Earth system modeling with complex dynamic human societies: the copan:CORE 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 entanglement with those in the physical, chemical and biological systems of the planet. This work (i) introduces design principles for constructing World-Earth models (WEM), i.e., models of social-ecological 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 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 are based on elementary entity types, e.g., grid cells, or fundamental process taxa, e.g., environment or culture. To illustrate the capabilities of the framework, this paper presents a WEM example 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.

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). Earth system analysis of the Anthropocene requires to close the loop by integrating the dynamics of complex human societies into integrated *whole* Earth system models (Verburg et al., 2016; Donges et al., 2017a, b). These are referred to as World-Earth models (WEMs) in this article that capture the coevolving dynamics of the social (the *World* of human societies) and natural (the biogeophysical *Earth*) spheres of the Earth system on up to global scales. World-Earth modeling builds upon the work done in the fields of social-ecological systems (Berkes et al., 2000; Folke, 2006) and coupled human and natural systems (Liu et al., 2007) research. However, it emphasizes the study of planetary scale interactions between human societies and parts of the Earth's climate system such as atmosphere, ocean and the biosphere, instead of more local and regional scale interactions with natural resources that these fields have focussed on in the past (Donges et al., 2018).

The contribution of this paper is twofold: First, following a more detailed motivation (Sect. 1.1), general theoretical considerations and design principles for a novel class of integrated WEMs are discussed (Sect. 1.2). Second, a concrete software design for the copan:CORE World-Earth modeling framework and its reference implementation in the programming language Python are developed and described (Sect. 2), including a study of a WEM example (Sect. 3). Finally, Sect. 4 concludes the paper.

1.1 Motivation

1.1.1 State of the art

Computer simulation models are pivotal tools for gaining scientific understanding and providing policy advice for addressing global change challenges such as anthropogenic climate change or rapid degradation of biosphere integrity and their interactions (Rockström et al., 2009; Steffen et al., 2015). At present, two large 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 consistency (van Vuuren et al., 2012; Foley et al., 2016; Dermody et al., 2018; Robinson et al., 2018).

1.1.2 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 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 et al., 2016; Lenton and Latour, 2018). 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 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 bio-physical, 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).

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

To this end, the case has been made that substantial efforts are required to advance 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)), advanced and process-detailed WEMs are not yet available for studying the deeper past and the longer-term Anthropocene future of this coupled system.

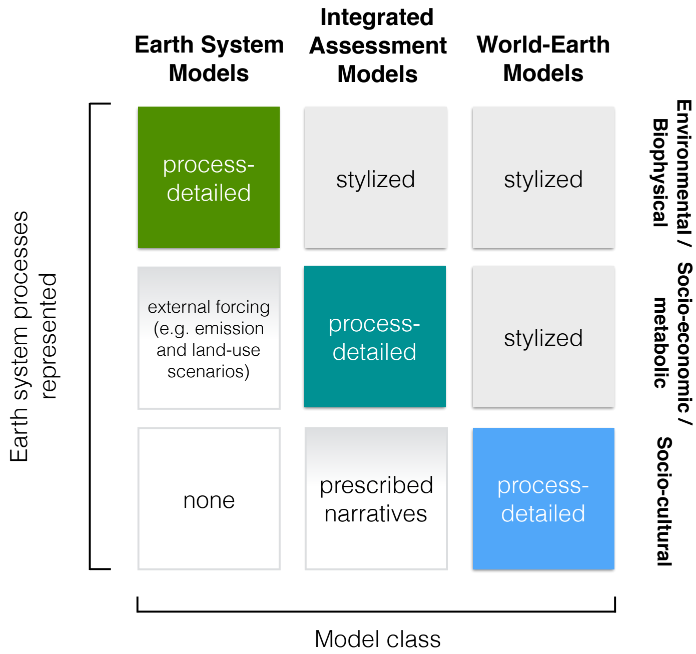

Figure 1. World-Earth models (WEMs) in the space of model classes used for scientific analysis of global change. It is shown to what degree current Earth system models, integrated assessment models and WEMs cover environmental/biophysical, socio-economic/metabolic, and socio-cultural processes, respectively.

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 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 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.

1.1.4 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.

