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Methods and approaches to modelling the Anthropocene

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ABSTRACT

The ‘Anthropocene’ concept provides a conceptual framework that encapsulates the current global situation in which society has an ever-greater dominating influence on Earth System functioning. Simulation models used to understand earth system dynamics provide early warning, scenario analysis and evaluation of environmental management and policies. This paper aims to assess the extent to which current models represent the Anthropocene and suggest ways forward. Current models do not fully reflect the typical characteristics of the Anthropocene, such as societal influences and interactions with natural processes, feedbacks and system dynamics, tele-connections, tipping points, thresholds and regime shifts. Based on an analysis of current model representations of Anthropocene dynamics, we identify ways to enhance the role of modeling tools to better help us understand Anthropocene dynamics and address sustainability issues arising from them. To explore sustainable futures (‘safe and operating spaces’), social processes and anthropogenic drivers of biophysical processes must be incorporated, to allow for a spectrum of potential impacts and responses at different societal levels. In this context, model development can play a major role in reconciling the different epistemologies of the disciplines that need to collaborate to capture changes in the functioning of socio-ecological systems. Feedbacks between system functioning and underlying endogenous drivers should be represented, rather than assuming the drivers to be exogenous to the modelled system or stationary in time and space. While global scale assessments are important, the global scale dynamics need to be connected to local realities and vice versa. The diversity of stakeholders and potential questions requires a diversification of models, avoiding the convergence towards single models that are able to answer a wide range of questions, but without sufficient specificity. The novel concept of the Anthropocene can help to develop innovative model representations and model architectures that are better suited to assist in designing sustainable solutions targeted at the users of the models and model results.

1. Introduction

The passage into the 21st century witnessed much debate and reflection on the relationship between humanity and the earth system. Most influentially, Crutzen and Stoermer (2000) argued that the cumulative effect of human activities on planetary scale processes has become so large as to warrant a new geological epoch. They suggested that the rise in greenhouse gases observed in ice cores from the start of the industrial revolution, some 250 years ago, heralded the start of the Anthropocene. The implication – that humanity was exerting an impact on ecosystems, ecological processes and biogeochemical cycles at planetary scales – focused attention on global environmental change research, particularly the scientific frameworks that would enable engagement with the growing complexity of interactions and feedback mechanisms. One conclusion was that appropriate policy and decision-making demanded much higher levels of scientific

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understanding, assessment and modelling if future human-environment interactions are to be anticipated correctly.

The implications of the Anthropocene concept reach far beyond the definition of a recent geological epoch characterized by human impacts on biogeochemical and biophysical processes. The Earth System perspective demands an understanding of both the system and human-derived forces and impacts on planetary processes. The Anthropocene essentially defines the growth of nested social-ecological systems where human-environment interactions are not only bi-directional but reach across different space and time scales. In this sense, the relevance of complexity science to a new understanding of human-environment interactions becomes apparent. The turn of the century also saw the International-Geosphere-Biosphere Programme (IGBP) community propose a 'second Copernican revolution' in our understanding of the Earth System (Schellnhuber, 1999), drawing upon complexity science to argue for a new generation of intermediate complexity simulation models that could simulate coupled human-environment relationships. The Amsterdam Declaration in 2001 extended these ideas to include the possibilities of threshold-dependent changes and tipping points (Moore et al., 2001). As IGBP and the GEC programs transition into the Future Earth program these ideas/foundations now advance to extend the inclusion of social dynamics and new forms of collaboration with model users and stakeholders.

The first model formulation at the scale of the Anthropocene and its interpretation are now over 40 years old with World3 and Limits to Growth, sponsored by the Club of Rome (Meadows et al., 1972) based on systems dynamics models of the Earth system developed by Forrester (1971). Despite the simplification of key global elements, these models embedded a large number of feedback loops in order to attempt useful simulations of human-environment interactions over many decades. World3 was used to explore different scenarios and how such scenarios differ giving different assumptions, rather than produce a particular prediction. At the time of publication, the World3 model was subjected to pointed critique (Cole, 1974). Yet the 'reference run' of World3 has been shown to produce a reasonably good fit to the empirical data since 1972 (Turner, 2008). World3 results highlight the growing risk of environmental degradation impacting catastrophically on the global population by the mid-21st century. Since the 1970s, there have been tremendous leaps in our understanding of biophysical aspects of the Earth system, some of which have come as a result of our ability to employ numerical methods on high performance computing platforms. As a result, several large integrated assessment models for global sustainability were developed and used to inform major science-policy reports (Hu et al., 2012; Meller et al., 2015; Schmitz et al., 2012). These modelling efforts underline the importance of dynamism and complexity as a defining property of the Anthropocene.

