taxon classes hold processes’ and variables’ metadata as *class attributes,* entity instances hold variable values and, where needed, their time derivatives as *instance attributes.* Processes’ logics can be specified via *symbolic expressions* in the process metadata (e.g., for simple algebraic or differential equations) or as imperative code in *instance methods* (e.g., for regular ‘steps’ and random ‘events’ in an agent-based modeling style), thereby providing a large flexibility in how the equations and rules of the model are actually represented in the code, without compromising the interoperability of model components.

2.3.2 Interface and implementation classes

All of this is true not only on the level of (composed) models but already on the level of model components, though restricted to the ~~entity-types~~entity types, processes and variables used in the respective component. To avoid name clashes but still be able to use the same simple naming convention throughout in all model components, each model component is represented by a *subpackage* of the main copan:CORE software package, containing class definitions for all used ~~entity-types~~ entity types and process taxa as follows. Each ~~entity-type~~ entity type and process taxon used in the model component is represented by two classes, (i) an *interface class* that has a class attribute of type ‘Variable’ (often imported from the master data model subpackage or another model component’s interface classes) for each variable of this ~~entity-type~~ entity type or process taxon this model component uses as input or output, containing that variable’s metadata (see Fig. ~~??~~ 1 in the Supplementary Information for an example), and (ii) an *implementation class* inherited from the interface class, containing a class attribute ‘processes’ and potentially some instance methods with process logics.

The attribute ‘processes’ is a list of objects of type ‘Process’, each of which specifies the metadata of one process that this model component contributes to this ~~entity-type~~ entity type or process taxon (see Figs. ~~??,??~~ 2 and 3 of the Supplementary

Information for examples). These metadata either contain the process logics as a symbolic expression or as a reference to some instance method(s). Instance methods do not return variable values but manipulate variable values or time derivatives directly via the respective instance attributes. As many variables are influenced by more than one process, some process implementation methods (e.g., those for differential equations or noise) only add some amount to an attribute value, while others (e.g., those for major events) may also overwrite an attribute value completely.

2.3.3 Model composition via multiple inheritance

Finally, a model's composition from model components is represented via multiple *inheritance* from the model component's implementation classes (which are thus also called ‘mixin’ classes) as follows. Each model is defined in a separate *module* (typically a single code file). For each ~~entity-type~~ entity type and process taxon that is defined in at least one of the used model component packages, the model module defines a composite class that inherits from all the mixin classes of that ~~entity-type~~ entity type contained in the used model component packages. Fig. 4 shows an example of this with just two components and two entity types.

2.3.4 Dimensional quantities, symbolic expressions, networks

To be able to specify values of dimensional quantities, mathematical equations, and networks of relationships between entities in a convenient and transparent way, we provide classes representing these types of objects, e.g., ~~’~~‘Dimension’, ~~’~~‘Unit’, ~~’~~‘DimensionalQuantity’, ~~’~~‘Expr’ (for symbolic expressions), ~~’~~‘Graph’ (for networks), ~~’~~‘ReferenceVariable’/~~’~~‘SetVariable’ (for references to single/sets of other entities).

2.3.5 Interoperability with other model software

copan:CORE can be used together with other simulation software to simulate coupled models consisting of “internal” components implemented in copan:CORE interacting in both directions with an “external” component provided by the other software. Currently, copan:CORE must act as the coupler to achieve this, which requires that the other software provides at least a minimal interface (e.g., conforming to the basic modeling interface (BMI), Syvitski et al. (2014)) that allows to read, set and change its state variables and to advance its model simulation by one time step.

To couple an external model component into a copan:CORE model, one must write a “wrapper” model component in the copan:CORE framework. For each relevant ‘external’ variable of the external model, the wrapper specifies a corresponding ‘internal’ copan:CORE variable in a suitable entity type or process taxon. In addition, the wrapper contributes a process implementation method of type ‘Step’ to a suitable process taxon, which uses the external software's interface to sync the external variables with their internal versions, using a suitable regridding strategy if necessary, and lets the external model perform a time step.