The *copan:CORE World-Earth modeling framework* presented 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 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 (e.g., of a labor market at the micro-level of individuals) with systems of ordinary differential equations (modeling for example a carbon cycle). Similarly, systems of implicit and explicit equations (e.g., representing a multi-sector economy) can be combined with Markov jump processes (for example representing economic and environmental shocks).

These features distinguish the copan:CORE 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.

1.2 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 research questions of the following type:

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)?

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

3. Are there 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 climate change or eco-migration) and how can they be avoided (Schellnhuber et al., 2016a; Steffen et al., 2018)?

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

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

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 (e.g., harvesting, afforestation, greenhouse gas emissions, waste dumping, land-use change, infrastructure building). Social metabolism refers to the material flows in human societies and the way societies organize their exchanges of energy and materials with nature (Fischer-Kowalski, 1997; Martinez-Alier, 2009).

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

1.2.2 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 that the development of WEMs of the type discussed in this paper should be guided by aiming for the following properties:

1. **Balanced process representation** Environmental and societal processes should be described on similar levels of complexity (e.g., in terms of the number of state variables representing the two spheres and three process taxa [see above], Fig. 2) to do justice to the dominant role of human societies in Anthropocene Earth system dynamics and to allow for balanced model design and analysis (in contrast to ESMs and many IAMs which are not balanced in that respect). One implication of this 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).

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

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

4. **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).

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. 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).

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

It is instructive to compare WEMs to the two existing classes of global change models in terms of to what degree they represent biophysical, socio-metabolic/economic and socio-cultural subsystems and processes in the World-Earth system (Fig. 1). 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 include all three domains equally. However, the focus of current and near-future developments in World-Earth modeling should lie on the development of a detailed description of socio-cultural processes because they are the ones where the least work has been done so far in formal modeling.

2 The copan:CORE World-Earth modeling framework

In this section, we present the World-Earth 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. 2.1 and 2.2, also using Sect. 1.2.1), then describing the software design independent of any programming language (Sect. 2.3), and finally presenting details of our reference implementation in the Python language (Sect. 2.4).

In summary, copan:CORE enables a flexible model design around standard components and model setups that allows investigation of a broad set of case studies and research questions (Fig. 2). 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 *LPJmL* working on the cell level (Bondeau et al., 2007) or other Earth system models or integrated assessment models based on time-forward integration (rather than intertemporal optimization) such as *IMAGE* (van Vuuren et al.). 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.

