Proposal for a 2nd revision of the copan:CORE paper for Earth System Dynamics

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We thank the editor and the referees for their insightful comments that helped to further improve and streamline the presentation of the copan:CORE World-Earth modeling framework in our manuscript under consideration for publication in Earth System Dynamics.

After consultation with the editor James Dyke, we present here a summary of the changes we proposed and implemented for a second revision of our copan:CORE paper under consideration at Earth System Dynamics (ESD). We here mainly build upon the editor's report (see below) that summarized the latest reports by two referees (see also below) and refer to the three main points C1–C3 that our paper intends to make:

> C1 - Argue that coupling of human actions on the Earth systems is necessary or important for a class of scientific and policy-relevant questions.
>
> C2 - Assume C1 (coupling is required) and then demonstrate how such coupling can be implemented into a scalable framework.
>
> C3 - Provide worked examples of the output of a coupling framework that provides new scientific insights and findings that may be of policy relevance.

The following summary of changes takes the role of a response to the editor's comments. Due to the detailed consultation process and since our summary of changes builds on the referees comments, the point-to-point response to their reviews is kept rather brief. (Editor's and referees' comments are in italics below)

Along these lines, we performed the following revisions:

1. Strengthen C1 in line with James Dykes' editorial summary and Axel Kleidon's review:

- We now even more clearly identify a set of research questions that need a 'LOOPS' approach and 'World-Earth modelling', and we more clearly define the dividing line to questions where this may not be needed.

- By turning down C2 (see below), we emphasize more how the paper fits into the scope of ESD as a journal and of the Special Issue in particular. The paper is explicitly part of the Special Issue on “Social dynamics and planetary boundaries in Earth system modeling” and we see a valuable role of it in this context, completing that Special Issue’s scope ranging from motivational and case-making work via theoretical and methodological considerations towards steps towards practical solutions and case studies.

- Hence, in our perspective the presented copan:CORE framework fits the scope of ESD as an interdisciplinary journal very well (specific points that we address in our paper are highlighted in bold):

  “*Earth System Dynamics (ESD) is a not-for-profit international scientific journal dedicated to the publication and public discussion of studies that take an* ***interdisciplinary perspective of the functioning of the whole Earth system and global change****. The overall behaviour of the Earth system is* ***strongly shaped by the interactions among its various component systems****, such as the atmosphere, cryosphere, hydrosphere, oceans, pedosphere, lithosphere, and the inner Earth, but also by life and* ***human activity****. ESD* ***solicits contributions that investigate these various interactions and the underlying mechanisms, ways how these can be conceptualized, modelled****, and quantified, predictions of the overall system behaviour to global changes, and the* ***impacts for its habitability, humanity, and future Earth system management by human decision making****.*” (Source: ESD website)

- We push an ‘open framework’ idea: this addresses the need to be epistemologically flexible because of the large diversity of theories and methodologies from diverse fields in devising “models of man”.

- We clarify that our framework can be used to study simple AND complex models, it is explicitly useful for both. (We actually focus on simple models in the copan collaboration most of the time and for good reasons, mainly the same ones that Axel Kleidon and James Dyke mention in their reviews).

- We make sure not to emphasize or promote agent-based modelling, as our references to them were apparently misleading to think that we explicitly want to promote them. We remain agnostic regarding their use, they can be useful for some research questions, less so for others. We now discuss more explicitly and in some detail in the paper when they could be useful, where too simple equation-based models fail: where there is a lot of heterogeneity, where representation of complex and hierarchical social structures is important, where agency, policies, governance on the level of agents, institutions, social structures is part of the research questions etc. ...

2. Turn down C2:

- We now focus on copan:CORE as an open framework for conceptualizing and constructing models of the Earth system in the Anthropocene and the underlying ontology / taxonomy here (with refs to taxonomy paper), independent of software implementation.

- We explain in more detail why such an open framework is useful.

- We moved the detailed description of the software design and implementation to the supplementary information (SI) and describe it only in summary in the main text.

- The focus of this section is, hence, the presentation of the open framework for World-Earth modeling which, in our view, fits well with the scope of the journal Earth System Dynamics.

3. Strengthen C3:

In much more detail, we now motivate present and analyse a much simplified version of the exemplary World-Earth model that was discussed in the paper before:

- To improve our proof of concept, we will replace the current section “Example of a World-Earth model implemented using copan:CORE” by a section “Influence of social dynamics in a minimum-complexity World-Earth model implemented using copan:CORE” in which we analyse a reduced version of the current example model, giving all necessary details in the main text and some additional information and possible extensions in the SI.

- The reduced model can be interpreted as a nested box model. On the coarsest level, it has one “planet” box with a maritime and an atmospheric carbon stock. On the middle level, it has two “social systems”, representing a “global North” that holds the larger part of capital, and a “global South” that holds the larger part of population. The only social-metabolic (MET) processes we keep are the extraction of fossil fuels, harvesting of biomass, production of renewable energy, production of a final consumption good, and investment into capital growth, this forming a minimal economic submodel that is able to display an energy transition from fossil- and biomass-based to renewables-based production. Processes we drop are population dynamics, migration, and knowledge spillovers.

- On the finer level, each social system possesses just two “cells”, a “boreal” and a “temperate” cell in the “global North”, and a “tropical” and a “subtropical” cell in the “global South”, all of which differ in their initial fossil stocks and solar insolation. The environmental processes (ENV) we keep are a simplistic carbon cycle in the “planet” box interacting with a simplistic vegetation model in the four cells.

- Finally, to be able to represent social dynamics interacting with the Earth system, the model has a representative sample of 100 individuals connected by a social network. The only socio-cultural processes (CUL) we keep are the social learning of environmental friendliness driven by differences in well-being, and the voting on energy policy, this forming a minimal feedback loop between economy and policy.

- The resulting model hence contains a minimal set of processes forming a feedback loop that spans the socio-cultural, socio-metabolic, and environmental spheres, and allows us to get an idea of how much difference the inclusion of the socio-cultural sphere in Earth system models can make. For this, we performed a bifurcation analysis that varies the overall strength of the socio-cultural processes. This analysis shows a transition between different regimes and provides evidence that the strength of socio-cultural processes has a nontrivial influence on the trajectory of the Earth system beyond what can be represented by simple exogenous emissions scenarios.

Editor’s summary

This is a timely, ambitious, and important contribution to the scientific debate about the role of human actions on the Earth system. While the authors have made improvements to the manuscript, I have concluded that it is not currently acceptable for publication based on the latest round of reviews and a consideration of previous reviews and how the manuscript has developed. Consequently I recommend revisions with another round of peer review. I am confident that this review process could be completed quickly and that this manuscript can be published in ESD in a timely manner.

I see three main possible contributions of the manuscript:

C1 - Argue that coupling of human actions on the Earth systems is necessary or important for a class of scientific and policy-relevant questions.

C2 - Assume C1 (coupling is required) and then demonstrate how such coupling can be implemented into a scalable framework.

C3 - Provide worked examples of the output of a coupling framework that provides new scientific insights and findings that may be of policy relevance.

In attempting all three contributions, the manuscript is at risk of not comprehensively addressing any. In its current guise the manuscript attempts to justify the requirement for coupling, show how it could be achieved with a particularly modelling or implementation framework, and then demonstrate output from this implementation. This is ambitious. My questions on publication surrounds whether its feasible, or even desirable, to do all of that in a single publication. The temptation is to ask for more in order to cover C1-C3, but this may not be the best approach.

Given the authors do not present a single model, but a framework with which a potentially very large range of models could be developed and then integrated, the issues of reproducibility are quite complicated.

Documentation of the software implementation of the python copan:CORE model is available at the GitHub site. There is also documentation available at https://pycopancore.readthedocs.io/en/latest/index.html

This includes a set of tutorials, e.g. how does a user uses the package. It also describes some of the implementation of the assumptions behind the model. I take the job this (or similar) documentation also needs to do, is establish C2. Presentation of a model framework (i.e. code that 'does something' with instructions of 'how to do something' does not necessarily establish that C2 has been satisfied.

In these respects, what is absent is software verification and validation. This is what I take to be the substantive issue of journal scope. ESD does not require nor does it request the presentation of the verification and validation of software that is used to produce scientific output. ESD would rely on the this activity being done in another journal, platform, or forum. From an editorial perspective, this has been one of the main challenges of ensuring appropriate review of the manuscript.

To proceed, I suggest the following routes to revision. Consider a clear separation between the model implementation and the assumptions surrounding it and its output. Specifically:

R1 - Argue that there is a need - scientific and of policy relevance - for such coupling and then

R2 - that the overall design approach taken - in particular the use of agent based implementations - satisfies this need.

R3 - Demonstrate the utility of this approach with results that either could not be produced via 'traditional' or established models and frameworks, or results that provide new insights into the class or perhaps example of the scientific (and potentially policy relevant) questions that the authors are motivated to address.

The existing manuscript does currently address R1-R3, but there are some gaps. For example, it may be argued that (potentially computationally expensive) agent based implementations are not required for some of the class of scientific questions that the authors argue their framework is designed for. There is a broader issue of to what extent human decision-making and behaviour needs to be disaggregated in social-ecological models. It is not the author's job to conclude such arguments! But the authors should be mindful that some readers (and reviewers) may need to carried along with their argument that is there is utility in agent based implementations.

Currently, for R1 a good deal of the 'intellectual heavy lifting - the 'motivation' comes from just two papers Verburg et al., 2016; Donges et al., 2017a, b and five bullet points in section 1.2.2 Design principles for World-Earth models. Given the planetary-scale ambition of the authors, it is understandable that there cannot be a sufficient list of possible scenarios and scientific questions that the framework will seek to address. But the absence of a discrete set of questions, plus some opacity as to the central modelling assumptions means that R1 is not sufficiently addressed.