In later versions, copan:CORE will include a standard wrapper template for models providing a BMI, and might also itself provide such an interface to external couplers.

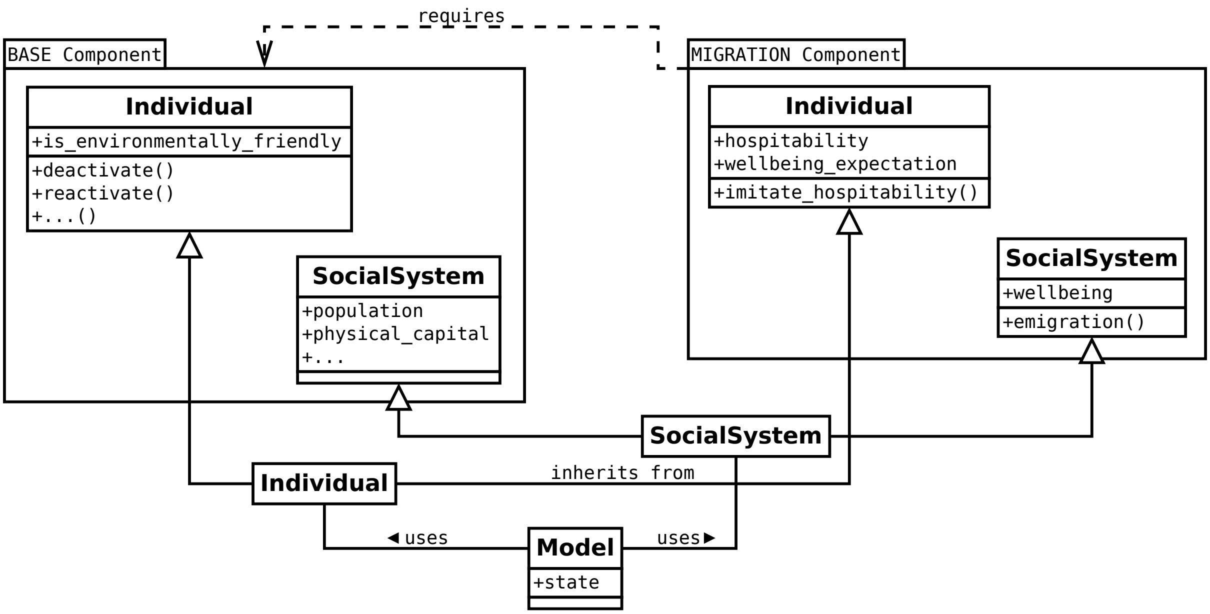

Figure 4. ~~**Stylized software diagram of a model in pycopancore displaying the inheritance structure**, showing~~ **Model composition through multiple inheritance of attributes and processes by process taxa and entity types.** This stylized class diagram shows how a model in copan:CORE can be composed from several model components (only two shown here, the mandatory component 'base' and ~~one other model~~ the fictitious component 'migration') that contribute component-specific processes and ~~just one entity-type and~~ attributes to the model's process ~~taxon. Large boxes are subpackages~~taxa and entity types (only two shown here, ~~colors indicate code sections which are provided or used by different user roles~~'Individual' and 'SocialSystem'). ~~Red: model end users, orange: model developers, blue: model component developers~~To achieve this, ~~green: modeling board members. Arrows indicate~~ the ~~relations "is using"~~ classes implementing these entity types on the model level are composed via multiple inheritance (~~dashed~~solid arrows) ~~and "inherits~~ from ~~"~~ their component-level counterparts (~~solid~~so-called 'mixin' classes).