2.1 Abstract structure

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

2.1.1 Entities, processes, attributes

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

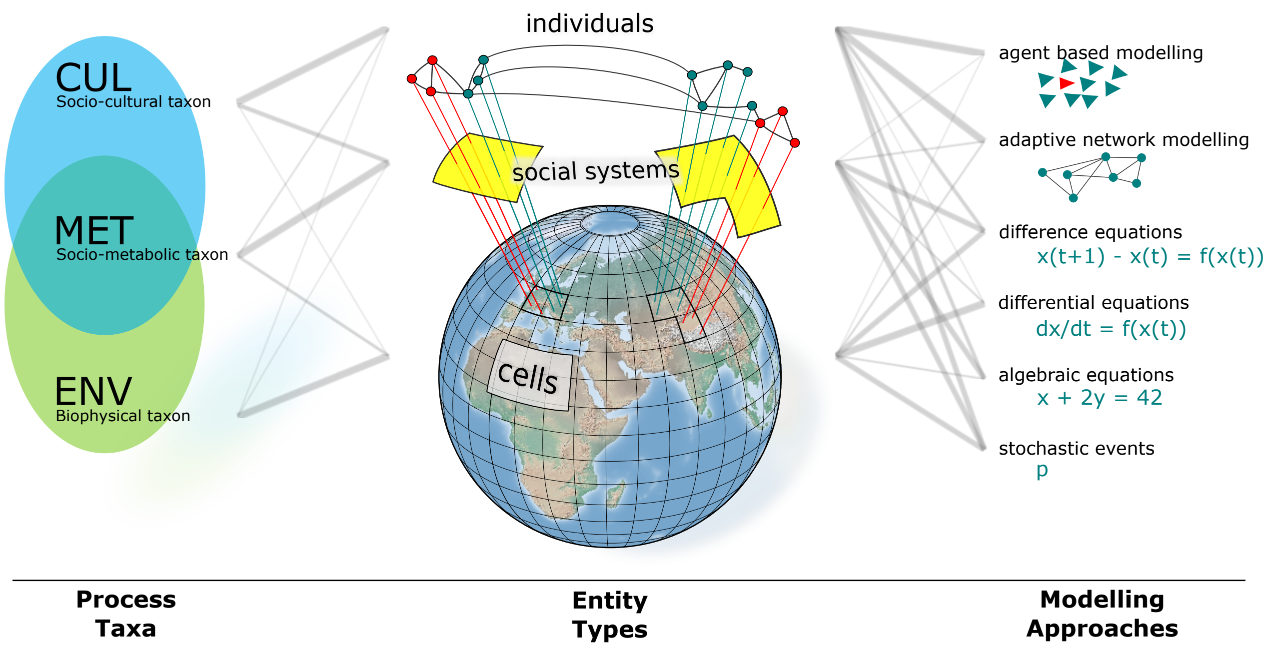

Figure 2. Overview of copan:CORE modeling framework. The entities in copan:CORE models are classified by *entity types* (e.g., grid cell, social system, individual, see middle column). Each process belongs to either a certain entity type or a certain *process taxon* (left column). Processes are further 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.

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

2.1.2 Entity types, process taxa, process types

copan:CORE classifies entities by *entity types* ("kinds of things that are", e.g., spatial grid cell, social system, individual), and allows to group (some or all) processes into *process taxa* (e.g., natural, socio-metabolic, cultural). Each process and each attribute *belongs to* either a certain entity type 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 *process type,* corresponding to different mathematical modeling and simulation/solving techniques:

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

the latter two potentially have probabilistic effects. Later versions will also include support for stochastic differential equations or other forms of time-continuous noise, currently noise can only be modeled via time-discretized steps. Similarly, attributes have *data types* (mostly physical or socio-economic simple quantities of various *dimensions* and *units,* 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. 2.2 and 1.2.1 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”). copan:CORE therefore allows modelers to treat some processes as if they were “done by” a certain entity (the “subject” of the process) “to” itself and/or certain other entities (the “objects” of the process). Other processes for which there appears to be no natural candidate entity to serve as the “subject” can be treated as if they are happening “inside” or “on” some larger entity that contains or otherwise supports all actually involved entities. In both cases, the process is treated as belonging to some entity type. Still other processes such as multilateral trade may best be treated as not belonging to a single entity and can thus be modeled as belonging to some process taxon.

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

2.1.3 Modularization, model components, user roles

copan:CORE aims at supporting a plug-and-play approach to modeling and a corresponding division of labour between several user groups (or *roles*) by dividing the overall model-based research workflow into several tasks. As a consequence, we formally distinguish between model components and (composed) models.

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

The suggested workflow is then this:

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

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

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

2.1.4 Master data model and master component repository

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

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

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

2.1.5 All attributes are treated as variables with metadata

Although many models make an explicit distinction between "endogenous" and "exogenous" variables and "parameters", our modular approach requires us to treat all relevant entity type or process taxon attributes a priori in the same way, calling them *variables* whether or not they turn out to be constant during a model run or are used for a bifurcation analysis in a study.

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

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

2.2 Basic entity types

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 copan:CORE *'base' model component* 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. 3).

