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

Jonathan F. Donges[1,2,*], Jobst Heitzig[1,*], Wolfram Barfuss[1,3], Marc Wiedermann[1], Johannes A. Kassel[1,4], Tim Kittel[3], Jakob J. Kolb[1,3], Till Kolster[1,3], Finn Müller-Hansen[1,3], Ilona M. Otto[1], Kilian B. Zimmerer[1,5], and Wolfgang Lucht[1,6,7]

[1]Earth System Analysis and Complexity Science, Potsdam Institute for Climate Impact Research, Member of the Leibniz Association, Telegrafenberg A31, D-14473 Potsdam, Germany
[2]Stockholm Resilience Centre, Stockholm University, Kräftriket 2B, 114 19 Stockholm, Sweden
[3]Department of Physics, Humboldt University, Newtonstr. 15, D-12489 Berlin, Germany
[4]Department of Physics, University of Göttingen, Friedrich-Hund-Platz 1, D-37077 Göttingen, Germany
[5]Department of Physics and Astronomy, University of Heidelberg, Im Neuenheimer Feld 226, D-69120 Heidelberg, Germany
[6]Department of Geography, Humboldt University, Unter den Linden 6, D-10099 Berlin, Germany
[7]Integrative Research Institute on Transformations of Human-Environment Systems, Humboldt University, Unter den Linden 6, D-10099 Berlin, Germany
[*]The first two authors share the lead authorship.

Correspondence to: Jonathan F. Donges (donges@pik-potsdam.de), Jobst Heitzig (heitzig@pik-potsdam.de)

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. 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) proposes design principles for constructing World-Earth Models (WEM) for Earth system analysis of the Anthropocene, i.e., models of social (World) - ecological (Earth) co-evolution on up to planetary scales, and (ii) presents the copan:CORE open simulation modeling framework for developing, composing and analyzing such WEMs based on the proposed principles. 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 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, we present an exemplary and highly stylized WEM implemented in copan:CORE that 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

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). 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 can benefit from and build upon the work done in 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 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) 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 (Sect. 2), 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 State of the art and research gaps in Earth system analysis

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 increasing their consistency (van Vuuren et al., 2012; Foley et al., 2016; Dermody et al., 2018; Robinson et al., 2018).

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 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., 2019; 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 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).

1.2 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-
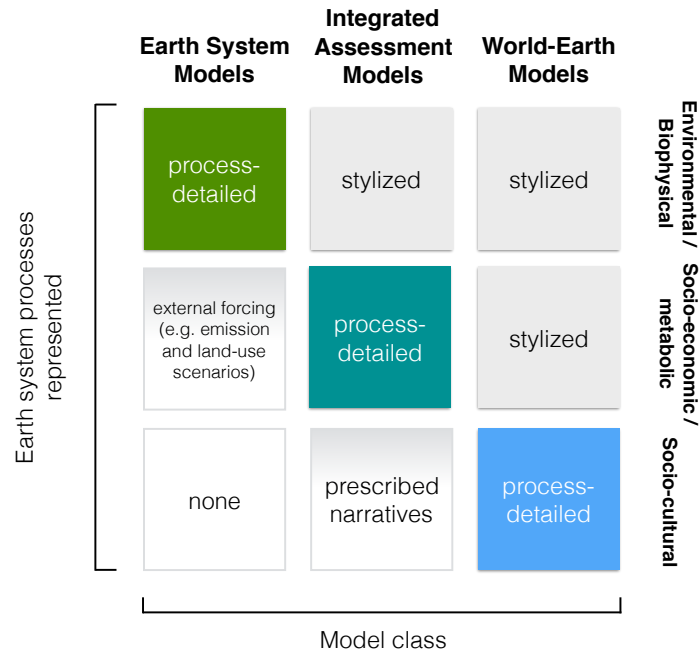
Figure 1. World-Earth models (WEMs) in the space of model classes used for scientific analysis of global change. It is shown to what degree current Earth system models, integrated assessment models and WEMs cover environmental/biophysical, socio-economic/metabolic, and socio-cultural processes, respectively. 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.

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 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 Research questions for World-Earth modeling

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 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. the analysis of first or second best climate change mitigation pathways, since this is the domain of state-of-the-art Integrated Assessment Models.

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 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. What are the 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 (Raworth, 2012)?

2. 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 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 do multilevel coalition formation processes (like the one modeled in Heitzig and Kornek (2018) assuming 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?

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. 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, or cultural endowment)? (Hewitt et al., 2019)

1.2.2 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 could be guided by aiming for the following properties:

1. **Explicit representation of social dynamics.** Societal processes should be represented in an explicit, dynamic fashion in order to do justice to the dominant role of human societies in 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.) 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 (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); Schlüter et al. (2017)), 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-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, 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., 2012). 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).

1.3 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). 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).

5 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

10 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

15 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

20 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., 2018)

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

25 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

30 include all three domains equally. However, the focus of current and near-future developments in World-Earth modeling 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

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) 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 using both simple and complex models. Its flexibility and role-based modularization support flexible scripting by end users, interoperability and dynamic coupling with existing models, 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 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., 2017). 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.

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 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.

A model composed with copan:CORE describes a certain part of the World-Earth system as consisting of a potentially varying set of *entities* ("things that are", e.g., a spot on the Earth's surface, the European Union, yourself), which are involved in *processes* ("things that happen", e.g., vegetation growth, economic production, opinion formation) 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) which represent the *variables* (including parameters) of a model. An attribute can have a simple or complex data type, e.g. representing a binary variable, a whole social network, or, to facilitate interoperability and validation, a dimensional quantity with a proper physical unit.