2.4 Reference implementation in Python

For the reference implementation of copan:CORE we chose the Python programming language to enable a fast development cycle and provide a low threshold for end users. It is available as ~~an~~ the open-source Python package *pycopancore* (~~http://github.com/pik-copan/pycopancore~~`https://github.com/pik-copan/pycopancore`) including the master data model and a small number of pre-defined model components and models as subpackages and modules. Symbolic expressions are implemented via the *sympy* package (Meurer et al., 2017) which was extended to support aggregation (as in Fig. ~~??~~3 of the Supplementary Information, top, line 5) and cross-referencing between entities ~~(as in Fig. ??~~(same Fig., bottom, line 14). ODE integration is currently implemented via the *scipy* package (Jones et al., 2001). While the reference implementation is suitable for moderately sized projects, very detailed models or large-scale Monte-Carlo simulations may require an implementation in a faster language such as C++, which we aim at realizing via a community-driven open-source software development project.

~~Model component developersadd their model component as a package to their local workspace folder, including the interface module and one module for each provided implementation class as in Figs. ??–??. In order to paralellize complex computations or couple to other model software, an implementation class may implement certain processes using an instance method that calls or communicates with other processes or external programs which provide a communication method supported by Python, e.g., MPI or JSON.~~

~~Model composersprovide a module that mainly composes the final entity type and process taxon classes via multiple inheritance from model components' implementation classes, e.g., specifying code like Model end usersuse a Python script that imports these model modules, instantiates a 'model' object, all needed process taxon objects and an initial set of entities, then initializes those variables that shall start with non-default values, uses a 'runner' object to run the model for a specified time and finally analyses the resulting trajectory.~~ Fig. 5 gives ~~a sketch of such a script (see the online tutorial for more detailed examples).~~

~~Upon instantiation, the 'model' object uses Python's introspectioncapabilities to analyse its own model structure including which variables depend on which others in which way, and this information is then used by the runner to simulate the model. Future versions will use this information further for improving performance and producing reports on model structure. The runner returns the time evolution of requested variables as a nested Python dictionary the first- and second-level keys of which are a 'variable' object and an entity or process taxon and whose values are lists of values ordered by time, which can then conveniently be analysed or plotted (e.g., Fig. 5, line 30)~~an impression of how user code in *pycopancore* looks like. See the *Supplementary Information* for further details.

3 ~~Examplary~~ Example of a World-Earth model implemented using copan:CORE

In this section, we shortly present an example of a model realized with the *pycopancore* reference implementation of the copan:CORE modeling framework. The example model was designed to showcase the concepts and capabilities of copan:CORE in a rather simple WEM, and its components were chosen so that all entity types and process taxa and most features of copan:CORE are covered. Although most model components are somewhat plausible versions of model components that can be found in the various literatures, the example model is ~~not~~ intended to be a ~~serious~~ toy representation of the real world rather than one that could be used directly for studying concrete research questions. Likewise, although we show example trajectories that are based on parameters and initial conditions that roughly reproduce current values of real-world global aggregates in order to make the example as accessible as possible, the shown time evolutions may not be interpreted as any kind of meaningful quantitative prediction or projection.

In spite of this modest goal here, it will become obvious from the two presented scenarios that including socio-cultural dynamics such as migration, environmental awareness, social learning, and policy making into more serious models of the global co-evolution of human societies and the environment will likely make a considerable qualitative difference for their results and thus have significant policy implications.

```
1  import pycopancore.models.my_model as M  # the model to be used
2  from pycopancore import master_data_model as D  # needed for dimensional quantities
3  from pycopancore.runners import DefaultRunner
4  # other imports
5
6  # instantiate the model, its process taxa, and some entities:
7  mod = M.Model()
8  world = M.World(environment=M.Environment(), metabolism=M.Metabolism(), culture=M.Culture(),
9                  atmospheric_carbon = 830 * D.gigatonnes_carbon)  # non-default initial value
10 socs = [M.SocialSystem(world=world) for s in range(10)]
11 cells = [M.Cell(socialsystem=random.choice(socs)) for c in range(100)]
12 inds = [M.Individual(cell=random.choice(cells),  # place individuals randomly on cells
13                      supports_emissions_tax = random.choice([False, True], p=[.7, .3]),
14                      imitation_rate = 1 / D.weeks)
15         for i in range(1000)]
16
17 # form an Erdos-Renyi random acquaintance network:
18 for index, i in enumerate(inds):
19     for j in inds[:index]:
20         if random.uniform() < 0.1: world.culture.acquaintance_network.add_edge(i, j)
21
22 # distribute initial global vegetation randomly among cells:
23 r = random.uniform(size=100)
24 M.Cell.terrestrial_carbon.set_values(cells, 2480 * D.gigatonnes_carbon * r / sum(r))
25
26 # run model and plot some results:
27 runner = DefaultRunner(model=mod)
28 traj = runner.run(t_0=2000, t_1=2200, dt=1)  # returns a dict of dicts of time-series
29 pylab.plot(traj[D.time], traj[M.World.surface_air_temperature][world], "r")
30 for s in socs: pylab.plot(traj[D.time], traj[M.SocialSystem.population][s], "y")
```