For R2, it should be sufficient to focus on the disaggregated social dynamics approach - that is to establish that at a planetary-scale, aggregating human behaviours is not sufficient as it means missing important dynamics. I would have assumed that a planetary-scale framework would have some sort of tunable parameter by which this level of disaggregation can be 'turned up/down' as appropriate. Arguing that it's important to include low(er) level dynamics in order to understand high(er) level behaviours/states/responses works inversely: that is, it is sometimes better (in terms not *just of computational cost/efficiency but also in terms of mathematical tractability and conceptual understanding) to simplify lower level dynamics. Sometimes more is less.*

For R3 you have already presented output from core:COPAN. This is 'toy' model output as I take your main motivation is to demonstrate that the core:COPAN framework works - it is able to produce model output. I do not think it is necessary to implement a real world model (to use empirical data for the choice of model elements and parameter values), but I do think that there could be more convincing results presented. It is not surprising that a more complex model will produce quite different results. What new insights, what new knowledge can be gained here? This questions can be addressed using a toy or conceptual model. I would hope, that once the manuscript is freed from the requirement of establishing that the copan:CORE framework is verified and validated, you would be able to concentrate on demonstrating some of its power. This would not require large numbers of new simulations and analysis.

In this way, the manuscript is bookended by R1 and R3. R3 in an important sense helps demonstrate R1 - why do we need these potentially very complex models and approaches?

Separate (and perhaps in parallel) to this, I would recommend you expose the modelling framework to suitable review with verification and validation built into that process via perhaps a dedicated modelling journal. This more modular approach would allow you to produce a series of publications using a common and well established foundation for the implemented framework which could be referred and referenced to accordingly.

If you are able to revise your manuscript, then I would seek an additional round of independent peer review - but of a potentially limited nature. While I do not want to prejudice future outcomes, it may be sufficient for the review to progress with the response of one of the reviewers from the last round of peer review. I do not think it would be necessary to effectively treat the manuscript as a new submission with an entirely new round of peer review. However, I am open to your alternative suggestions.

Thank you for your continued contribution to Earth System Dynamics.

Referee 1 comments on revised manuscript copan:CORE
(Brian Dermody)

I am pleased to comment favourably on this revised manuscript. The authors have made considerable efforts to improve the manuscript. The revised manuscript now *clearly outlines the motivation for a new generation of WEMs, the theoretical foundation for their framework and how they have implemented it. I hope that the authors will be able to successfully develop what they present here. That undertaking will make an urgent and important contribution to understanding the complex drivers of social and environmental change in our globalised world.*

Specific comments

The revised structure for sections 1.1 and 1.2 is much improved and clearly outlines the current state of modelling earth system processes, the shortcomings of these approaches and the motivation for the new framework presented here as well as a helpful introductory overview to the theories and concepts relevant for WEMs. The addition of a rationale section is a great help for helping the reader understand the motivation and relevance of model design choices. I think it is a good decision to move most of the detailed code description to the SI and point readers to the most recent API documentation online. I agree with the editor on this that the discussion manuscript was somewhat caught between framework specification which might be more appropriate for a software journal such as Geoscientific Model Development and an introduction and academic motivation of your modelling framework, which I think is what you want to achieve here. The link between abstract concepts of culture, social-metabolism and environment in figure 2 with figures 3 and 4 is a big help in linking there theoretical grounding for your framework with how it will actually be implemented.

Section 1.2.2 on design principles is much improved and provides a powerful motivation for a new generation of WEMs.

> Motivated by this assessment, we tried to improve it further to make an even stronger case.

The new section 2.3.5 is a welcome addition, which clarifies how the model may serve to couple internal and external model components.

> We think so, too, and kept this, but we had to move it to the SI
> to accommodate the new overall design of the manuscript agreed with the editor.

Page 9, line 16: Perhaps provide the link to the git here.

> We have included that link in the manuscript now.

Referee 3 comments on revised manuscript

The manuscript by Donges et al deals with a highly timely and, I think, innovative approach to include human societies into an Earth system context, and thus the topic is certainly suitable for publication. With this manuscript, however, I have some problems that prevent me from recommending acceptance.

What I find difficult is that the paper lacks a clear focus. It describes the challenge associated with bringing socio-cultural dynamics into an Earth system model, a modelling approach, and an application. I think that each of these points are potentially valid and scientifically challenging topics, but the level at which these are dealt with in the manuscript is rather shallow and I feel that not much can be learned from it. So I think it needs a major revision.

To start with, why is it important to couple socio-cultural dynamics with the biophysical Earth system dynamics? There should clearly be a dividing line for topics that require such kind of model, and other topics that do not. It reminds me of an equivalent question that regards the coupling of atmosphere and ocean models. Not all studies require an interactive ocean model to run, and simply using prescribed boundary conditions in terms of sea surface temperatures is for quite a range of topics fully sufficient, and, in fact, quite often also more realistic because it does not allow the atmospheric model to drift as much. So I imagine that something similar would apply to the coupling of socio-cultural dynamics and the Earth. But this manuscript does not contain much about the conceptual challenge and the topics for which such a model would be needed and for which it would not be needed. Such a clearer conceptual description, best illustrated with a concrete example, I think would really improve the manuscript.

> We agree with the referee and expanded the discussion of more concrete research questions for WEM and added a discussion of questions that do not require such a coupling in Section 1.

Second, a thorough model description should enable a reader to reproduce the model. At the moment, this manuscript would not allow this level of reproducibility. It perhaps does not need to be provided at that level, because if it would describe it at this level, the manuscript would be more suitable for a model description journal like GMD. At the moment, the level of model description provides some parts that I think are probably too detailed, but on the other hand, it does not allow me to understand (or reproduce) the example provided in section 3 of the manuscript. For instance, what are the major assumptions, what are the critical parameters and the key uncertainties?

As agreed with the editor, we have now simplified the example model, moved the model detail from the SI to the main text, and added missing details. In addition, all model code is freely available on the git repository.

I may also point out that I do not think that neither an object-oriented framework nor an agent-based approach are essential to reproduce human dynamics. It is fine to use this, but I am sure one could equally represent these dynamics with conventional differential equations. Even more so, the use of agent-based dynamics and stochasticity may introduce an element of randomness which could impact the extent to which the results are reproducible, which would be a big problem. There are sufficient number of examples in the ecological literature where spatial population dynamics are represented with differential equations. So I think it is important to be clear about separating the conceptual challenge from the implementation.

We believe there are several aspects to this.

We agree that the question of whether or not to use an object-oriented framework is not determined by the system one wants to model. Our reason for choosing it is rather a methodological one: since we argue World-Earth modeling is an inherently interdisciplinary challenge that needs to use a language and framework accessible to several communities, we believe an object-oriented approach is the most natural way of thinking about the system, as nearly all disciplines' verbal language suggests the existence of entities of different types, possessing attributes that may change due to processes.

Regarding the use of agent-based model (ABM) components, we remain agnostic but argue that this is a technique a sufficiently open framework should allow among other approaches. Whether or not all ABMs can just as well be described (or at least their average behaviour approximated, e.g. methods from statistical physics) by ordinary differential equations remains an open question that we do not have to solve here. Other works by us make heavy use of macroscopic approximations, so we do not want to promote ABMs here but rather enable their use where the modeler deems them appropriate, e.g. when representing a large degree of heterogeneity and social structure is important to certain research questions . We have therefore reduced their mentioning in the text now and also argue that the modular design of copan:CORE explicitly supports comparison studies between ABM-based and ODE-based versions of a model.

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

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Abstract.

Analysis of Earth system dynamics in the Anthropocene requires to explicitly take into account the increasing magnitude of processes operating in human societies, their cultures, economies and technosphere and their growing feedback entanglement with those in the physical, chemical and biological systems of the planet. ~~This work~~ However, current state-of-the-art Earth System Models do not represent dynamic human societies and their feedback interactions with the biogeophysical Earth system and macroeconomic Integrated Assessment Models typically do so only with limited scope. This paper (i) ~~introduces~~ proposes design principles for constructing World-Earth ~~models~~ Models (WEM) for Earth system analysis of the Anthropocene, i.e., models of ~~social-ecological~~ social (World) - ecological (Earth) co-evolution on up to planetary scales, and (ii) presents the copan:CORE open ~~source software library that provides a~~ simulation modeling framework for developing, composing and ~~running~~ analyzing such WEMs based on the proposed principles. ~~copan:CORE is an object-oriented software package currently implemented in Python. It provides components of meaningful yet minimal collections of closely related processes 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~~ The framework provides a modular structure to flexibly construct and study WEMs. These can contain biophysical (e.g. carbon cycle dynamics), socio-metabolic/economic (e.g. economic growth or energy system changes) and socio-cultural processes (e.g. voting on climate policies or changing social norms) and their feedback interactions, and are based on elementary entity types, e.g., grid cells ~~, or fundamental process taxa, e. g., environment or culture~~and social systems. Thereby, copan:CORE enables the epistemic flexibility needed for contributions

towards Earth system analysis of the Anthropocene given the large diversity of competing theories and methodologies used for describing socio-metabolic/economic and socio-cultural processes in the Earth system by various fields and schools of thought. To illustrate the capabilities of the framework, ~~this paper presents a WEM example~~ we present an exemplary and highly stylized WEM implemented in copan:CORE 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 integrated models in Earth system science but also climatology, economics, ecology, or sociology, and allows combining them for interdisciplinary studies.~~ illustrates how endogenizing socio-cultural processes and feedbacks such as voting on climate policies based on socially learned environmental awareness could fundamentally change macroscopic model outcomes.

1 Introduction~~and theoretical considerations~~

In the Anthropocene, Earth system dynamics is equally governed by two kinds of internal processes: 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; Crutzen, 2002; Steffen et al., 2018). The history of global change is the history of the increasing planetary-scale entanglement and strengthening of feedbacks between these two domains (Lenton and Watson, 2011). Therefore, 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~~ Such models need to capture the co-evolving dynamics of the social (the *World* of human societies) and natural (the biogeophysical *Earth*) spheres of the Earth system on up to global scales ~~.~~ and are referred to as World-Earth models (WEMs) in this article. In pursuing this interdisciplinary integration effort, World-Earth modeling ~~builds~~ can benefit from and build upon the work done in ~~the fields of~~ fields such as social-ecological systems (Berkes et al., 2000; Folke, 2006) and coupled human and natural systems (Liu et al., 2007) research or land-use (Arneth et al., 2014) and socio-hydrological modeling (Di Baldassarre et al., 2017). However, it emphasizes more 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~~ typically focused 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. 1.2) ~~. Second, a concrete software design for~~ and WEMs are discussed in the context of existing global modelling approaches (Sect. 1.3). Second, after a short overview of the copan:CORE open 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~~ an exemplary full-loop WEM is presented and studied (Sect. 3), showing the relevance of internalizing socio-cultural processes. Finally, Sect. 4 concludes the paper.