Entities are *classified* by *entity type* (cell, social system, individual, . . .), processes by their formal *process type* (see below), and both are represented by objects in an object-oriented software design, currently using the Python programming language.

| Process | Entity | Modelling |
| Taxa | Types | Approaches |
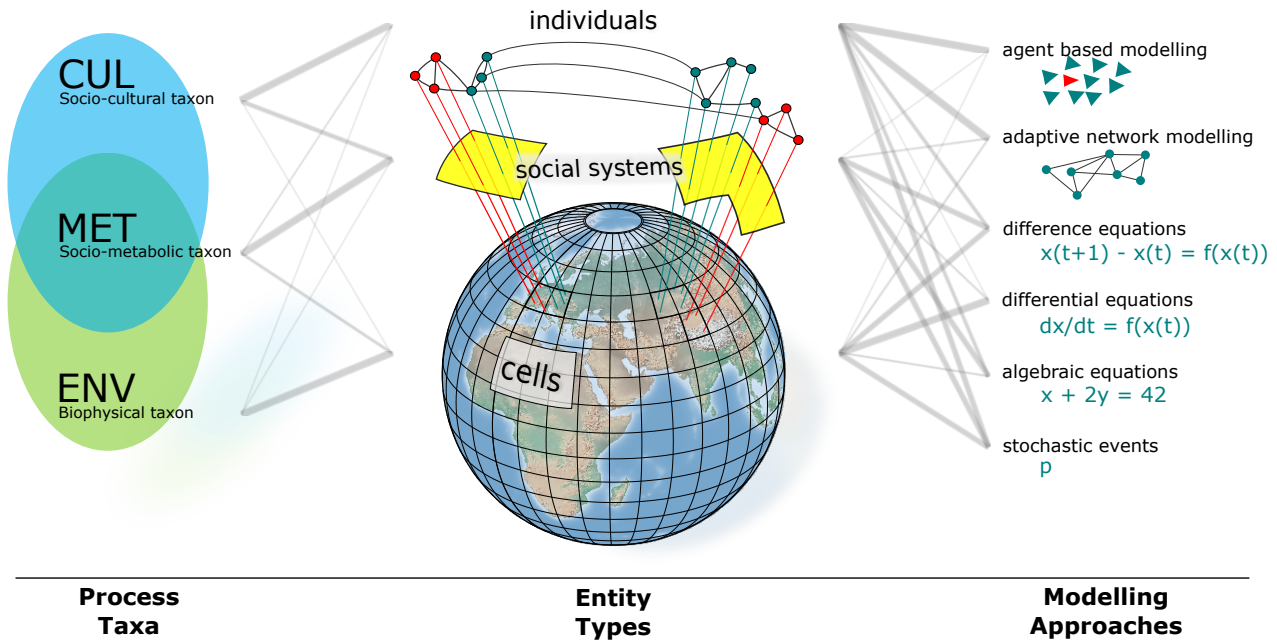
Figure 2. Overview of copan:CORE open World-Earth modeling framework. The entities in copan:CORE models are classified by *entity types* (e.g., grid *Cell*, *Social system*, *Individual*, see middle column). Each process belongs to either a certain entity type or a certain *process taxon* (left column). 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. 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.

Each process and each attribute *belongs* to an entity type or a *process taxon* (environmental, socio-metabolic, socio-cultural). Currently, the following formal process types are supported, enabling typical modeling approaches:

- *Ordinary differential equations* representing continuous time dynamics,

- *Explicit* or *implicit algebraic equations* representing (quasi-)instantaneous reactions or equilibria,

- *Steps* in discrete time representing processes aggregated at the level of some regular time interval or for coupling with external, time-step-based models or model components, and

- *Events* happening at irregular or random time points, representing e.g. agent-based and adaptive network components or externally generated extreme events).

Processes can be implemented either using an imperative programming style via class methods, or using symbolic expressions representing mathematical formulae. copan:CORE's *modularization* and *role concept* distinguishes

- *Model components* developed by *model component developers*, implemented as subpackages of the copan:CORE software package providing interface and implementation mixin classes for entity types and process taxa,

- *Models* made from these by *model composers*, implemented by forming final entity types and process taxa from these mixin classes,

- *Studies* by *model end users* in the form of scripts that import, initialize and run such a model,

- A *master data model* providing metadata for common variables to facilitate interoperability of model components and a common language for modelers, managed by a *modeling board*.

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

- *'World',* 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.

- *'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. 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), 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).

- *'Individual'*, representing a person, typically used in an network-, game-theoretic, or agent-based component. In contrast

to certain economic modeling approaches that use "representative" consumers, an 'individual' in copan:CORE is not 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. Each individual resides in a cell that belongs to a social system.

25 Fig. 2 illustrates these concepts. Although there is no one-to-one correspondence between process taxa, 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 environmental (ENV) 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 systems' (for mesoscopic processes described at the level of a