Figure 5. Sketch of a model end user's Python script running a model and plotting some results, featuring dimensional quantities and a network. Variable values can be set either at instantiation (line 9), via the entity object attribute (line 20) or the Variable object (line 24).

The example model includes the following components: (1) a spatially resolved version of the simple carbon cycle used in ~~Nitzbon et al. (2017) (based on Anderies et al. (2013)) ; regionalised versions~~ Nitzbon et al. (2017) (based on Anderies et al., 2013) ; (2) a regionalised version of the well-being-driven population dynamics and simple economy used in ~~Nitzbon et al. (2017) , adding to its~~ Nitzbon et al. (2017). The fossil and biomass energy sectors are complemented by a renewable energy sector with technological progress based on learning by doing ~~(Nagy et al. (2013))~~ (Nagy et al., 2013) and with international technology spillovers and human capital depreciation; (3) international migration driven by differences in well-being ~~(see, e.g., Lilleoer and van den Broeck (2011)); and a~~ (see, e.g., Lilleoer and van den Broeck, 2011); and (4) domestic voting on subsidizing renewables, taxing greenhouse gas emissions, and banning fossil fuels that is driven by individual environmental friendliness. The latter results from getting aware of environmental problems by observing the local biomass density and diffuses through a social acquaintance network via a standard model of social learning ~~(see e.g., Holley and Liggett (1975))~~(see e.g., Holley and Liggett, 1975). These processes cover all possible process taxon interactions as shown in Table 1 and are distributed over eight model components in the code as shown in Fig. 6.

In order to show in particular what effect the inclusion of the socio-cultural processes into WEMs can have on their results, we compare two representative hundred-year runs from this example model, one without the social processes migration, environmental awareness, social learning, and voting, and another with these processes included. Both runs start from the same initial conditions and use the same parameters which were chosen to roughly reflect real-world global aggregates of the year

→	**CUL**	**MET**	**ENV**
CUL	social learning, voting	migration, energy policy	environmental protection
MET	wellbeing	production, capital & pop. growth	extraction, harvest, emissions
ENV	wellbeing, awareness	resource availability	carbon cycle

Table 1. Possible classification of example model processes by owning process taxon (row) and affected process taxon (column) (following Donges et al., 2018): environment (~~following Donges et al. (2018)~~ENV), metabolism (MET) and culture (CUL) ~~.~~