1.1 ~~Motivation~~State of the art and research gaps in Earth system analysis

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 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 (IAMs) are operated using storyline-based 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~~ increasing their consistency (van Vuuren et al., 2012; Foley et al., 2016; Dermody et al., 2018; Robinson et al., 2018).

1.1.1 ~~Current gap in the Earth system modeling landscape~~

However, the existing scientific assessment models of global change include only to a limited degree – if at all – dynamic representations of the socio-cultural dimensions of human societies (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), providing the bases for different ~~emision~~ emission pathways. These are in turn used in ESMs as external forcing, constraints and boundary conditions to the modeled Earth system dynamics. 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, economic interests, and political ideologies of various social groups, and their metabolic profiles, which are related to their access and use of energy and resources ~~(Fischer-Kowalski, 1997; Otto et al., in review; Lenton~~ Historical examples show that these differences might lead to rapid social changes, revolutions and sometimes also devastating conflicts, 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 (see the discussion around the tragedy of the commons, Ostrom, 1990; Jager et al., 2000; Janssen, 2002). Climate change is ~~the~~ a paradigmatic example of a global commons that needs global institutional arrangements for the usage of the atmosphere as a deposit for greenhouse gas emissions if substantial environmental and social damages are to be avoided in the future (Edenhofer et al., 2015; Schellnhuber et al., 2016b; Otto et al., 2017).

In order to explore the risks, dangers and opportunities for sustainable development, it is important to understand how biophysical, 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). 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 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 natural Earth System, can be reconciled with human development to produce an ethically defensible trajectory of the whole Earth system (i.e., sustainable development) (Raworth, 2012; Steffen et al., 2018).

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

1.2 World-Earth modeling: contributions towards Earth system analysis of the Anthropocene

To this end, the case has been made that substantial efforts are required to advance 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; Robinson et al., 2018), and the globalized food-water-climate nexus (Dermody et al., 2018). While in recent years there has been some progress in developing stylized models that combine socio-cultural with economic and natural dynamics (e.g. Janssen and De Vries (1998); Kellie-Smith and Cox (2011); Garrett (2014); Motesharrei et al. (2014); Wiedermann et al. (2015); Heck et al. (2016); Barfuss et al. (2017); Nitzbon et al. (2017)), more advanced and process-detailed WEMs are not yet available for studying the deeper past and the longer-term Anthropocene future of this coupled system. The research program investigating the dynamics and resilience of the World-Earth system in the Anthropocene can benefit from recent advances in the theory and modeling of complex adaptive systems (Farmer et al., 2015; Verburg et al., 2016; Donges et al., 2017a, b). When going beyond stylized modelling, a key challenge for World-Earth modeling is the need 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 co-evolution.

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 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 complex social systems are increased and become more concrete. Recent advances for example in complex systems theory, computational social sciences, social simulation and social-ecological systems 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

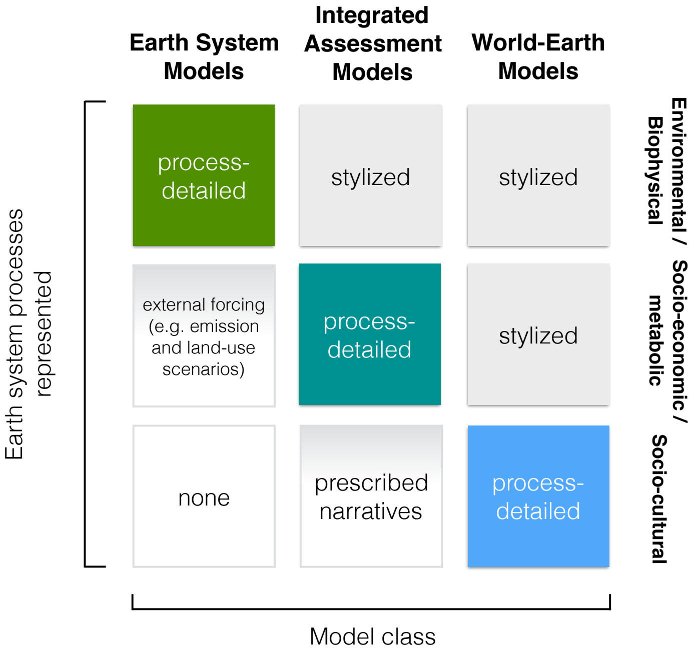


Figure 1. World-Earth models (WEMs) in the space of model classes used for scientific analysis of global change. It is shown to what degree current Earth system models, integrated assessment models and WEMs cover environmental/biophysical, socio-economic/metabolic, and socio-cultural processes, respectively. The term "process-detailed" indicates the types of Earth system processes that the different model classes typically focus on representing. However, also in these core areas the level of detail may range from very stylized to complex and highly structured.

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 basis for inter- and trans-disciplinary research that could support such an ambitious modeling program.

1.2.1 ~~Features of the copan:CORE modeling framework~~

~~There is a wealth of software frameworks and platforms for modeling complex social dynamics using agent-based and network approaches (Kravari and Bassiliades, 2015). However, platforms like Netlogo (Wilensky and Rand, 2015), Repast (North et al., 2013) and Cormas (Bousquet et al., 1998) tend to focus on applications to rather local systems and none of them is specialized for an Earth~~

~~system analysis context. 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.~~

1.2.1 Research questions for World-Earth modeling

~~The copan:CORE World-Earth modeling frameworkpresented in this paper 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~~ We envision World-Earth modeling to be complementary to existing simulation approaches for the analysis of global change. WEMs are not needed where the focus is on the ~~detailed processes embedded in these models.~~

~~Finally, copan:CORE facilitates the integration of different types of modeling techniques. It permits for example to combine agent-based models (~~study of the biophysical and climatic implications of certain prescribed socio-economic development pathways (e.g. in terms of emission and land-use scenarios), since this is the domain of Earth System Models as used in the World Climate Research Programme’s Coupled Model Intercomparison Project (CMIP) (Eyring et al., 2016) that provides input to the Intergovernmental Panel on Climate Change (IPCC) reports. Similarly, WEMs are not the tool of choice if the interest is in the normative macro-economic projection of optimal socio-economic development and policy pathways internalizing certain aspects of climate dynamics, 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).~~ the analysis of first or second best climate change mitigation pathways, since this is the domain of state-of-the-art Integrated Assessment Models.

~~These features distinguish the copan:CORE 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.~~

1.3 ~~General characteristics of integrated World-Earth models~~

~~In this section, we discuss general characteristics and design principles for the construction of the novel class of WEMs that constrain their properties for to allow for addressing~~ In turn, WEMs as envisioned by us here are needed when the research questions at hand require the explicit and internalized representation of socio-cultural processes and their feedback interactions with biophysical and socio-economic dynamics in the Earth system. In the following, we give examples for research questions of ~~the following type :~~ this type that could be studied with WEMs in the future, as they have been already elaborated in more detail by, e.g. Verburg et al. (2016) and Donges et al. (2017a, b):

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 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)?~~ What are the ~~social, economic~~ socio-cultural, -economic and environmental preconditions for sustainable development towards and within a “safe and just” operating space for humankind (Barfuss et al., 2018; O’Neill et al., 2018), i.e., for a trajectory of the Earth system that eventually neither violates precautionary planetary boundaries (Rockström et al., 2009; Steffen et al., 2015) nor acceptable social foundations ~~(Rockström et al., 2009; Steffen et al., 2015; Raworth, 2012)?~~ (Raworth, 2012)?

2. ~~Are there~~ A more specific example of the previous questions is: How can major socio-economic transitions towards a decarbonized social metabolism, such as a transformation of the food and agriculture system towards a sustainable, reduced-meat diet that is in line with recent recommendations by the EAT-Lancet Commission on healthy diets (Willett et al., 2019), be brought about in view of the strong socio-cultural drivers of current food-related and agricultural practises and the reality of the political economy in major food-producing countries? And how would their progress be influenced by realized or anticipated tipping of climatic tipping elements like the Indian monsoon system?

3. Under which conditions can cascading interactions between climatic (e.g., continental ice sheets or major biomes such as the Amazon rain forest) and potential social tipping elements (e.g., in attitudes towards ongoing or anticipated climate change or eco-migration) be triggered and how can they be ~~avoided~~governed (Schellnhuber et al., 2016a; Steffen et al., 2018)? What are implications for biophysical and social-ecological dimensions of Earth system resilience in the Anthropocene (Donges et al., 2017a)?

4. ~~How does climate change feed back on complex social structures and their dynamics? How do societal transformations affect the natural Earth system ?~~ How do multilevel coalition formation processes (like the one modeled in Heitzig and Kornek (2018) a static climate) interact with Earth system dynamics via changes in regional damage functions, mitigation costs, and realized or anticipated distributions of extreme events that drive changes in public opinions which in turn influence the ratification of international treaties and the implementation of domestic climate policies?