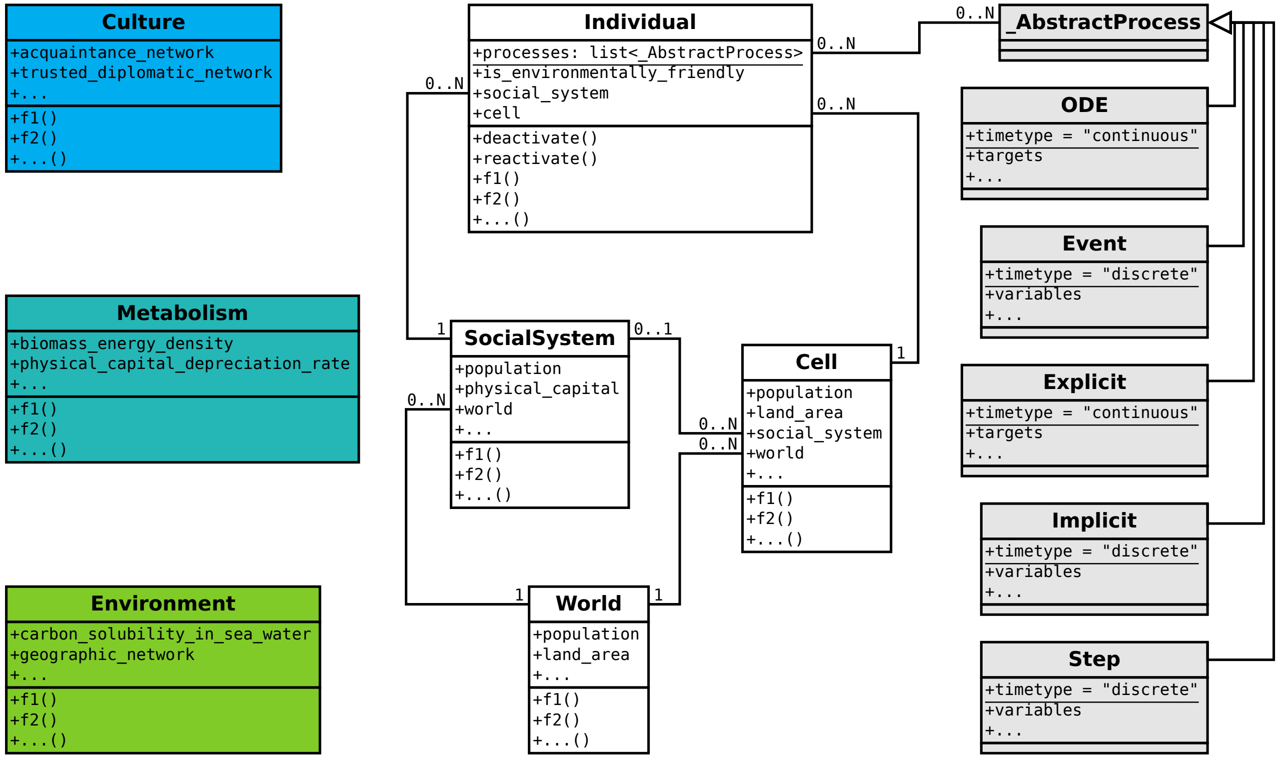

Figure 3. Basic relationships between entities in the copan:CORE framework. This UML class diagram shows the most important entity types and relationships, and a selection of entities' attributes, as implemented in the 'base' model component of the *pycopancore* reference implementation. 'f1()' and 'f2()'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

2.2.1 Cells

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

2.2.2 Social systems

An entity of type 'social system' is meant to represent what is sometimes simply called a 'society', i.e. "an economic, social, industrial or cultural infrastructure" (Wikipedia, 2017) such as a megacity, country, or the EU. We understand a social system 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 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. 2.2.3).

Social systems in this sense typically have a considerable size (e.g., a sovereign nation state such as the United States of America, a federal state or country such as Scotland, an urban area such as the Greater Tokyo Area, or an economically very closely integrated world region such as the EU), controlling a well-defined territory (represented by a set of cells) and encompassing all the socio-metabolic and cultural processes occurring within that territory. Social systems are not meant to represent a single social group, class, or stratum, for which different entity types 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 agent-based model components but an alternative choice would be to use ‘individuals’ like their ‘head of government’ or ‘social groups’ like a ‘ruling elite’ as agents.

2.2.3 Individuals

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

2.2.4 Relationships between entity types and process taxa

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

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

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

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

2.3 Software design

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

2.3.1 Object-oriented representation

Entity types 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 as *class attributes,* entity instances hold variable values and, where needed, their time derivatives as *instance attributes.* Processes' logics can be specified via *symbolic expressions* in the process metadata (e.g., for simple algebraic or differential equations) or as imperative code in *instance methods* (e.g., for regular 'steps' and random 'events' in an agent-based modeling style), thereby providing a large flexibility in how the equations and rules of the model are actually represented in the code, without compromising the interoperability of model components.