30 social system's territory, e.g., the environmental diffusion and decomposition of industrial wastes). Socio-metabolic (MET) processes will primarily deal with 'social systems' (e.g., for processes described at national or urban level), 'cells' (for local
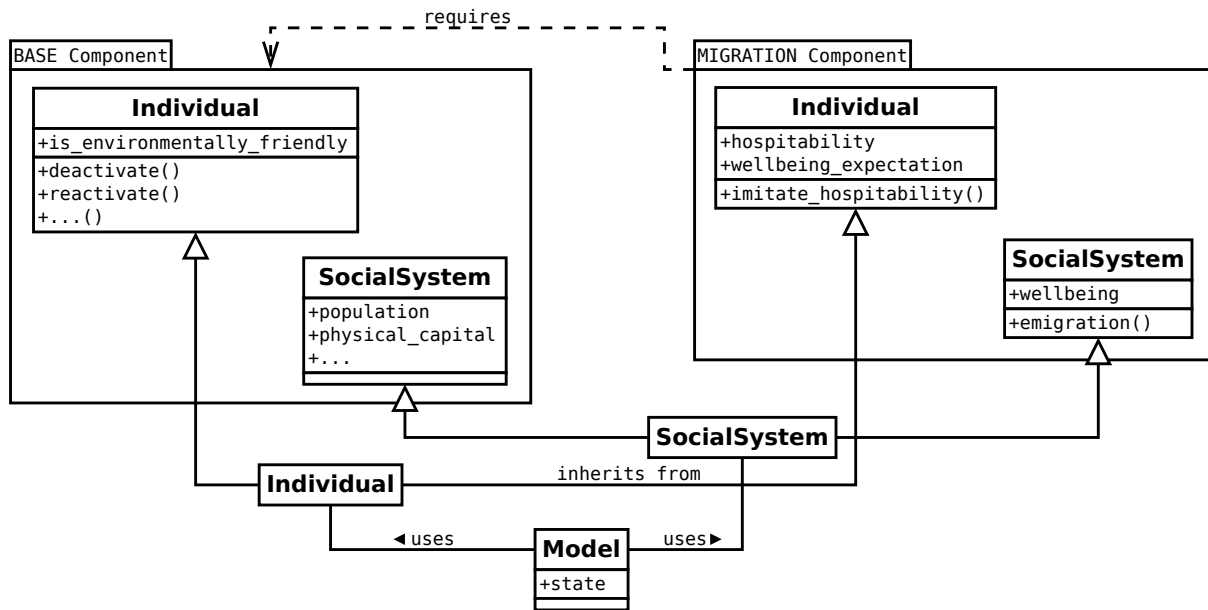
Figure 3. Model composition through multiple inheritance of attributes and processes by process taxa and entity types. This stylized class diagram shows how a model in copan:CORE can be composed from several model components (only two shown here, the mandatory component 'base' and the fictitious component '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).

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 'individuals' (e.g., for micro-economic model components such as consumption, investment or the job market). Socio-cultural (CUL) processes will mostly deal with 'individuals' (for "micro"-level descriptions) and 'social systems' (for "macro"-level descriptions), and rarely 'world(s)' (for

5 international processes such as diplomacy or treaties). Other entity types such as, e.g., firms, social groups or institutions can be added to the framework if needed.

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

In this section, we present an illustrative example of a model realized with 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

10 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

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

Table 1. Possible classification of exemplary model processes by owning process taxon (row) and affected process taxon (column) (following the taxonomy developed in the companion paper Donges et al., 2018): environmental (ENV), social-metabolic (MET) and socio-cultural (CUL)

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 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 groups of processes: (1) a 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 version of the 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 human capital depreciation; and (3) domestic voting on subsidizing renewables and banning fossil fuels that is driven by individual environmental friendliness. The latter results from 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 six model components in the code as shown in Fig. 4.

We now describe the model components in detail. As many processes add terms to variables' time derivatives, we use the notation $\dot{X} += Y$ 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.
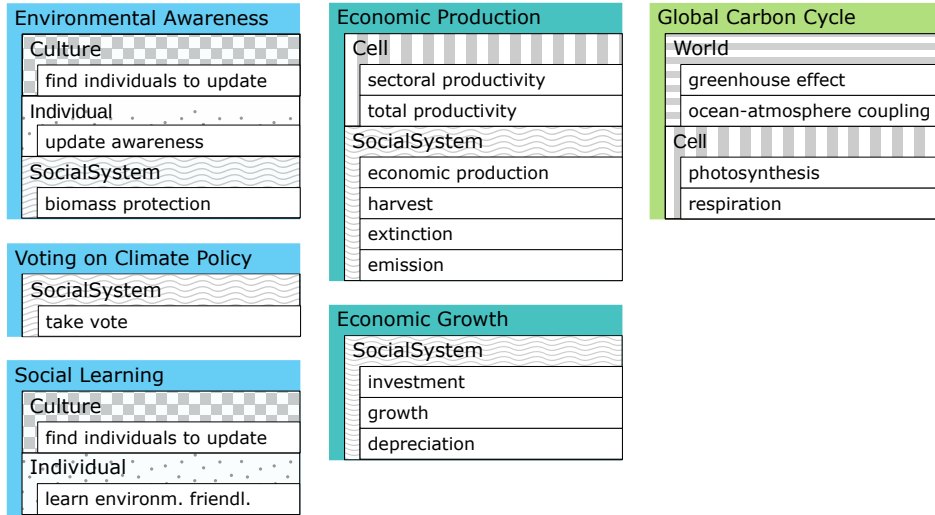
Figure 4. Components, entity types, and processes of the example model. Each box represents a model component that contributes several processes (white bars) to different entity types and process taxa (differently hashed rectangles).

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 $830\,\mathrm{GtC}$) linearly into a mean surface air temperature $T = T_\mathrm{ref} + a(A - A_\mathrm{ref})$ (a process of type 'explicit

5 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 $1065\,\mathrm{GtC}$),

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

(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 $620\,\mathrm{GtC}$ for all four c) are changed by a respiration flow RF_c and a

10 photosynthesis flow PF_c,

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

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

$$RF_c = (a_0 + a_A A/\Sigma)L_c \qquad\qquad (3)$$

15 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 $l_0 = 34\,\mathrm{km/GtC^{1/2}/yr}$ and $l_A = 1.1e6\,\mathrm{km^3/GtC^{3/2}/yr}$, 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
5 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
10 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:

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

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

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

15 $$R_c = b_{R,c} K_{R,c}^{\kappa_R} P_{R,c}^{\pi_R} S_s^{\sigma}. \tag{8}$$

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 0.1×1125 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
20 $b_{\bullet}$ have units that depend on the elasticities and are chosen so that initial global energy flows roughly match the observed values: $b_F = 1.4e9\,\mathrm{(GJ/yr)^5/(GtC\,\$)^2}$, $b_B = 6.8e8\,\mathrm{(GJ/yr)^5/(GtC\,\$)^2}$, and $b_{R,c} = 0.7, 0.9, 1.1$ and 1.3 times the mean value $b_R = 1.75 \times 10^{-11}\,\mathrm{(GJ/yr)^5/(GJ\,\$)^2}$ 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
25 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:

30 $$\partial y_E E_{F,c}/\partial P_{F,c} \equiv \partial y_E E_{B,c}/\partial P_{B,c} \equiv \partial y_E R_c/\partial P_{R,c} \equiv w_s \tag{10}$$

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

5 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,

10 $$\dot{K}_s \mathrel{+}= iY_s. \tag{11}$$

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

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

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

15 $$\dot{S}_s \mathrel{+}= R_s. \tag{13}$$

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.),

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

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

20 $P_{South}s = 4.5e9$ 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

25 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 socio-cultural processes into WEMs can have on their results, we compare two representative hundred-year runs of the example model described above, one without the 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 conditions and use the same parameters which were chosen to roughly reflect real-world global aggregates of the year 2000 (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 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.
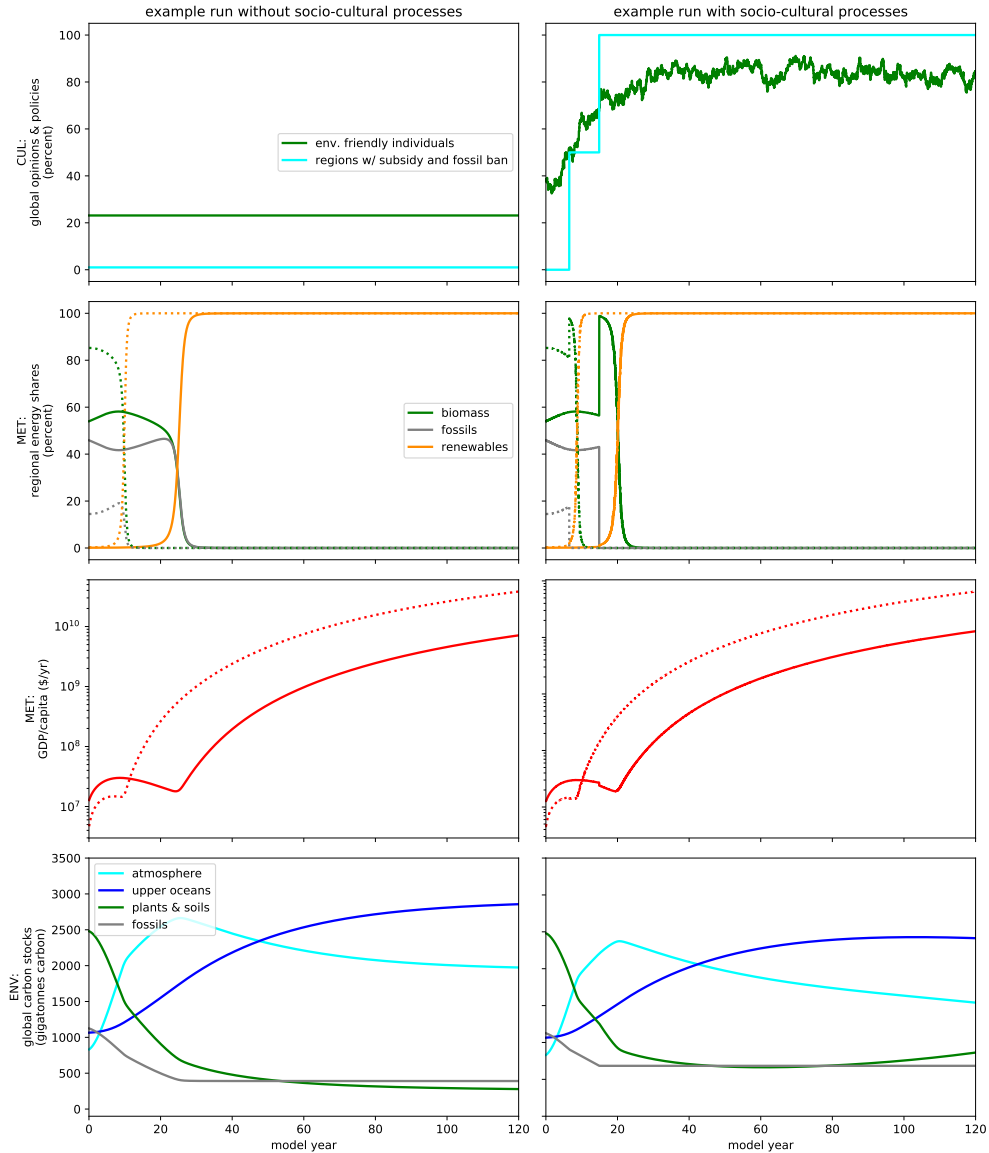
Figure 5. Two runs from a World-Earth model example, one without (left) and one with (right) the socio-cultural processes of environmental awareness, social learning, and voting included, showing different transient (and asymptotic) behavior. The top row shows variables related to the cultural process 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'.