1.2.1 ~~Basic process taxa in World-Earth models~~

~~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~~

5. How do certain social innovations including technology, policies or behavioral practises diffuse in heterogeneous agent networks that could have global-scale impacts on planetary-boundary dimensions (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; Martine~~

~~Culture (CUL; socio-cultural processes)~~ ~~The ‘culture’ process taxon is meant to contain socio-cultural processes from immaterialsubsystems~~ Farmer et al. (2019); Tàbara et al. (2018))? Which factors such as network structure, information access as well as information feedback and update time affect the innovation uptake? What are the impacts of a certain social innovation uptake on different agent groups (e.g. on agents with different economic, social, ~~opinion adoption, sociallearning, 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).~~ or cultural endowment)? (Hewitt et al., 2019)

1.2.1 ~~Design principles for World-Earth models~~

~~The research program investigating the dynamics and resilience of the World-Earth system in the Anthropocene should be built upon recent advances in the theory and 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 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, such approaches need to be scaled up to the planetary scale and incorporate insights from macro-level and global modeling exercises. Accordingly, we propose~~

1.2.1 Design principles for World-Earth models

To address research questions of the kinds suggested by the examples given above, we suggest that the development of WEMs of the type discussed in this paper ~~should~~ could be guided by aiming for the following properties:

1. ~~**Balanced process**~~ **Explicit representation of social dynamics.** ~~Environmental and societal~~ 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)~~ represented in an explicit, dynamic fashion in order 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 contrastto ESMs and many IAMs which are not balanced in that respect).One implication of this principle is that WEMs should have the ability to reflect a similar number of planetary boundaries and social foundations, respectively. The modeled subsystems and processes can be further structured into biophysical, socio-metabolic and socio-cultural taxa (Donges et al., 2018) (see 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).~~

   the Anthropocene. (In contrast, social process occur typically non-dynamically in ESMs as fixed socio-economic pathways; and in IAMs as inter-temporal optimization problem.) ~~**Heterogeneity, agency and complex social structures**~~ ~~WEMs should allow~~ Such social processes such as social learning may be included in models via comparably simple equation-based descriptions (e.g. Donges et al. (2018)). Yet, more detailed WEMs should also allow also 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 modeling ~~(Müller-Hansen et al., 2017). The rationale behind this design principle is the observation that the~~ (Farmer and Foley, 2009; Farmer et al., 2015; Müller-Hansen et al., 2017). 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, 2017). While there is a rich literature on modeling various aspects of socio-cultural dynamics (e.g. ~~Castellano et al. (2009); Snijders et al. (2010); Müller-Hansen et al. (2017)~~Castellano et al. (20
   this work so far remains mostly disconnected from Earth system modeling. Accordingly, more detailed 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.

2. **Feedbacks and ~~co-evolution~~co-evolutionary dynamics** WEMs should incorporate as dynamic processes the feedbacks of collective social processes on biogeophysical Earth system components and vice versa. 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 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.

3. **Nonlinearity and tipping dynamics** WEMs should be able to capture the nonlinear dynamics that is a prerequisite for modeling climatic (Lenton et al., 2008) and social tipping 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).

4. **Cross-scale interactions** 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. Therefore, such approaches need to be connected across scales and up to the planetary scale and incorporate insights from macro-level and global modeling exercises (Cash et al., 2006).

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 optimizations but focus on the exploration of the space of dynamic possibilities to gain systemic understanding. This 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 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 understanding and quantifying planetary boundaries, safe operating spaces and their manageability and reachability as emergent system properties across scales (Heitzig et al., 2016; Kittel et al., 2017).

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

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

It is instructive to compare WEMs more explicitly than above to the two existing classes of global change models, Earth System Models and Integrated Assessment Models, in terms of to what degree they represent biophysical, socio-metabolic/economic and socio-cultural subsystems and processes in the World-Earth system (Fig. 1). ~~Earth System~~ Before discussing how model classes map to these process types, we describe the latter in more detail.

1.3.1 Basic process taxa in World-Earth models

Based on the companion article by Donges et al. (2018) that is also part of the Special Issue in Earth System Dynamics on “Social dynamics and planetary boundaries in Earth system modeling", 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 possess as members of society (Bierstedt, 1963, p. 129). Socio-cultural processes such as value and norm changes have been suggested to be key for understanding the deeper human dimensions of Earth systen dynamics in the Anthropocene (Nyborg et al., 2016; Gerten et al., 20

1.3.2 Mapping model classes to Earth system processes

Earth System Models 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 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 ultimately include all three domains equally. However, the focus of current and near-future developments in World-Earth modeling ~~should~~ would likely 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 Earth system modeling.

2 The copan:CORE open World-Earth modeling framework

~~In this section, we present~~ Here we give a short overview of the World-Earth open modeling framework copan:CORE that was designed following the principles given above (Sect. 1.2) ~~. We describe our framework on three levels, starting with the abstract level independent of any software (Sects. **??** and **??**, also using Sect. 1.3.1), then describing the software design independent of any programming language (Sect. **??**), and finally presenting details of our reference implementation in the Python language (Sect. **??**).~~

~~In summary, copan:CORE~~ and is more formally described and justified in detail in the Supplementary Information. It 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).~~ using both simple and complex models. Its flexibility and role-based modularization ~~are realized within an object-oriented software design and~~ support flexible scripting by end users~~and~~ , interoperability and dynamic coupling with existing models~~– e. g., the terrestrial vegetation model LPJmLworking on the cell level (Bondeau et al., 2007) or other~~ , and a collaborative and structured development in larger teams. copan:CORE is an open, code-based (rather than graphical) simulation modeling framework with a clear focus on Earth system models ~~or integrated assessment models based on time-forward integration (rather than intertemporal optimization) such as IMAGE (van Vuuren et al.). On the level of model infrastructure, a careful documentation and software versioning via the 'git' versioning system aim to support collaborative and structured development in large teams using copan:CORE~~with endogenous human societies. In other words, it is a tool that provides a standard way to build and run simulation models without giving preference to any particular modeling approach or theory describing human behavior and decision making and other aspects of social dynamics (Müller-Hansen et al., 2017; Schlüter et al., 20 Different model 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.

2.1 ~~Abstract structure~~

~~This section describes the abstract structure of models that can be developed with copan:CORE and gives rationales for~~ 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. The framework facilitates the integration of different types of modeling approaches. It permits for example to combine micro-economic models (e.g., of a labor market at the 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 natural hazards). It also provides coupling capabilities to preexisting biophysical Earth system and economic integrated assessment models and thus helps to benefit from the detailed process representations embedded in these models. Many of 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 for a broader community, and a high level of consistency without losing flexibility. These features distinguish the copan:CORE modeling framework from existing modeling frameworks and platforms.

2.0.1 ~~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~~ varying set of *entities* (“things that are”, e.g., a spot on the Earth’s surface, the European Union~~EU~~, yourself)~~. Entities~~ , which are involved in ~~a number of sufficiently well-distinguishable~~ *processes* (“things that happen”, e.g., vegetation growth, economic production, opinion formation) ~~.~~ ~~Processes in turn affect one or more~~ that affect entities’ *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 modelrun, 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” (~~which represent the *variables* (including parameters) of a model. An attribute can have a simple or complex data type, e.g.~~, an occupied country may regain independence).~~ representing a binary variable, a whole social network, or, to facilitate interoperability and validation, a dimensional quantity with a proper physical unit.

~~**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.~~

2.0.2 ~~Entity types, process taxa, process types~~

~~copan:CORE classifies entities~~ Entities are *classified* by *entity* ~~*types*~~*type* (~~“kinds of things that are”, e.g., spatial grid~~ cell, social system, individual~~), and allows to group (some or all)processes into~~ , . . .), processes by their formal *process* ~~*taxa*~~*type* (~~e.g., natural, socio-metabolic, cultural)~~see below), and both are represented by objects in an object-oriented software design, currently using the Python programming language. Each process and each attribute *belongs*~~*to*~~ ~~either a certain entity type or a certain process taxon. We deliberately do not specify 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.~~

~~Similarly, attributes may be modeled as belonging to some entity type (e.g., ‘total population’ might be modeled as an attribute of the ‘social system’ 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 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~~ to an entity type or a ~~process type, corresponding to different mathematical modeling and simulation/solving techniques~~*process taxon* (environmental, socio-metabolic, socio-cultural). Currently, the following formal process types are supported, enabling typical modeling approaches:

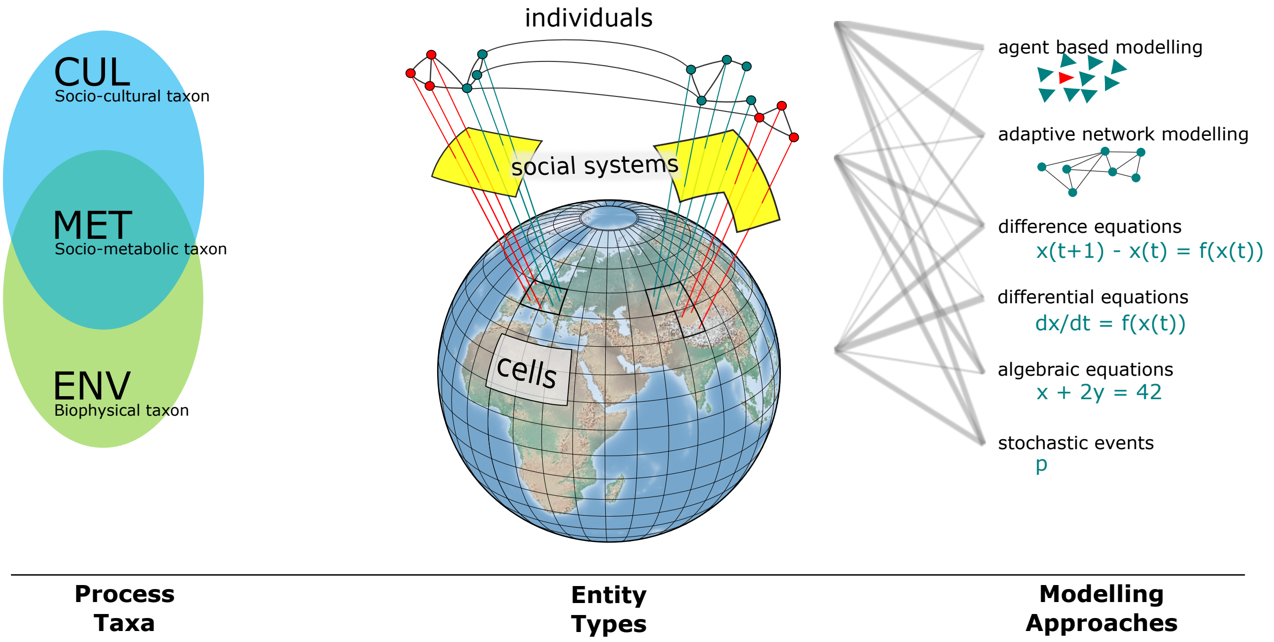


Figure 2. ~~**Overview of copan:CORE modeling framework.**~~ **Overview of copan:CORE open World-Earth modeling framework.** The entities in copan:CORE models are classified by *entity types* (e.g., grid ~~cell~~*Cell*, ~~social system~~*Social system*, ~~individual~~*Individual*, see middle column). Each process belongs to either a certain entity type or a certain *process taxon* (left column). Processes are further distinguished by formal process types (see text for a list) which allow for various different *modeling approaches* (right column). Entity types, process taxa and process types can be freely combined with each other (grey lines). Thick grey lines indicate which combinations are most common. The copan:CORE framework allows to consistently build World-Earth models across the spectrum from stylized and globally aggregated to more complex and highly resolved in terms of space and social structure. Hence, entity types, process taxa and types may or not be present in specific models. For example, a stylized and globally aggregated model would describe the dynamics of entity types *World* and *Social system* and neither contain *Cells* nor *Individual* agents as entities.