Unprecedented rates of change, complex interactions and new boundary conditions produce new challenges for managing contemporary social-ecological systems. Not least, static indicators of environmental change are now accepted as insufficient to understand the impacts of changing conditions (Jackson et al., 2009). Modelling the dynamical relationships between social, and environmental phenomena is increasingly demanded as part of the evidence base for making appropriate management decisions. We now have the challenge of moving from science-discovery questions to solution-driven questions; from questions related to the functioning of specific systems (process-response relationships, thresholds, tipping points, early warning signals and connectivity), to questions related to management (adapting to future climate change, identifying the unintended consequences of specific actions, or maximizing social-ecological resilience). The management questions can often only be answered through models that successfully capture, and develop from, the former science-discovery questions. Models that combine both are conceptually and technically difficult to develop, and there remains a tendency towards models designed to address management concerns while ignoring feedbacks, thresholds and spill-over effects (Maestre Andrés et al., 2012; Nicholson et al., 2009) or the inverse, models describing the socio-ecological dynamics without any direct relevance to decision-making or management.

There are many roles both for science and management driven models, for example, participatory and learning tools, ex-ante assessment of alternative actions, predictions and projections, and solution-oriented use. Since 1988, the Intergovernmental Panel on Climate Change has arguably done more than any other organization to instil in the minds of non-scientists the potential for science to project likely environmental conditions over several decades. Despite the current political or anti-science impasse, global climate models have provided key information to public or political debates for at least 20 years. The result is a widespread view that similar integrated and scenario-driven models for coupled social-ecological systems could also be readily available to aid decision-making. Associated problems of parameterizing social dynamics, such as individual behaviour, governance and macroeconomic shifts, are profound and probably intractable over the near future (Silver 2012). Complex dynamical systems are inherently unpredictable—especially when they include humans. At the same time, the ability of a model to simulate reality, and provide consistent output results remains a key goal if Anthropocene models are to be useful.

This paper aims to assess the extent to which current models represent the Anthropocene. If humans have become important drivers of Earth system processes then how can we develop a new generation of models that put behaviour and social processes into the machine? How can we avoid models of models that we can no longer understand, or interrogate, or trust? What are the appropriate levels of abstraction and representation given the questions we seek to address? The paper begins with a description of the different uses of models in science-discovery and in the practice of policy formulation and environmental management. Based on the needs of the Anthropocene we next critically review the strengths and limitations of current models. Then we identify ways to better adapt our models to the issues identified and advance on the one hand the relationship between modellers and the users of models, and on the other the technical/design aspects of models.

This article is part of a special issue of Global Environmental Change on "the Anthropocene". The special issue represents a collaborative effort between the International Geosphere Biosphere Program (IGBP) and International Human Dimensions Program (IHDP) to develop an integrated natural and social science perspective of the Anthropocene. Thus, these articles provide forward-looking syntheses aiming at informing socio-ecological systems research on global change and the Future Earth program.

2. Uses of models and simulations

A multitude of models are available that represent aspects of global environmental change. Models differ in scope, purpose and structure. Most models are designed in response to either a science question or a management question, to address a specific spatial and temporal scale and consider varying aspects of the Earth System as exogenous to the model representation. In terms of purpose, such models offer us a simplified understanding of complex system functioning, extending our capacity to study system dynamics. In this perspective, models provide for a virtual laboratory from which to study dynamics of real-world systems, where experimentation is otherwise difficult (Magliocca et al., 2013). In many research projects models act as a platform for integration of findings of different research groups, requiring a structured and quantified specification of individual relations and information exchange between team members from different disciplines (Parker et al., 2002). By comparing model simulations with data over a known period, the capacity of the model to represent observed real-world dynamics provides scientists with insight into the extent that representations and simplifications of the system are successful. Model building and validation are, in this sense, learning tools to iteratively improve our understanding and representation of the dynamics or behaviour of a real world system. The model spectrum ranges from models of reduced complexity, to models that include as many processes and elements that computational resources allow. Models address very different kinds of physical and social processes depending on the time scale, such as in the case of the climate models that are used in IPCC Assessments (Intergovernmental Panel on Climate Change, 2013) and the weather models employed by the World Weather Research Program. A review of part of the range of integrated modelling techniques aimed to address regional and global environmental change is provided by Kelly et al. (2013).

Some models are used to support management and policy decisions, sometimes framed as decision support. However, the differences in questions posed by different stakeholders often require different types of models. In a review of land use models, Brown et al. (2013) note that different model types and model structures address different phases of the policy cycle or environmental management decisions (Fig. 1). Scenarios are used to explore the possible outcomes of uncertain (societal) developments. Such simulations are important in raising policy issues and creating societal awareness of possible future challenges. Scenarios are used to capture some of the assumed range in uncertainty of major drivers of global environmental change such as population, economic development and policy. The models that supported the Club of Rome report (Meadows et al., 1972) and the scenario studies of the IPCC (van Vuuren et al., 2008) and the Global Biodiversity Outlook (Pereira et al., 2010) are good examples of this type of model application. In a policy design phase, models can play a role in designing possible solutions, e.g. the optimal allocation of resources or localization of protected areas (Pouzols et al., 2014). In these cases, models are goal-oriented and often use optimization techniques to design solutions accounting for present and future boundary conditions set by the socio-ecological system (Seppelt et al., 2013). Although such models can account for the constraints associated with the implementation of the prescribed ‘optimal’ management, they do not provide insights in the pathway to achieving these outcomes and are often difficult to align with real-world decision processes. Maybe more importantly, by making simulations they can support target-setting by analysing the trade-offs resulting from alternative ‘optimal’ management strategies. Often clear visions of what is a ‘good Anthropocene’ are lacking and different stakeholders may have conflicting objectives. Visualizing the outcomes of optimized outcomes can help to discuss and revise targets.