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 an illustration of such an analysis we now vary the learning rate
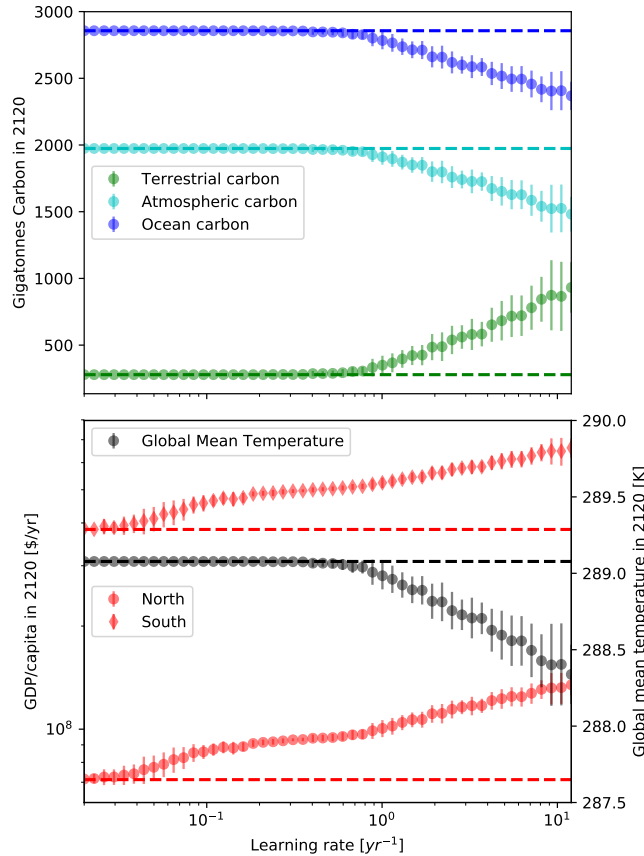
Figure 6. Dependency of some selected variables after 120 model years on the learning rate of environmental awareness. Scatter points denote (the average over 50) simulations with social processes and error bars denote one standard deviation for each choice of learning rate. Dashed lines indicate the 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.

from $1/50$yr (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).

For learning rates lower than $1/$yr (slow learning) the carbon stocks as well as the global mean temperature align well for
5   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).

The metabolic variable GDP per capita interestingly already increases much earlier (i.e., for much lower learning rates than $1/\text{yr}$) 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 290 seconds (including socio-cultural processes) on an 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 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; 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 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.

Competing interests. The authors declare no competing interests.

Acknowledgements. This work has been carried out within the framework of PIK's flagship project on Coevolutionary Pathways in the Earth system (copan, www.pik-potsdam.de/copan). We are grateful for financial support by the Stordalen Foundation via the Planetary Boundary Research Network (PB.net), the Earth League's EarthDoc programme, the Leibniz Association (project DominoES), the European Research Council (ERC advanced grant project ERA), and the German Federal Ministry of Education and Research (BMBF, project CoNDyNet). We acknowledge additional support by the Heinrich Böll Foundation (WB), the Foundation of German Business (JJK), the Episcopal Scholarship Foundation Cusanuswerk (JK) and DFG/FAPESP (IRTG 1740/TRP 2015/50122-0, FMH). The European Regional Development Fund, BMBF, and the Land Brandenburg supported this project by providing resources on the high-performance computer system at the Potsdam Institute for Climate Impact Research. We thank the participants of the three LOOPS workshops (www.pik-potsdam.de/loops) in Kloster Chorin (2014), Southampton (2015) and Potsdam (2017) for discussions that provided highly valuable insights for conceptualizing World-Earth modeling and the development of the copan:CORE open simulation modeling framework.

References

Anderies, J. M., Carpenter, S. R., Steffen, W., and Rockström, J.: The topology of non-linear global carbon dynamics: from tipping points to planetary boundaries, Environmental Research Letters, 8, 044 048, 2013.

Arneth, A., Brown, C., and Rounsevell, M.: Global models of human decision-making for land-based mitigation and adaptation assessment, Nature Climate Change, 4, 550–557, 2014.

Auer, S., Heitzig, J., Kornek, U., Schöll, E., and Kurths, J.: The dynamics of coalition formation on complex networks, Scientific reports, 5, 13 386, 2015.

Barfuss, W., Donges, J. F., Wiedermann, M., and Lucht, W.: Sustainable use of renewable resources in a stylized social–ecological network model under heterogeneous resource distribution, Earth System Dynamics, 8, 255–264, 2017.

Barfuss, W., Donges, J. F., Lade, S. J., and Kurths, J.: When optimization for governing human-environment tipping elements is neither sustainable nor safe, Nature communications, 9, 2354, 2018.

Berkes, F., Folke, C., and Colding, J.: Linking social and ecological systems: management practices and social mechanisms for building resilience, Cambridge University Press, 2000.

Betts, R. K.: Conflict after the Cold War: arguments on causes of war and peace, Taylor & Francis, 2017.

Bierstedt, R.: The Social Order, McGraw-Hill, New York, 1963.

Cai, Y., Lenton, T. M., and Lontzek, T. S.: Risk of multiple interacting tipping points should encourage rapid CO_2 emission reduction, Nature Climate Change, 6, 520–525, 2016.

Cash, D., Adger, W. N., Berkes, F., Garden, P., Lebel, L., Olsson, P., Pritchard, L., and Young, O.: Scale and cross-scale dynamics: governance and information in a multilevel world, Ecology and society, 11, 2006.

Castellano, C., Fortunato, S., and Loreto, V.: Statistical physics of social dynamics, Reviews of Modern Physics, 81, 591, 2009.

Crutzen, P. J.: Geology of mankind, Nature, 415, 23–23, 2002.

Cumming, G. S. and Peterson, G. D.: Unifying research on social–ecological resilience and collapse, Trends in ecology & evolution, 32, 695–713, 2017.