- ~~continuous dynamics given by ordinary differential equations~~*Ordinary differential equations* representing continuous time dynamics,
- *Explicit* or *implicit algebraic equations* representing (quasi-)instantaneous reactions ~~given by algebraic equations (e.g., for describing economic equilibria)~~or equilibria,
- ~~steps~~ *Steps* in discrete time ~~(e.g., for~~ representing processes aggregated at ~~annual level~~ the level of some regular time interval or for coupling with external, time-step-based models or model components~~), or~~ , and
- ~~events~~ *Events* happening at irregular or random time points~~(~~, representing e.g.~~, for~~ agent-based and adaptive network components or externally generated extreme events).

~~the latter two potentially have probabilistic effects. 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~~ Processes can be implemented either using an imperative programming style via class methods, or using symbolic expressions representing mathematical formulae. copan:CORE's ~~*data types*~~*modularization* ~~(mostly physical or socio-economic simple quantities of various~~ and ~~*dimensions*~~*role concept* ~~and~~ distinguishes

- ~~*units,*~~*Model components* ~~but also more complex data types such as references or networks).~~

  ~~Fig. 2 summarizes our basic process taxa and 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. **??** and 1.3.1 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”).~~ developed by *model component developers*, implemented as subpackages of the 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 taxamay be represented by ODEs or via stochastic events, and all shown entity types can own regular time stepped processes.~~

2.0.3 ~~Modularization, model components, user roles~~

~~copan:CORE aims at supporting a plug-and-play approach to modeling and a corresponding division of labour between several user groups (or~~ software package providing interface and implementation mixin classes for entity types and process taxa,

- ~~*roles*~~*Models* ~~) by dividing the overall model-based research workflow into several tasks. As a consequence, we formally distinguish between model components and (composed) models.~~

  ~~A~~ made from these by *model* ~~*component*~~*composers*~~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~~ , implemented by forming final entity types and process taxa ~~these processes and attributes belong to. A~~ from these mixin classes,

– ~~*model*~~*Studies* ~~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~~ by ~~*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*~~*users* ~~).~~ in the form of scripts that import, initialize and run such a model,

– ~~If not, decide what model components the question at hand needs. If all components exist, compose a new model from them (role:~~ A ~~*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.*~~ **??**~~*), 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).*~~

~~***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 modelcomponents (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.*~~

2.0.4 ~~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~~ providing metadata for common variables to facilitate interoperability of 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~~ a common language for modelers, managed by a ~~*master component repository*~~*modeling board*~~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.~~

2.0.5 ~~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 or process taxon attributes a priori in the same way, calling them variableswhether or not they turn out to be constant during a model run or are used for a bifurcation analysis in a study.~~

~~A variable's specification contains metadatasuch 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.~~

2.1 ~~Basic entity types~~

~~**Basic relationships between entities in the copan:CORE framework.** This 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 pycopancorereference 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.~~

~~We try to keep the number of explicitly considered 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 '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.~~

~~Although further entity types (e.g., ‘household’, ‘firm’, ‘social group’, ‘policy’, or ‘river catchment’) will eventually be included into the master data model, at this point the~~ .

Entity types and their basic relations shipped with copan:CORE are:

- *‘~~base’model component~~World’,* ~~only provides the entity types which all models must contain, described in this section, in addition to an overall entity type ‘world’ that may serve as an anchor point for relations between entities (see also Fig. **??**).~~

2.0.1 ~~Cells~~

~~An entity of type ‘cell’represents a small~~ representing the whole Earth (or some other planet).

- *‘Cell’,* representing a regularly or irregularly shaped 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’.~~

2.0.2 ~~Social systems~~

~~An entity of type ‘social system’ is meant to represent~~

- *‘Social system’,* representing what is sometimes simply called a ‘society’, i.e. “an economic, social, industrial or cultural infrastructure” (Wikipedia, 2017) such as a megacity, country, or the EU. ~~We understand a social system~~ It can be interpreted as a 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 (Fischer-Kowalski, 1997; Otto et al., in review)~~. Equally importantly, social systems~~ , and may include social institutions such as informal systems of norms, 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. **??**).~~

~~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 should be used (e.g., a generic 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~~

- *‘Individual’*, representing a person, typically used in an network-, game-theoretic, or 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.~~

2.0.3 ~~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~~component. 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 relevant real-world people~~, and consequently each individual carries a quantity ‘represented population’ as an attribute to be used in statistical aggregations, e.g., within~~. Each individual resides in a cell that belongs to a social system.

2.0.4 ~~Relationships between entity types and process taxa~~

Fig. 2 illustrates these concepts. Although there is no one-to-one correspondence between process taxa~~and~~, entity types, and modeling approaches, some combinations are expected to occur more often than others, as indicated by the thicker gray connections in Fig. 2.

~~We expect processes from the~~ We expect environmental (ENV) ~~process taxon to deal primarily with the entity types ‘cell~~processes to deal mostly with ‘cells’ (for local processes such as terrestrial vegetation dynamics described with spatial resolution) and ‘world(s)’ (for global processes described without spatial resolution, e.g., the greenhouse effect) and sometimes ‘social ~~system~~systems’ (for mesoscopic processes described at the level of a social system’s territory, e.g., the ~~environment~~ environmental diffusion and decomposition of industrial wastes).

Socio-metabolic (MET) ~~processes are expected to deal primarily with the entity types 'social system~~processes will primarily deal with 'social systems' (e.g., for processes described at national or urban level), '~~cell~~cells' (for local socio-metabolic processes described with additional spatial resolution for easier coupling to natural processes) and 'world(s)' (for global socio-metabolic processes such as international trade), and only rarely with ~~the entity type 'individual~~'individuals' (e.g., for micro-economic model components such as consumption, investment or the job market).

~~Finally, processes from the socio-cultural~~ Socio-cultural (CUL) ~~taxon are expected to deal primarily with the entity types 'individual~~processes will mostly deal with 'individuals' (for "micro"-level descriptions) and 'social ~~system~~systems' (for "macro"-level descriptions), and rarely 'world(s)' (for international processes such as diplomacy or treaties).

2.1 ~~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, modularizationand object-orientationare 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 scriptsfollowing a mainly imperative programming style that uses the classes provided by the framework. Fig. 3 summarizes the main aspects of this design which are described in detail in the following.~~

2.0.1 ~~Object-oriented representation~~

~~Entity types and process taxa are represented by classes('Cell', 'SocialSystem', 'Culture', . . .), individual entities by instances(objects) of the respective entity type class, and process taxon classes have exactly one instance. While entity type and process taxon classes hold processes' and variables' metadata asclass attributes, entity instances hold variable values and, where needed, their time derivatives as instance attributes.Processes' logics can be specified via symbolic expressionsin the process metadata (~~Other entity types such as, 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.~~ firms, social groups or institutions can be added to the framework if needed.

2.0.2 ~~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, 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 subpackageof the main copan:CORE software package, containing class definitions for all used entity types and process taxa as follows. Each entity type and process taxon used in the model component is represented by two classes, (i) an interface classthat 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 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 classinherited 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 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.~~

2.0.3 ~~Model composition via multiple inheritance~~

~~Finally, a model’s composition from model components is represented via multiple inheritancefrom 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 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 contained in the used model component packages. Fig. 3 shows an example of this with just two components and two entity types.~~

2.0.4 ~~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).~~

2.0.5 ~~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 syne the~~

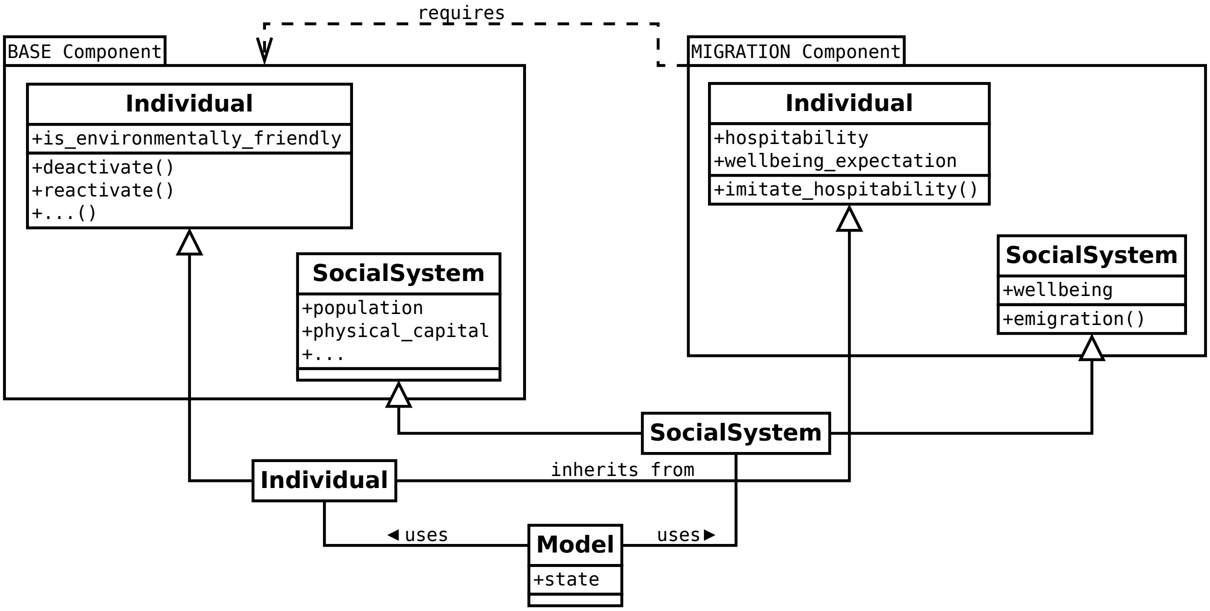


Figure 3. Model composition through multiple inheritance of attributes and processes by process taxa and entity types. This stylized class diagram shows how a model in copan:CORE can be composed from several model components (only two shown here, the mandatory component 'base' and the fictitious component 'migration') that contribute component-specific processes and attributes to the model's process taxa and entity types (only two shown here, 'Individual' and 'SocialSystem'). To achieve this, the classes implementing these entity types on the model level are composed via multiple inheritance (solid arrows) from their component-level counterparts (so-called 'mixin' classes).