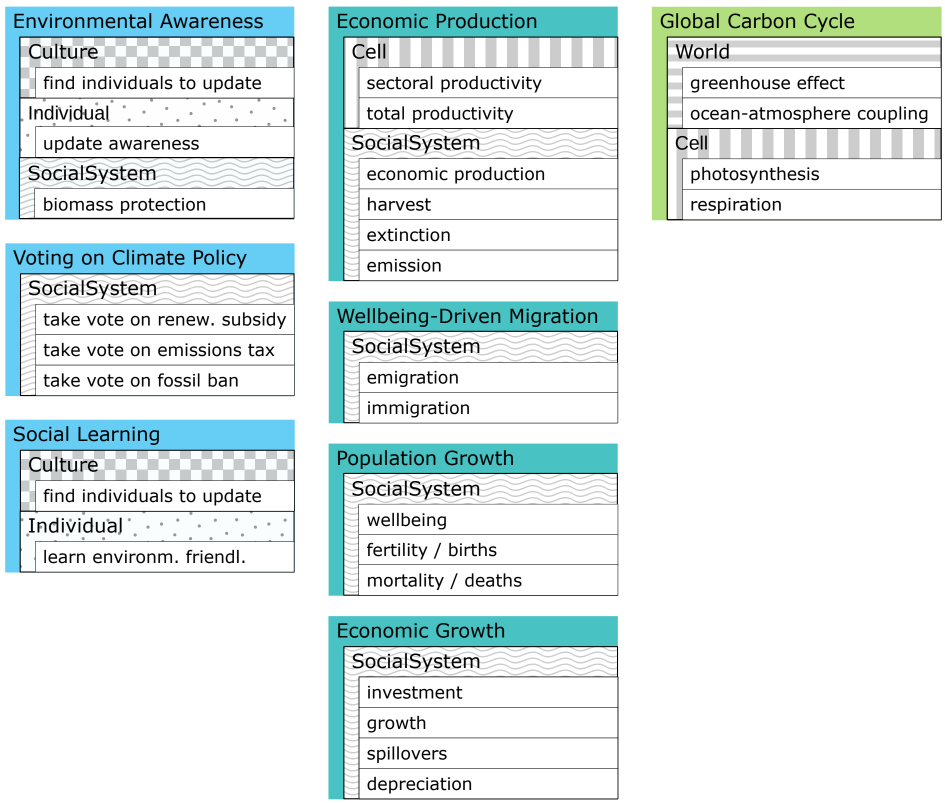

Figure 6. Components, entity types, and processes of the example model. Each ~~white~~ box represents a model component that contributes several processes (~~smallest rectangles~~white bars) to different entity types and process taxa (differently ~~colored boxes~~hashed rectangles).

2000 but were otherwise randomly distributed on an Earth-like planet with five fictitious social systems, 100 grid cells and 1000 representative individuals. See the *Supplementary Information* for model and parameter details.

As can be seen in Fig. 7 (left), without the social processes, our fictitious societies go on burning the fossil carbon stock, driving atmospheric and ultimately ocean carbon stocks further up considerably despite a temporary reduction in the latter two stocks (Fig. 7 bottom panels show these variables corresponding to the environmental process taxon). The unrealistic initial decline in atmospheric carbon is due to the oversimplified representation of vegetation growth without considering water, nutrient and other constraints. Although terrestrial carbon grows initially, it also eventually gets exploited severely once fossil stocks are down and the share of biomass in the energy sector grows (middle panels show these energy sector shares in all five social systems). Although one social system has a renewable energy policy in place throughout and renewable energy knowledge spills over to other social systems, the renewable sectors only become really competitive and get significant shares towards the end of the century when unprotected biomass becomes scarce.

Things are very different when the social processes are included, Fig. 7 (right). As can be seen in the upper panel with variables corresponding to the socio-cultural process taxon, the share of environmentally friendly individuals grows rapidly due to the combined effects of environmental awareness and social learning. Since this implies that a proportionally growing percentage of the terrestrial carbon gets protected, the growing environmental friendliness at first implies a declining share of the biomass sector and hence an even growing share of the fossil sector. But after about two decades, this evolution gets reversed fast due to energy policy: growing environmental friendliness also causes all social systems to implement a renewable subsidy at different time points but within only several years, then an emissions tax and ultimately banning fossils completely shortly after. After that, despite the renewable subsidy and vast protection of terrestrial carbon, the energy system is dominated by biomass for about another three to five decades before renewables take over. Still, in contrast to the first scenario, atmospheric carbon declines and terrestrial carbon remains high.

With the *pycopancore* reference implementation, running the above two simulations took 140 seconds (without socio-cultural processes) and 520 seconds (including socio-cultural processes) on an i7-6600U CPU at 2.60 GHz. Since further performance improvements are desirable to support Monte-Carlo simulations, we aim at a community-supported development of an alternative, more production-oriented implementation in the C++ language.