2.3.2 Interface and implementation classes

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

The attribute 'processes' is a list of objects of type 'Process', each of which specifies the metadata of one process that this model component contributes to this entity type or process taxon (see Figs. 2 and 3 of the Supplementary Information for examples). These metadata either contain the process logics as a symbolic expression or as a reference to some instance method(s). Instance methods do not return variable values but manipulate variable values or time derivatives directly via the respective instance attributes. As many variables are influenced by more than one process, some process implementation methods (e.g., those for differential equations or noise) only add some amount to an attribute value, while others (e.g., those for major events) may also overwrite an attribute value completely.

2.3.3 Model composition via multiple inheritance

Finally, a model's composition from model components is represented via multiple *inheritance* from the model component's implementation classes (which are thus also called 'mixin' classes) as follows. Each model is defined in a separate *module* (typically a single code file). For each entity type 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. 4 shows an example of this with just two components and two entity types.

2.3.4 Dimensional quantities, symbolic expressions, networks

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

2.3.5 Interoperability with other model software

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

To couple an external model component into a copan:CORE model, one must write a "wrapper" model component in the copan:CORE framework. For each relevant 'external' variable of the external model, the wrapper specifies a corresponding 'internal' copan:CORE variable in a suitable entity type or process taxon. In addition, the wrapper contributes a process implementation method of type 'Step' to a suitable process taxon, which uses the external software's interface to sync the

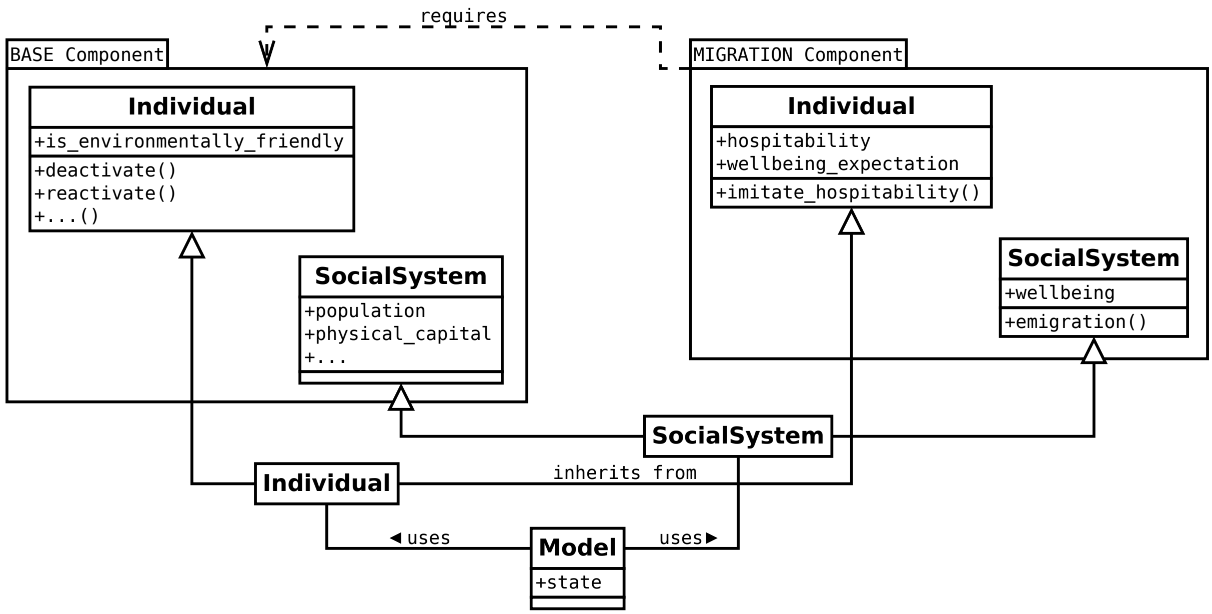

Figure 4. Model composition through multiple inheritance of attributes and processes by process taxa and entity types. This stylized class diagram shows how a model in copan:CORE can be composed from several model components (only two shown here, the mandatory component 'base' and the fictitious component '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.