~~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.~~

2.1 ~~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 the open-source Python package 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 sympypackage (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 (same Fig., bottom, line 14). ODE integration is currently implemented via the scipypackage (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.~~

~~Fig. ?? gives an impression of how user code in *pycopancore* looks like. See the *Supplementary Information* for further details.~~

~~**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).~~

3 ~~Example~~ Influence of social dynamics in a minimum-complexity World-Earth model implemented using copan:CORE

In this section, we ~~shortly present an~~ present an illustrative example of a model realized with ~~the *pycopancore* reference implementation of the copan:CORE modeling~~ our 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 intended to be a 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.

The example model includes the following ~~components~~groups of processes: (1) a ~~spatially resolved~~ version of the simple carbon cycle used in Nitzbon et al. (2017) (based on Anderies et al., 2013) coarsely spatially resolved into four heterogeneous boxes; (2) a ~~regionalised~~ version of the ~~well-being-driven population dynamics and~~ simple economy used in Nitzbon et al. (2017) resolved into two world regions. 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) and with ~~international technology spillovers and~~ human capital depreciation; and (3) ~~international migration driven by differences in well-being (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~~ becoming 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). These processes cover all possible process taxon interactions as shown in Table 1 and are distributed over ~~eight~~ six model components in the code as shown in Fig. 4.

→	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~~ exemplary model processes by owning process taxon (row) and affected process taxon (column) ~~(following Donges et al., 2018)~~(following the taxonomy developed in the companion paper Donges et al., 2018): ~~environment~~ environmental (ENV), ~~metabolism~~ social-metabolic (MET) and ~~culture~~ socio-cultural (CUL)

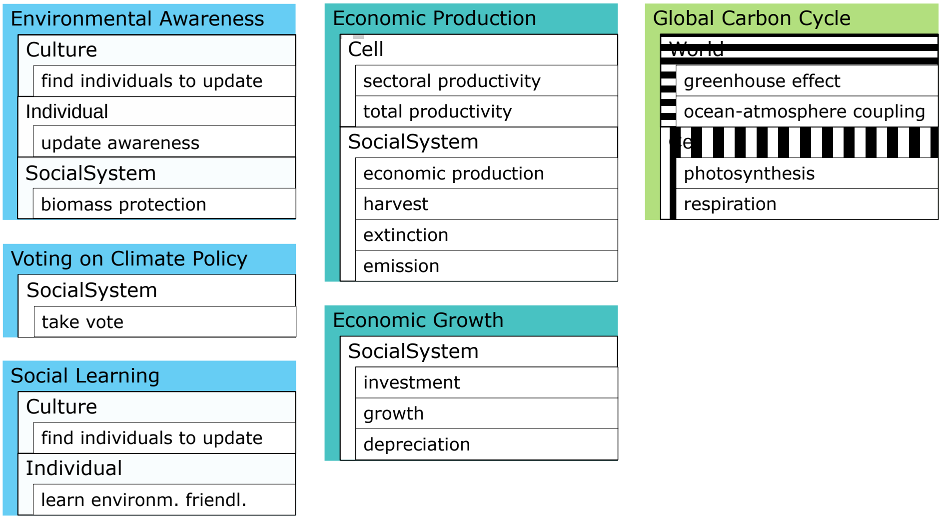


Figure 4. Components, entity types, and processes of the example model. Each box represents a model component that contributes several processes (white bars) to different entity types and process taxa (differently hashed rectangles).

We now describe the model components in detail. As many processes add terms to variables' time derivatives, we use the notation $\dot{X} \mathrel{+}= Y$ to indicate this. The effective time evolution of X is then determined by the sum of the individual processes given below.

3.1 Entity types

The example model contains one 'world' representing the planet, two 'social systems' representing the global North and South, four 'cells' representing major climate zones: 'Boreal' and 'Temperate' belonging to the territory of North, and 'Subtropical' and 'Tropical' belonging to South, and 100 representative 'individuals' per cell which form the nodes of a fixed acquaintance network.

3.2 Global carbon cycle

Our carbon cycle follows a simplified version of Anderies et al. (2013) presented in Nitzbon et al. (2017) with a coarsely spatially resolved vegetation dynamics. On the world level, an immediate greenhouse effect translates the atmospheric carbon stock A (initially 830 GtC) linearly into a mean surface air temperature $T = T_{\mathrm{ref}} + a(A - A_{\mathrm{ref}})$ (a process of type 'explicit equation') with a sensitivity parameter $a = 1.5\,\mathrm{K}/1000\,\mathrm{GtC}$ and reference values $T_{\mathrm{ref}} = 287\,\mathrm{K}$ and $A_{\mathrm{ref}} = 589\,\mathrm{GtC}$. There is ocean-atmosphere diffusion between A and the upper ocean carbon stock M (initially 1065 GtC),

$$\dot{A} += d(M - mA), \qquad \dot{M} += d(mA - M) \tag{1}$$

(processes of type 'ODE'), with a diffusion rate $d = 0.016/\mathrm{yr}$ and a solubility parameter $m = 1.5$. On the level of a cell c, A and the cell's terrestrial carbon stock L_c (initially 620 GtC for all four c) are changed by a respiration flow RF_c and a photosynthesis flow PF_c,

$$\dot{A} += RF_c - PF_c, \qquad \dot{L}_c += PF_c - RF_c. \tag{2}$$

The respiration rate depends linearly on temperature, which is expressed as a dependency on atmospheric carbon density A/Σ, where $\Sigma = 1.5e8\,\mathrm{km}^2$ is the total land surface area, so that

$$RF_c = (a_0 + a_A A/\Sigma)L_c \tag{3}$$

with a basic rate $a_0 = 0.0298/\mathrm{yr}$ and carbon sensitivity $a_A = 3200\,\mathrm{km}^2/\mathrm{GtC}/\mathrm{yr}$. The photosynthesis rate also depends linearly on temperature (and hence on A) with an additional carbon fertilization factor growing concavely with A/Σ and a space competition factor similar to a logistic equation, giving

$$PF = (l_0 + l_A A/\Sigma)\sqrt{A/\Sigma}(1 - L_c/k\Sigma_c)L_c, \tag{4}$$

with land area $\Sigma_c = \Sigma/4$, parameters $l_0 = 34\,\mathrm{km}/\mathrm{GtC}^{1/2}/\mathrm{yr}$ and $l_A = 1.1e6\,\mathrm{km}^3/\mathrm{GtC}^{3/2}/\mathrm{yr}$, and per-area terrestrial carbon capacity $k = 25e3\,\mathrm{GtC}/1.5e8\,\mathrm{km}^2$. Note that especially the linear temperature dependency and the missing water dependency make this model rather stylized, see also Lade et al. (2017).

3.3 Economic production

As in Nitzbon et al. (2017), economic activity consists of producing a final good Y from labour (assumed to be proportional to population P), physical capital K (initially $K_{North} = 4e13\,\$$, $K_{South} = 2e13\,\$$), and energy input flow E. The latter is the sum of the outputs of three energy sectors, fossil energy flow E_F, biomass energy flow E_B, and (other) renewable energy flow R. The process is described by a nested Leontieff/Cobb–Douglas production function for Y and Cobb–Douglas production functions for E_F, E_B, R, all of them here on the level of a cell c:

$$Y_c = y_E \min(E_c, b_Y K_{Y,c}^{\kappa_Y} P_{Y,c}^{\pi_Y}), \qquad E_c = E_{F,c} + E_{B,c} + R_c, \tag{5}$$

$$E_{F,c} = b_F K_{F,c}^{\kappa_F} P_{F,c}^{\pi_F} G_c^{\gamma}, \tag{6}$$

$$E_{B,c} = b_B K_{B,c}^{\kappa_B} P_{B,c}^{\pi_B} (L_c - L_c^p)^{\lambda}, \tag{7}$$