Dermody, B. J., Sivapalan, M., Stehfest, E., van Vuuren, D. P., Wassen, M. J., Bierkens, M. F. P., and Dekker, S. C.: A framework for modelling the complexities of food and water security under globalisation, Earth System Dynamics, 9, 103–118, 2018.

Di Baldassarre, G., Martinez, F., Kalantari, Z., and Viglione, A.: Drought and flood in the Anthropocene: feedback mechanisms in reservoir operation, Earth System Dynamics, 8, 225–233, 2017.

Donges, J. F. and Barfuss, W.: From Math to Metaphors and Back Again: Social-Ecological Resilience from a Multi-Agent-Environment Perspective, GAIA-Ecological Perspectives for Science and Society, 26, 182–190, 2017.

Donges, J. F., Lucht, W., Müller-Hansen, F., and Steffen, W.: The technosphere in Earth System analysis: A coevolutionary perspective, The Anthropocene Review, 4, 23–33, 2017a.

Donges, J. F., Winkelmann, R., Lucht, W., Cornell, S. E., Dyke, J. G., Rockström, J., Heitzig, J., and Schellnhuber, H. J.: Closing the loop: Reconnecting human dynamics to Earth System science, The Anthropocene Review, 4, 151–157, 2017b.

Donges, J. F., Lucht, W., Heitzig, J., Lade, S. J., Cornell, S. E., and Schlüter, M.: Taxonomies for structuring models for World-Earth system analysis of the Anthropocene: subsystems, their interactions and social-ecological feedback loops, Earth System Dynamics Discussions, https://doi.org/10.5194/esd-2018-27, 2018.

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., and Minx, J., eds.: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014.

5 Edenhofer, O., Flachsland, C., Jakob, M., and Lessmann, K.: The atmosphere as a global commons, in: The Oxford Handbook of the Macroeconomics of Global Warming, edited by Bernard, L. and Semmler, W., 2015.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organisation, Geoscientific Model Development, 9, 1937–1958, 2016.

Farmer, J., Hepburn, C., Ives, M., Hale, T., Wetzer, T., Mealy, P., Rafaty, R., Srivastav, S., and Way, R.: Sensitive intervention points in the
10 post-carbon transition, Science, 364, 132–134, 2019.

Farmer, J. D. and Foley, D.: The economy needs agent-based modelling, Nature, 460, 685–686, 2009.

Farmer, J. D., Hepburn, C., Mealy, P., and Teytelboym, A.: A third wave in the economics of climate change, Environmental and Resource Economics, 62, 329–357, 2015.

Fischer-Kowalski, M.: On the Childhood and Adolescence of a Rising Conceptual Star, in: The International Handbook of Environmental
15 Sociology, Edward Elgar Publishing, Cheltenham, UK, 1997.

Foley, A. M., Holden, P. B., Edwards, N. R., Mercure, J.-F., Salas, P., Pollitt, H., and Chewpreecha, U.: Climate model emulation in an integrated assessment framework: a case study for mitigation policies in the electricity sector, Earth System Dynamics, 7, 119–132, 2016.

Folke, C.: Resilience: The emergence of a perspective for social–ecological systems analyses, Global Environmental Change, 16, 253–267, 2006.

20 Future Earth: Future Earth Strategic Research Agenda 2014, International Council for Science (ICSU), Paris, 2014.

Gaffney, O. and Steffen, W.: The Anthropocene equation, The Anthropocene Review, 4, 53–61, 2017.

Garrett, T. J.: Long-run evolution of the global economy: 1. Physical basis, Earth's Future, 2, 127–151, 2014.

Geier, F., Barfuss, W., Wiedermann, M., Kurths, J., and Donges, J. F.: The physics of governance networks: critical transitions in contagion dynamics on multilayer adaptive networks with application to the sustainable use of renewable resources, arXiv preprint arXiv:1906.08679,
25 2019.

Gerten, D., Schönfeld, M., and Schauberger, B.: On deeper human dimensions in Earth system analysis and modelling, Earth System Dynamics, 9, 849–863, 2018.

Gross, T. and Blasius, B.: Adaptive coevolutionary networks: a review, Journal of the Royal Society Interface, 5, 259–271, 2008.

Haff, P.: Technology and human purpose: the problem of solids transport on the Earth's surface, Earth System Dynamics, 3, 149–156, 2012.

30 Haff, P.: Humans and technology in the Anthropocene: Six rules, The Anthropocene Review, 1, 126–136, 2014.

Heck, V., Donges, J. F., and Lucht, W.: Collateral transgression of planetary boundaries due to climate engineering by terrestrial carbon dioxide removal, Earth System Dynamics, 7, 783–796, 2016.

Heitzig, J. and Kornek, U.: Bottom-up linking of carbon markets under far-sighted cap coordination and reversibility, Nature Climate Change, 8, 204, 2018.

35 Heitzig, J., Kittel, T., Donges, J. F., and Molkenthin, N.: Topology of sustainable management of dynamical systems with desirable states: from defining planetary boundaries to safe operating spaces in the Earth system, Earth System Dynamics, 7, 21, 2016.

Helbing, D., Bishop, S., Conte, R., Lukowicz, P., and McCarthy, J. B.: FuturICT: Participatory computing to understand and manage our complex world in a more sustainable and resilient way, The European Physical Journal Special Topics, 214, 11–39, 2012.

Hewitt, R., Bradley, N., Baggio Compagnucci, A., Barlagne, C., Ceglarz, A., Cremades, R., McKeen, M., Otto, I., and Slee, B.: Social Innovation in Community Energy in Europe: A Review of the Evidence. Front, Energy Res, 7, 31, 2019.

Holley, R. A. and Liggett, T. M.: Ergodic theorems for weakly interacting infinite systems and the voter model, The Annals of Probability, 3, 643–663, 1975.