4 Conclusions

In this paper, we presented a novel simulation modeling framework that aims at facilitating the implementation and analysis of World-Earth (or planetary social-ecological) models. It follows a modular design such that various model components can be combined in a plug-and-play fashion to easily explore the influence of specific processes or the effect of competing theories of social dynamics from different schools of thought (Schlüter et al., 2017) on the ~~coevolutionary~~ co-evolutionary trajectory of the system. The model components describe fine-grained yet meaningfully defined subsystems of the social and environmental domains of the Earth system and thus enable the combination of modeling approaches from the natural and social sciences. In the modeling framework, different entities such as geographic cells, individual humans, and social systems are represented and their attributes are shaped by environmental, socio-metabolic, and socio-cultural processes. The mathematical types of processes that can be implemented in the modeling framework range from ordinary differential and algebraic equations to deterministic and stochastic events. Due to its flexibility, the model framework can be used to ~~analyse~~ analyze interactions at and between various scales – from local to regional and global.

The current version of the copan:CORE ~~framework also comes with some~~ modeling framework includes a number of tentative model components implementing, e.g., basic economic, climatic, biological, demographic and social network dynam-

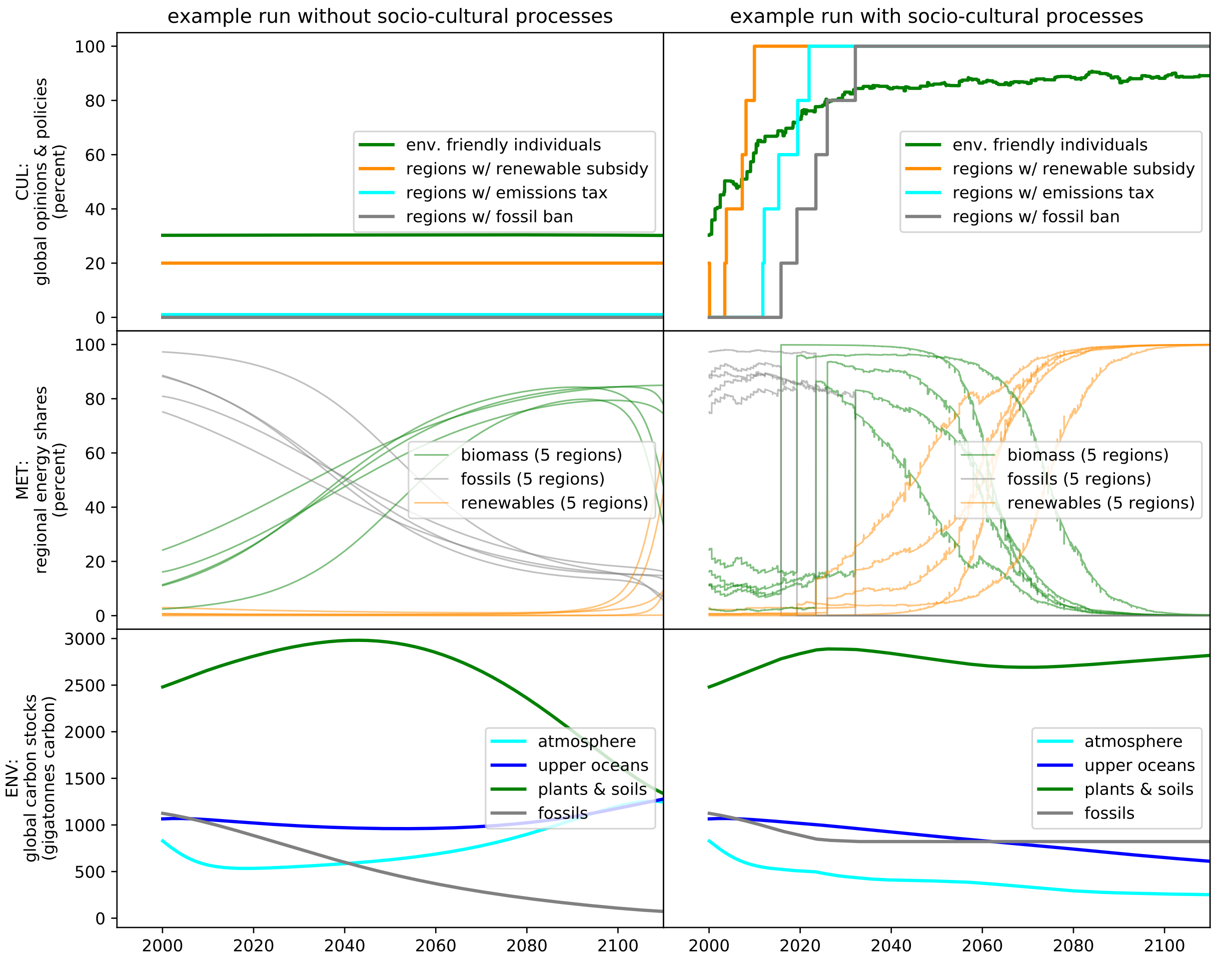

Figure 7. ~~**Two runs from an example model,**~~ **Two runs from a World-Earth model example,** one without (left) and one with (right) the ~~social~~ socio-cultural processes of migration, environmental awareness, social learning, and voting included, showing very different transient (and asymptotic, though not shown here) ~~behaviour~~behavior. Colors differ from other figures: green for variables related to terrestrial carbon, orange for those related to renewables, cyan for those related to atmospheric carbon, and gray for those related to fossils.

ics. However, to use the modeling framework for rigorous scientific analyses, these components have to be refined, their details have to be spelled out, and new components have to be developed that capture processes with crucial influence on World-Earth ~~coevolutionary~~ co-evolutionary dynamics. For this purpose, various modeling approaches from the social sciences are available to be applied to develop comprehensive representations of