$$R_c = b_{R,c} K_{R,c}^{\kappa_R} P_{R,c}^{\pi_R} S_s^{\sigma}. \tag{8}$$

In this, $y_E = 147\,\$/\mathrm{GJ}$ is the energy efficiency, G_c is the cell's fossil reserves (initially 0.4, 0.3, 0.2 and $0.1 \times 1125\,\mathrm{GtC}$ in the Boreal, Temperate, Subtropical and Tropical cells), L_c^p is the environmentally protected amount of terrestrial carbon (see below), S_s gives the renewable energy production knowledge stock of the corresponding social system s (initially $2e11\,\mathrm{GJ}$), and $\kappa_\bullet = \pi_\bullet = \gamma = \lambda = \sigma = 2/5$ are elasticities leading to slightly increasing returns to scale. The productivity parameters $b_\bullet$ have units that depend on the elasticities and are chosen so that initial global energy flows roughly match the observed values: $b_F = 1.4e9\,(\mathrm{GJ/yr})^5/(\mathrm{GtC}\,\$)^2$, $b_B = 6.8e8\,(\mathrm{GJ/yr})^5/(\mathrm{GtC}\,\$)^2$, and $b_{R,c} =$ 0.7, 0.9, 1.1 and 1.3 times the mean value $b_R = 1.75 \times 10^{-11}\,(\mathrm{GJ/yr})^5/(\mathrm{GJ}\,\$)^2$ in Boreal, Temperate, Subtropical and Tropical to reflect regional differences in solar insolation. As in Nitzbon et al. (2017), we assume $b_Y \gg b_B, b_F, b_R$ so that its actual value has no influence because then $K_{Y,c} \ll K_s$ and $P_{Y,c} \ll Y_s$. Furthermore, $K_{\bullet,c}, P_{\bullet,c}$ are the shares of a social system s's capital K_s and labour L_s that are endogenously allocated to the production processes in cell c so that

$$K_s = \sum_{c \in s} (K_{Y,c} + K_{F,c} + K_{B,c} + K_{R,c}) \tag{9}$$

and similarly for its population P_s. The latter shares are determined on the social system level in a general equilibrium fashion by equating both wages (= marginal productivity of labour) and rents (= marginal productivity of capital) in all cells and sectors, assuming costless and immediate labour and capital mobility between all cells and sectors within each social system:

$$\partial y_E E_{F,c}/\partial P_{F,c} \equiv \partial y_E E_{B,c}/\partial P_{B,c} \equiv \partial y_E R_c/\partial P_{R,c} \equiv w_s \tag{10}$$

for all $c \in s$, and similarly for $K_{\bullet,c}$. The production functions and elasticities are chosen so that the corresponding equations can be solved analytically (see Nitzbon et al. (2017) for details), allowing us to first calculate a set of "effective sector/cell productivities" by a process of type 'explicit equation' on the Cell level, which are used to determine the labour and capital allocation weights $P_{\bullet,c}/P_s$ and $K_{\bullet,c}/K_s$, and then calculate output Y_s, carbon emissions, and all cells' fossil and biomass extraction flows in another process of type 'explicit equation' on the social system level. Given the latter, a second process of type 'ODE' on the social system level changes the stocks A, G_c and L_c for all cells accordingly.

3.4 Economic growth

Again as in Nitzbon et al. (2017), but here on the social system level, a fixed share i (here 0.244) of economic production Y_s is invested into physical capital K_s,

$$\dot{K}_s += iY_s. \tag{11}$$

Capital also depreciates at a rate that depends linearly on surface air temperature to represent damages from climate change,

$$\dot{K}_s += -(k_0 + k_T(T - T_K))K_s, \tag{12}$$

with $k_0 = 0.1/\text{yr}$, $k_T = 0.05$/yr/K, and $T_K = 287\,$K. In addition, renewable energy production knowledge S_s grows proportional to its utilization via learning-by-doing,

$$\dot{S}_s += R_s. \tag{13}$$

Finally, we interpret S_s as a form of human capital that also depreciates at a constant rate (due to forgetting or becoming useless because of changing technology, etc.),

$$\dot{S}_s += -\beta S_s \tag{14}$$

with $\beta = 0.02/\text{yr}$. Note that unlike in Nitzbon et al. (2017), we consider populations to be constant at $P_{North}s = 1.5e9$ and $P_{South}s = 4.5e9$ to avoid the complexities of a wellbeing-driven population dynamics component (which could however be implemented in the same way as in Nitzbon et al. (2017) on the social system level).

3.5 Environmental awareness

On the level of the 'Culture' process taxon, an "awareness updating" process of type 'event' occurs at random time points with a constant rate (i.e., as a Poisson process, here with rate 4/yr), representing times at which many people become aware of the state of the environment, e.g., because of notable environmental events. At each such time point, each individual independently updates her environmental friendliness (a Boolean variable) with a certain probability. When i updates, she switches from "false" to "true" with a probability ψ^+ depending on the terrestrial carbon density in her cell c, $TCD_c = L_c/\Sigma_c$, given by

$$\psi^+ = \exp(-TCD_c/TCD^\perp), \tag{15}$$

and switches from "true" to "false" with a probability

$$\psi^- = 1 - \exp(-TCD_c/TCD^\top), \tag{16}$$

where $TCD^\perp = 1e{-}5$ and $TCD^\top = 4e{-}5$ are sensitivity parameters with $TCD^\perp < TCD^\top$ to generate hysteresis behaviour. As a consequence, a fraction L_c^p of the terrestrial carbon L_c is protected from harvesting for economic production. This fraction is proportional to the cell's social system's population share represented by those individuals i which are environmentally friendly. The initial share of environmentally friendly individuals will be varied in the bifurcation analysis below.

3.6 Social learning

Similarly, on the Culture level, “social learning” events occur at random time points with a constant rate (here 4/yr), representing times at which the state of the environment becomes a main topic in the public debate. At each such time point, each individual i independently compares her environment with that of a randomly chosen acquaintance j with a certain fixed probability (here $1/10$). j then convinces i to copy j’s environmental friendliness with a probability ψ that depends via a sigmoidal function on the difference-in-logs between both home cells’ terrestrial carbon densities,

$$\psi = 1/2 + \arctan(\pi\phi'(\log TCD_j - \log TCD_i - \log\rho'))/\pi, \tag{17}$$

where $\phi' = 1$ and $\rho' = 1$ are slope and offset parameters. The underlying social network is a block model network in which each individual is on average linked to 10 randomly chosen others: 5 in the same cell, 3.5 in the other cell of the same social system, and 1.5 in the other social system.

3.7 Voting on climate policy

Each (of the two) social systems performs general elections at regular time intervals (hence implemented as a process of type ‘step’, here every 4 years) which may lead to the introduction or termination of climate policies. If at the time t of the election, more than a certain threshold (here $1/2$) of the population is environmentally friendly, both a subsidy for renewables (here 50 \$/GJ) is introduced and use of fossils is banned. This leads to a shift in the energy price equilibrium that determines the energy sector’s allocation of labour and capital, which then reads

marginal production cost of biomass energy

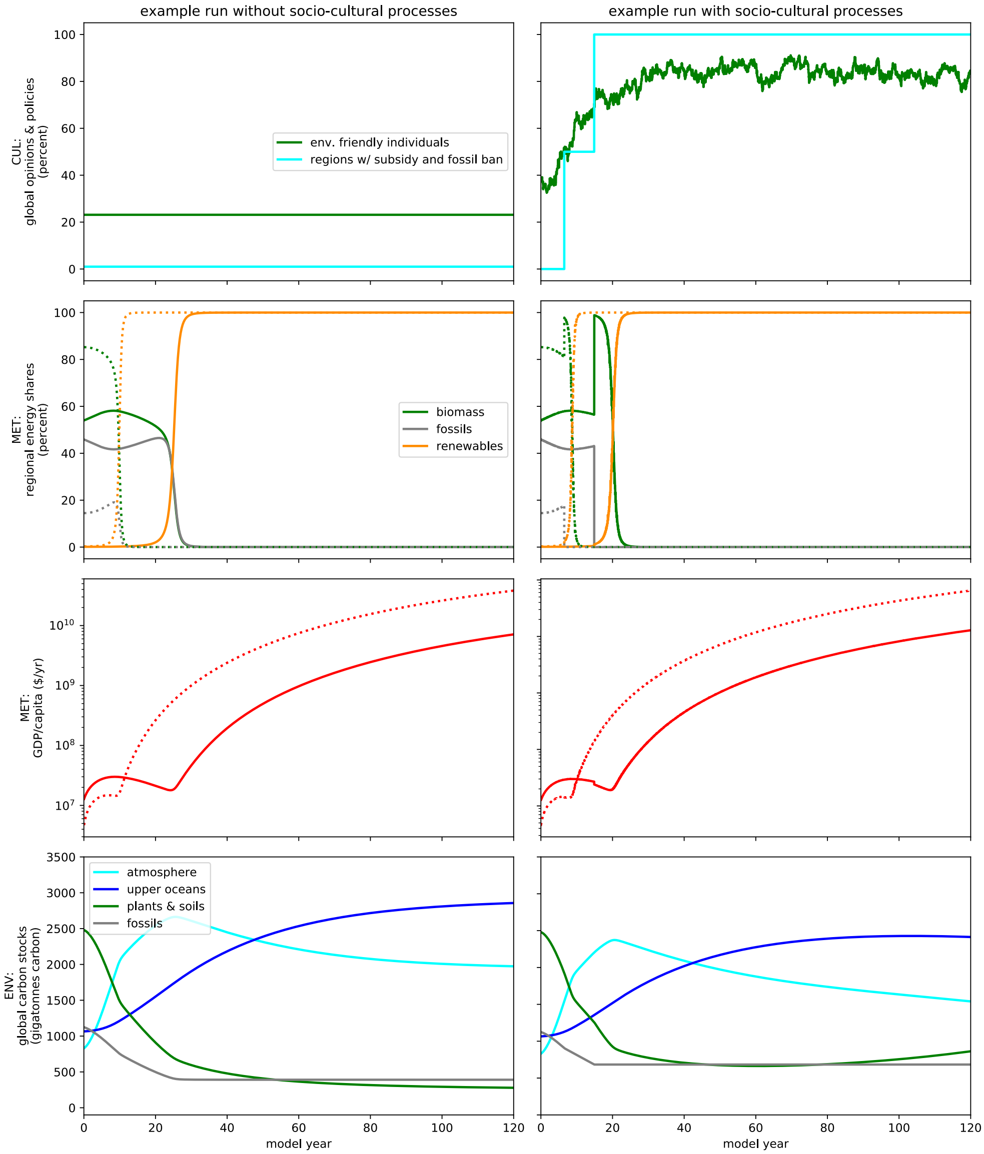
= marginal production cost of renewable energy − renewable subsidy.