5 Jager, W., Janssen, M., De Vries, H., De Greef, J., and Vlek, C.: Behaviour in commons dilemmas: Homo economicus and Homo psychologicus in an ecological-economic model, Ecological Economics, 35, 357–379, 2000.

Janssen, M.: Complexity and ecosystem management: the theory and practice of multi-agent systems, Edward Elgar Publishing, 2002.

Janssen, M. and De Vries, B.: The battle of perspectives: a multi-agent model with adaptive responses to climate change, Ecological Economics, 26, 43–65, 1998.

10 Kellie-Smith, O. and Cox, P. M.: Emergent dynamics of the climate–economy system in the Anthropocene, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 369, 868–886, 2011.

Keys, P. W. and Wang-Erlandsson, L.: On the social dynamics of moisture recycling, Earth System Dynamics, 9, 829–847, 2018.

Kittel, T., Koch, R., Heitzig, J., Deffuant, G., Mathias, J.-D., and Kurths, J.: Operationalization of Topology of Sustainable Management to Estimate Qualitatively Different Regions in State Space, arXiv preprint arXiv:1706.04542, 2017.

15 Kopp, R. E., Shwom, R. L., Wagner, G., and Yuan, J.: Tipping elements and climate–economic shocks: Pathways toward integrated assessment, Earth's Future, 4, 346–372, 2016.

Kriegler, E., Hall, J. W., Held, H., Dawson, R., and Schellnhuber, H. J.: Imprecise probability assessment of tipping points in the climate system, Proceedings of the national Academy of Sciences, 106, 5041–5046, 2009.

Lade, S. J., Donges, J. F., Fetzer, I., Anderies, J. M., Beer, C., Cornell, E., Gasser, T., Norberg, J., Richardson, K., Rockström, J., and Steffen, 20 W.: Analytically tractable climate-carbon cycle feedbacks under 21st century anthropogenic forcing, Earth System Dynamics Discussions, pp. 1–23, 2017.

Lenton, T. and Watson, A. J.: Revolutions that made the Earth, Oxford University Press, 2011.

Lenton, T., Pichler, P.-P., and Weisz, H.: Revolutions in energy input and material cycling in Earth history and human history, Earth System Dynamics, 7, 353–370, 2016.

25 Lenton, T. M. and Latour, B.: Gaia 2.0, Science, 361, 1066–1068, 2018.

Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., and Schellnhuber, H. J.: Tipping elements in the Earth's climate system, Proceedings of the National Academy of Sciences, 105, 1786–1793, 2008.

Liu, J., Dietz, T., Carpenter, S. R., Alberti, M., Folke, C., Moran, E., Pell, A. N., Deadman, P., Kratz, T., Lubchenco, J., et al.: Complexity of coupled human and natural systems, Science, 317, 1513–1516, 2007.

30 Martinez-Alier, J.: Social metabolism, ecological distribution conflicts, and languages of valuation, Capitalism Nature Socialism, 20, 58–87, 2009.

Menck, P. J., Heitzig, J., Marwan, N., and Kurths, J.: How basin stability complements the linear-stability paradigm, Nature Physics, 9, 89–92, 2013.

Milkoreit, M., Hodbod, J., Baggio, J., Benessaiah, K., Calderón-Contreras, R., Donges, J. F., Mathias, J.-D., Rocha, J. C., Schoon, M., and 35 Werners, S. E.: Defining tipping points for social-ecological systems scholarship—an interdisciplinary literature review, Environmental Research Letters, 13, 033 005, 2018.

Motesharrei, S., Rivas, J., and Kalnay, E.: Human and Nature Dynamics (HANDY): Modeling inequality and use of resources in the collapse or sustainability of societies, Ecological Economics, 101, 90–102, 2014.

Müller-Hansen, F., Schlüter, M., Mäs, M., Hegselmann, R., Donges, J. F., Kolb, J. J., Thonicke, K., and Heitzig, J.: How to represent human behavior and decision making in Earth system models? A guide to techniques and approaches, Earth System Dynamics, 8, 977–1007, 2017.

Nagy, B., Farmer, J. D., Bui, Q. M., and Trancik, J. E.: Statistical Basis for Predicting Technological Progress, PLoS ONE, 8, 1–7, https://doi.org/10.1371/journal.pone.0052669, 2013.

Nitzbon, J., Heitzig, J., and Parlitz, U.: Sustainability, collapse and oscillations in a simple World-Earth model, Environmental Research Letters, 12, 2017.

Nyborg, K., Anderies, J. M., Dannenberg, A., Lindahl, T., Schill, C., Schlüter, M., Adger, W. N., Arrow, K. J., Barrett, S., Carpenter, S., et al.: Social norms as solutions, Science, 354, 42–43, 2016.

Ostrom, E.: Governing the commons: The evolution of institutions for collective action, Cambridge University Press, 1990.

Otto, I. M., Biewald, A., Coumou, D., Feulner, G., Köhler, C., Nocke, T., Blok, A., Gröber, A., Selchow, S., Tyfield, D., et al.: Socio-economic data for global environmental change research, Nature Climate Change, 5, 503–506, 2015.

Otto, I. M., Reckien, D., Reyer, C. P., Marcus, R., Le Masson, V., Jones, L., Norton, A., and Serdeczny, O.: Social vulnerability to climate change: a review of concepts and evidence, Regional Environmental Change, 17, 1651–1662, 2017.

Otto, I. M., Kim, K. M., Dubrovsky, N., and Lucht, W.: Shift the focus from the super-poor to the super-rich, Nature Climate Change, 9, 82, 2019.

Otto, I. M., Donges, J. F., Lucht, W., Cremades, R., and Wiedermann, M.: Human agency in the Anthropocene, in review.