2.4 Reference implementation in Python

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

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

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

realizing via a community-driven open-source software development project. Fig. 5 gives an impression of how user code in *pycopancore* looks like. See the *Supplementary Information* for further details.

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

In this section, we shortly present an example of a model realized with the *pycopancore* reference implementation of the copan:CORE modeling framework. The example model was designed to showcase the concepts and capabilities of copan:CORE in a rather simple WEM, and its components were chosen so that all entity types and process taxa and most features of copan:CORE are covered. Although most model components are somewhat plausible versions of model components that can be found in the various literatures, the example model is 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

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

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

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: (1) a spatially resolved version of the simple carbon cycle used in Nitzbon et al. (2017) (based on Anderies et al., 2013); (2) a regionalised version of the well-being-driven population dynamics and simple economy used in Nitzbon et al. (2017). 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; (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 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 model components in the code as shown in Fig. 6.

In order to show in particular what effect the inclusion of the socio-cultural processes into WEMs can have on their results, we compare two representative hundred-year runs from this example model, one without the social processes migration, environmental awareness, social learning, and voting, and another with these processes included. Both runs start from the same initial conditions and use the same parameters which were chosen to roughly reflect real-world global aggregates of the year 2000 but were otherwise randomly distributed on an Earth-like planet with five fictitious social systems, 100 grid cells and 1000 representative individuals. See the *Supplementary Information* for model and parameter details.

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

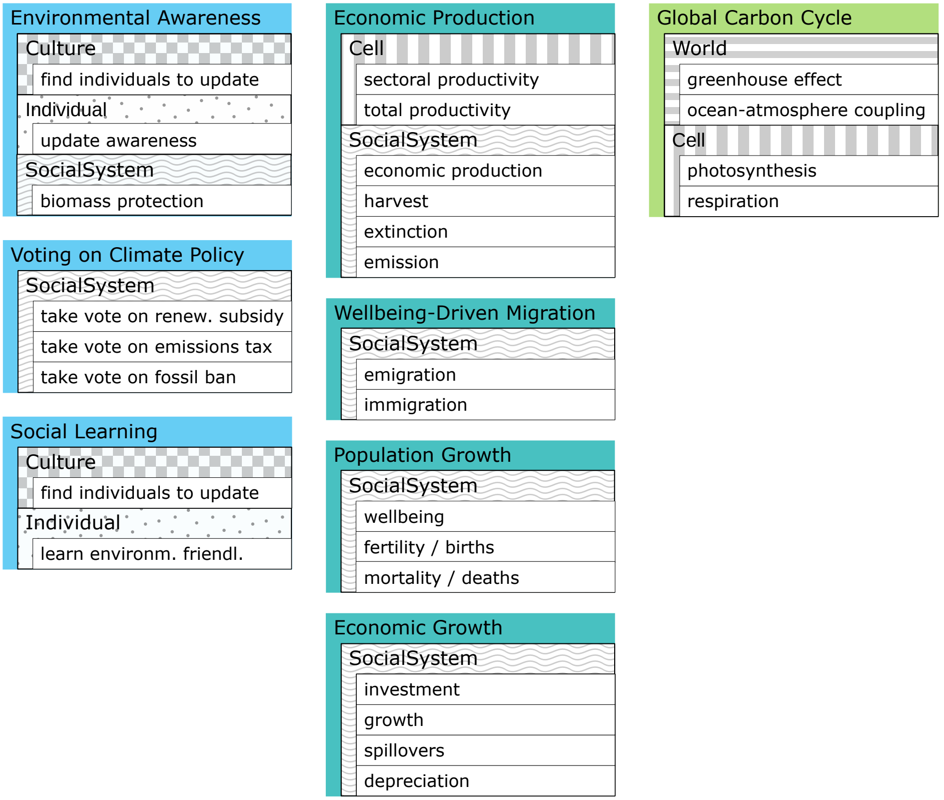

Figure 6. Components, entity types, and processes of the example model. Each box represents a model component that contributes several processes (white bars) to different entity types and process taxa (differently hashed rectangles).