Conversely, if these policies are already in place but the environmentally friendly population share is below some other thresholds (here as well $1/2$), these policies are terminated.

Note that we have chosen to model awareness-formation and social learning in an agent-based fashion here mainly to illustrate that such an approach can be easily combined with other approaches in copan:CORE, not because we want to claim that an agent-based approach is the most suitable here. Indeed, one may well want to replace these two agent-based model components by equation-based versions which approximate their behaviour in terms of macroscopic quantities (e.g. as in Wiedermann et al. (2015)), and because of the modular design of copan:CORE, this can easily be done and the two model versions could be compared (still, this is beyond the scope of this paper).

3.8 Results

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~~ of the example model described above, one without


example run without socio-cultural processes

example run with socio-cultural processes

Figure 5. **Two runs from a World-Earth model example,** one without (left) and one with (right) the socio-cultural processes of environmental awareness, social learning, and voting included, showing different transient (and asymptotic) behavior. The top row shows variables related to the cultural process taxon, the center row those related to the metabolic process taxon and the bottom row those related to the environmental process taxon. Green/orange/cyan/blue/gray lines correspond to variables related to terrestrial carbon / renewables / atmospheric carbon / ocean carbon / fossils. In the middle two panels, dashed lines belong to the 'South', solid lines to the 'North'.

the ~~social processes migration,~~ socio-cultural processes environmental awareness, social learning, and voting (left panel of Fig. 5), and another with these processes included ~~.~~ (right panel of Fig. 5). Both runs start in model year 0 from the same initial

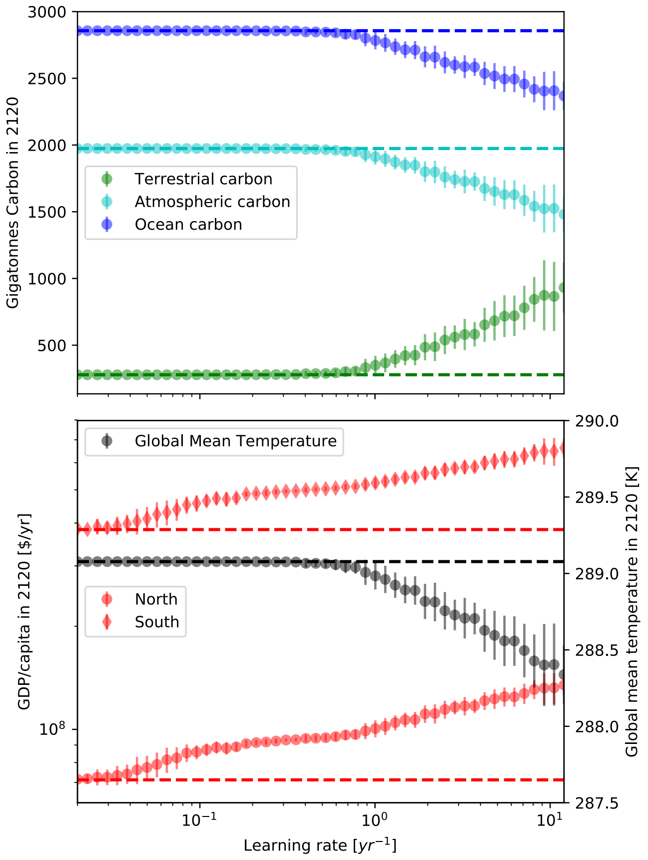


Figure 6. Dependency of some selected variables after 120 model years on the learning rate of environmental awareness. Scatter points denote (the average over 50) simulations with social processes and error bars denote one standard deviation for each choice of learning rate. Dashed lines indicate the corresponding values for a simulation without social processes. The top panel shows the three environmental (non-fossil) carbon stocks, the bottom panel shows the GDP per capita in the two social systems as well as the global mean temperature.

conditions and use the same parameters which were chosen to roughly reflect real-world global aggregates of the year 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 Informationfor model and parameter details.~~

~~As can be seen in Fig. 5(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. 5 bottom panels show these variables corresponding to the environmental process taxon). The unrealistic initial decline in atmospheric~~ (see above). For the simulation without social processes (left panel of Fig. 5) both social systems ('North' in solid and 'South' in dashed lines) initially rely on fossil energy in order to meet their energy needs, thus causing a rise in in atmospheric and ocean 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~~and a decline in fossil carbon stocks. Similarly both social systems initially rely heavily on energy from biomass, with the consequence of a reduction in terrestrial carbon. Due to the technology becoming competitive, the South changes its energy production to renewable energy comparatively early in the simulation, resulting in a fast fading out of biomass and fossils as an energy source. Due to its larger fossil reserves and lower solar insolation, the North takes two decades longer to make this switch. However, this delay in the North causes high atmospheric carbon, hence a high global mean temperature, which due to our oversimplified vegetation model makes the terrestrial carbon stock decline further even after biomass has been phased out as an energy source as well, recovering only much later (not shown). In both social systems, economic growth declines until the switch, then boosts and later declines again since neither population nor total factor productivity grow in our model. Once the South switches to renewables, they hence overtake the North, and this reversed inequality is then sustained since our model includes no trade, knowledge spillovers, migration or other direct interaction which would lead to economic convergence. Certainly, such results are not in itself realistic (as this model does not intend to be) or transferable to real-world application. Future WEM's, therefore, should include such processes beyond pure economic ones in order to properly capture real-World-Earth dynamics; see the Supplementary Information for some corresponding extensions of this model.

If social processes are considered, we obtain qualitatively similar, but quantitatively different trajectories, e.g. in the right panel of Fig. 5, where we assume initially 40% are environmentally friendly. As before, both social systems initially rely on energy produced from fossils and biomass, but as biomass reduces terrestrial carbon density, environmental awareness makes some people environmentally friendly and this spreads via social learning. Once half of the population is environmentally friendly, the next elections in that social system bring a fossil ban and subsidies for renewables. This causes a slightly earlier switch to renewables than before, especially in the North (dashed lines in Fig. 5). This ultimately results in lower atmospheric and ocean carbon stocks, lower peak temperatures, less cumulative use of fossil fuels, and a much faster recovery of terrestrial carbon.

~~Things are very different when the social processes are included, Fig. 5 (right~~copan:CORE further allows for a systematic investigation of the influence of individual parameter on the outcome of the simulation (e.g. along the lines of a bifurcation analysis). 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 systemis 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.~~ an illustration of such an analysis we now vary the learning rate from 1/50yr (less than once in a generation) to 12/yr (once every month) and compute the carbon stocks as well as the GDP per capita and the global mean temperature in model year 120 for an ensemble of 50 simulations per learning rate (Fig. 6) and the same initial conditions for all runs (we thus do not test for a possible multistability of the system).

~~**Two runs from a World-Earth model example,** one without (left) and one with (right) the socio-cultural processes of migration, environmental awareness, social learning, and voting included, showing very different transient (and asymptotic, though not shown here) 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.~~ For learning rates lower than 1/yr (slow learning) the carbon stocks as well as the global mean temperature align well for the two simulation setups, i.e, the one with (scatter points) and without social processes (dashed lines). In contrast, for learning rates larger than 1/yr (faster learning) the individuals become more capable of assessing the consequences of their behaviour (in our case extensive biomass use) before the system has reached a state with low terrestrial and high atmospheric and ocean carbon stocks. As such, increasing the learning rate also causes an increase in the terrestrial carbon stock combined with a decrease of the atmospheric and ocean carbon stocks (in model year 120). This behaviour is also reflected in the global mean temperature which decreases as the learning rate increases. Hence, with respect to the environment social learning only has a positive effect if it happens at sufficiently high rate (around once to more than once a year). It remains to note that learning rates have in the past already been shown to have a profound impact on the state and dynamics of a coupled socio-ecological system, a feature that is recovered in our simple WEM as well (Wiedermann et al., 2015; Auer et al., 2015; Barfuss et al., 2017).

~~With~~ The metabolic variable GDP per capita interestingly already increases much earlier (i.e., for much lower learning rates than 1/yr) as compared to the changes in the environmental variables. This implies that for our specific WEM social processes generally seem to foster the economy regardless of their actual rate. Furthermore we observe that the South shows an approximately 3 times higher GDP per capita than the North, which is caused by the earlier switch to renewable energies in that social system (see third row of Fig. 5). As already stated above, note again, that these results are not intended as a realistic projection of future trajectories of the Earth System, but are discussed here to showcase the capabilities of the copan:CORE framework.

Using the *pycopancore* reference implementation, running the above two simulations (Figure 5) took 140 seconds (without socio-cultural processes) and ~~520~~ 290 seconds (including socio-cultural processes) on an ~~i7-6600U~~ E5-2690 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 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 analyze interactions at and between various scales – from local to regional and global.

The current version of the copan:CORE open modeling framework includes a number of tentative model components implementing, e.g., basic economic, climatic, biological, demographic and social network dynamics. 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 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 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)~~(Gross and Blasius, 2008; Donges et al., 2017a; Geier et al., 2019).

Making such an endeavor prosper requires the collection and synthesis of knowledge from various disciplines. The modular approach of the copan:CORE ~~simulation~~ open modeling framework supports well-founded development of single model components, helps to integrate various processes and allows to analyze their interplay. We therefore call upon the interdisciplinary social-ecological 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 open World-Earth modeling framework, its detailed documentation and the World-Earth model example are available at https://github.com/pik-copan/pycopancore.

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Third, the example provided in section 3 sounds interesting, but there is far too little information provided for me to understand what is happening and why.

> As mentioned above, we now explain and discuss that model in much more detail now.

So overall, I think the manuscript would be much improved (and suitable for publication) if it strengthened the conceptual challenge, provides a description of the key processes that are needed to describe the example in section 3 in the methods, and then describe the results of the example in much greater detail. The present version of the manuscript I find lacks the depth and details to make it a scientifically reproducible contribution, and it misses to more clearly describe the conceptual challenge associated with bringing human dynamics into Earth system modelling.

> We address these points in our second revision of the manuscript as we have summarized in our response to the editor's comments above.