such socio-metabolic and ~~cultural processes (Müller-Hansen et al. (2017) and references therein)~~socio-cultural processes (Müller-Hansen et al., 2017, and references therein). For example, hierarchical adaptive network approaches could be used to model the development of social groups, institutions and organizations spanning local to global scales or the interaction of economic sectors via resource, energy and information flows (Gross and Blasius, 2008; Donges et al., 2017a).

Making such an endeavor prosper requires the collection and synthesis of knowledge from various disciplines. The modular approach of the copan:CORE simulation modeling framework supports well-founded development of single model components, helps to integrate various processes and allows to ~~analyse~~ analyze their interplay. We therefore call upon the interdisciplinary social-ecological ~~modelling community~~ modeling community and beyond to participate in further model and application development to facilitate "whole" Earth system analysis of the Anthropocene.

Code availability. A Python 3.6.x implementation of the copan:CORE World-Earth modeling framework, its detailed documentation and the World-Earth model example are available at https://github.com/pik-copan/pycopancore.

Competing interests. The authors declare no competing interests.

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~~Sketch of a model component's interface, implemented as a Python module that lists the variables. The component contributes to the various entity types and process taxa, either referenced from the master data model (line 13) or defined newly (line 15).~~

~~Sketches of implementation classes for three entity-types in two model components, to be used as mixin classes in model composition. Each class defines processes (here steps and events) that the owning model component contributes to a certain process taxon or entity type. Note how the examples feature process implementation via instance methods (l.4 of each example) networks (top, l.6–9), dimensional quantities (top, l.14), stochasticity (middle, l.5), and the use of a social system's individuals as a representative sample of its population (bottom, l.5+6). See inline comments in magenta for detailed explanations.~~

~~Sketches of implementation classes (continued), featuring explicit and implicit equations (top, l.4–10) and ODEs (bottom, l.23–26), symbolic expressions (bottom, l.7–8) and equations (top, l.9–10), aggregation (top, l.6), and cross-referencing between entities (bottom, l.16–18).~~

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