O'Neill, D. W., Fanning, A. L., Lamb, W. F., and Steinberger, J. K.: A good life for all within planetary boundaries, Nature Sustainability, 1, 88, 2018.

Raworth, K.: A safe and just space for humanity: can we live within the doughnut, Oxfam Policy and Practice: Climate Change and Resilience, 8, 1–26, 2012.

Robinson, D. T., Di Vittorio, A., Alexander, P., Arneth, A., Michael Barton, C., Brown, D. G., Kettner, A., Lemmen, C., O'Neill, B. C., Janssen, M., Pugh, T. A., Rabin, S. S., Rounsevell, M., Syvitski, J. P., Ullah, I., and Verburg, P. H.: Modelling feedbacks between human and natural processes in the land system, Earth System Dynamics, 9, 895–914, https://doi.org/10.5194/esd-9-895-2018, https://www.earth-syst-dynam-discuss.net/esd-2017-68/, 2018.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., et al.: A safe operating space for humanity, Nature, 461, 472–475, 2009.

Rockström, J., Brasseur, G., Hoskins, B., Lucht, W., Schellnhuber, J., Kabat, P., Nakicenovic, N., Gong, P., Schlosser, P., Máñez Costa, M., et al.: Climate change: The necessary, the possible and the desirable Earth League climate statement on the implications for climate policy from the 5th IPCC Assessment, Earth's Future, 2, 606–611, 2014.

Schellnhuber, H. J.: Discourse: Earth System analysis—The scope of the challenge, in: Earth System Analysis, pp. 3–195, Springer, 1998.

Schellnhuber, H. J.: Earth system analysis and the second Copernican revolution, Nature, 402, C19–C23, 1999.

Schellnhuber, H. J., Rahmstorf, S., and Winkelmann, R.: Why the right climate target was agreed in Paris, Nature Climate Change, 6, 649–653, 2016a.

Schellnhuber, H. J., Serdeczny, O., Adams, S., Köhler, C., Otto, I., and Schleussner, C.: The Challenge of a 4 Degrees Celcius World by 2100, in: Hexagon Series on Human Environmental Security and Peace, edited by Brauch, Springer, 2016b.

Schlüter, M., McAllister, R. R. L., Arlinghaus, R., Bunnefeld, N., Eisenack, K., Hölker, F., and Milner-Gulland, E. J.: New horizons for managing the environment: A review of coupled social-ecological systems modeling, Natural Resource Modeling, 25, 219–272, 2012.

Schlüter, M., Baeza, A., Dressler, G., Frank, K., Groeneveld, J., Jager, W., Janssen, M. A., McAllister, R. R., Müller, B., Orach, K., et al.: A framework for mapping and comparing behavioural theories in models of social-ecological systems, Ecological Economics, 131, 21–35, 2017.

Snijders, T. A., Van de Bunt, G. G., and Steglich, C. E.: Introduction to stochastic actor-based models for network dynamics, Social Networks, 32, 44–60, 2010.

Steffen, W., Crutzen, P. J., and McNeill, J. R.: The Anthropocene: are humans now overwhelming the great forces of nature, AMBIO: A Journal of the Human Environment, 36, 614–621, 2007.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., et al.: Planetary boundaries: Guiding human development on a changing planet, Science, p. 1259855, 2015.

Steffen, W., Rockström, J., Richardson, K., Lenton, T., Folke, C., Liverman, D., Summerhayes, C., Barnosky, A., Cornell, S., Crucifix, M., Donges, J., Fetzer, I., Lade, S., Scheffer, M., Winkelmann, R., and Schellnhuber, H.: Trajectories of the Earth system in the Anthropocene, Proceedings of the National Academy of Sciences of the United States of America, 115, 8252–8259, 2018.

Stocker, T., Qin, D., Plattner, G.-K., Tignor, M., Allen, S., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P., eds.: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

Tàbara, J. D., Frantzeskaki, N., Hölscher, K., Pedde, S., Kok, K., Lamperti, F., Christensen, J. H., Jäger, J., and Berry, P.: Positive tipping points in a rapidly warming world, Current Opinion in Environmental Sustainability, 31, 120–129, 2018.

van Kan, A., Jegminat, J., Donges, J. F., and Kurths, J.: Constrained basin stability for studying transient phenomena in dynamical systems, Physical Review E, 93, 042 205, 2016.

van Vuuren, D. P., Bayer, L. B., Chuwah, C., Ganzeveld, L., Hazeleger, W., van den Hurk, B., Van Noije, T., O'Neill, B., and Strengers, B. J.: A comprehensive view on climate change: coupling of earth system and integrated assessment models, Environmental Research Letters, 7, 024 012, 2012.

van Vuuren, D. P., Lucas, P. L., Häyhä, T., Cornell, S. E., and Stafford-Smith, M.: Horses for courses: analytical tools to explore planetary boundaries, Earth System Dynamics, 7, 267–279, 2016.

Verburg, P. H., Dearing, J. A., Dyke, J. G., van der Leeuw, S., Seitzinger, S., Steffen, W., and Syvitski, J.: Methods and approaches to modelling the Anthropocene, Global Environmental Change, 39, 328–340, 2016.

Wiedermann, M., Donges, J. F., Heitzig, J., Lucht, W., and Kurths, J.: Macroscopic description of complex adaptive networks co-evolving with dynamic node states, Physical Review E, 91, 052 801, 2015.

Wikipedia: Wikipedia article on "Society" (last checked on 12-23-2017), https://en.wikipedia.org/wiki/Society, 2017.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., et al.: Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems, The Lancet, 393, 447–492, 2019.

Williamson, O. E.: Transaction cost economics: how it works; where it is headed, De economist, 146, 23–58, 1998.