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

With the *pycopancore* reference implementation, running the above two simulations took 140 seconds (without socio-cultural processes) and 520 seconds (including socio-cultural processes) on an i7-6600U CPU at 2.60 GHz. Since further performance

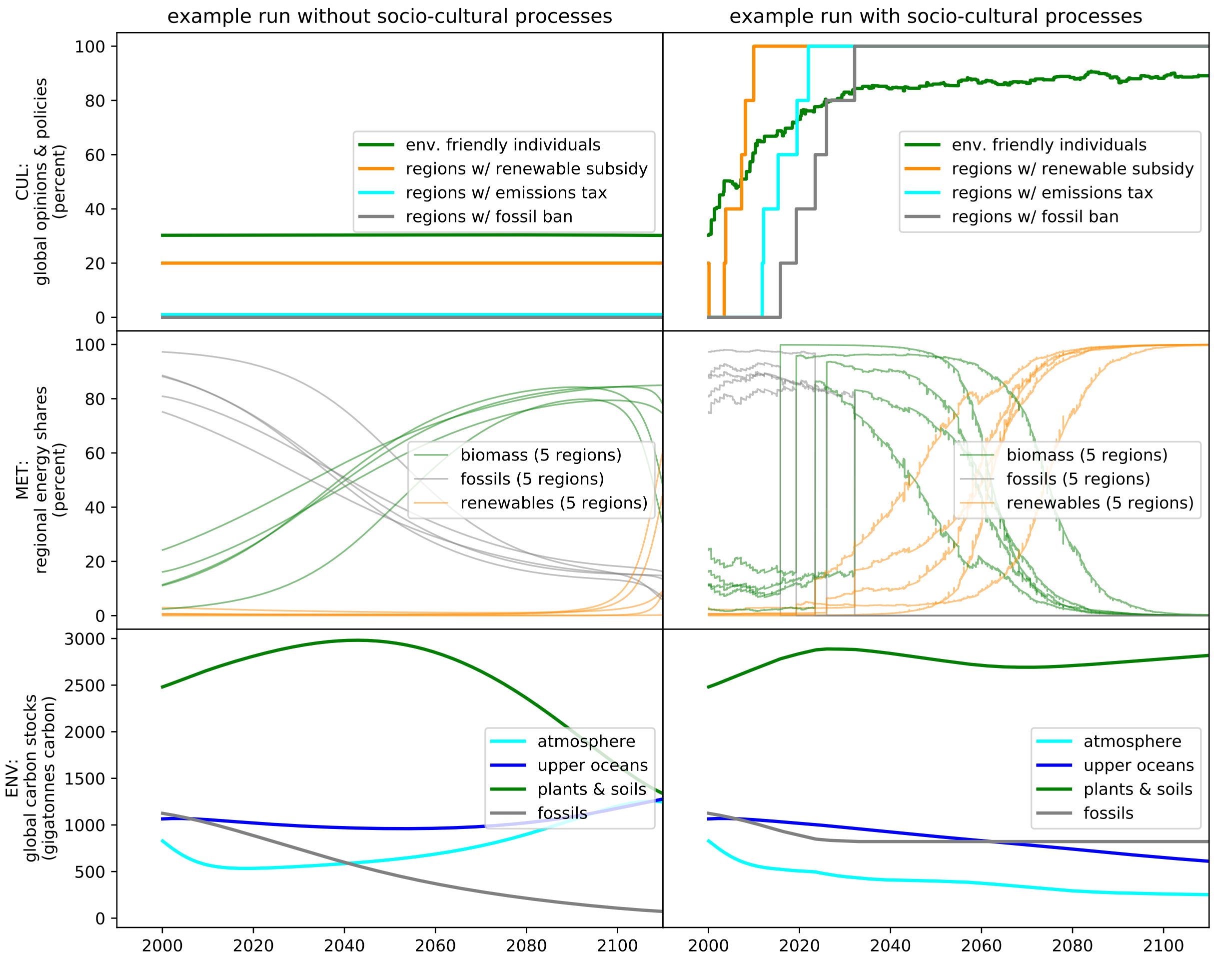

Figure 7. Two runs from a World-Earth model example, one without (left) and one with (right) the socio-cultural processes of migration, environmental awareness, social learning, and voting included, showing very different transient (and asymptotic, though not shown here) behavior. Colors differ from 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.

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 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).

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

Competing interests. The authors declare no competing interests.

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