Alternatively, models can be used to investigate the effectiveness and unintended consequences of proposed policy measures through ex-ante assessment (Helming et al., 2011). Such models require a detailed specification of the impact and uptake of policy measures on human behaviour, often focusing on shorter, policy-relevant, time frames than scenario models. Especially economic and sector-based models are dominant here as the economic consequences and cost-benefit assessment of the proposed measures are essential in decision making. Finally, ex-post evaluation can combine monitoring with econometric models to evaluate the effects of the implemented policies or management practices (Joppa and Pfaff, 2010).

The different spatial and temporal scales of the processes modelled and mode of decision-making addressed require models to be different in terms of the domain they address, the simplifications made in representing the real-world and the model structure itself.

3. Strengths and limitations of current models to address Anthropocene dynamics

Anthropocene dynamics require models to connect social and biophysical dimensions of the Earth System in terms of complex system dynamics, i.e., the feedbacks and dynamics between the social and natural system components that lead to changes in system functioning (Costanza et al., 2007). Here the Anthropocene is characterized by strong links across spatial and temporal scales. Local decisions have global impacts and global change affects local places and people in different ways. Phenomena occurring over long time-scales impact on decision-making and policy at much shorter time scales and vice-versa, installing path dependencies that are not always explicitly understood. Appropriate models must reconcile different spatial and temporal scales. Finally, dealing with Anthropocene problems requires models that offer insights into the questions posed by a range of stakeholders, and address the concerns of policy makers and society as a whole. How do current models handle these issues and address the questions of the Anthropocene? In Table 1 we have provided a strongly generalized characterization of how (a selection of) existing model types deal with exactly these aspects of socio-ecological systems behaviour in terms of their actual characteristics and potentials. This overview shows the differences between model categories, but also the overall weaknesses in addressing these aspects. In the following we discuss these in more detail.

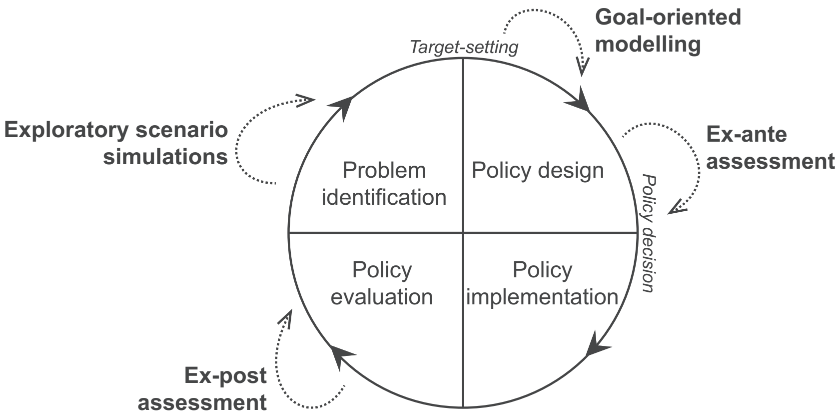

Fig. 1. Differential roles of models in policy and management design and implementation.

Table 1
Generalized representation of the capacity and performance of broad model categories in terms of key indicators relevant to Anthropocene dynamics.

Generic model category	Notable model types	Coupling	Scales	Data and computing	Complex dynamics	Policy tools	Validation and skill
Deterministic process-based biophysical models	Global Climate Models. Earth System Models.	Low potential; social subsystem often represented by plausible pathways and emission scenarios.	Mainly global (20–200 km resolution) and long (decadal) timescales.	Large data and computing requirements.	Theoretically capture feedbacks and emergence in biophysical processes. Lack of feedbacks with other (socio-ecological) system components.	Limited because of high complexity. Scenario results are input in inter-governmental processes.	Difficult to validate. Comparisons against historical data and model inter-comparisons are common.
Deterministic economic models	General and Partial Computational Equilibrium Models.	One way coupling in which biophysical subsystem often reduced to climate effect on the agricultural sector.	Regional to global. Often limited spatial detail (world regions); timescales often limited to several decades.	Large data and computing requirements.	Feedbacks only accounted for through market mechanisms.	Dominant use in ex-ante assessment of policy instruments.	Difficult to validate. Comparisons against historical data are scarce while model inter-comparisons are common.
Reduced-complexity social-ecological models	Integrated Assessment Models. Earth system models of intermediate complexity (EMICs). System Dynamics Models.	Moderate potential but biophysical and social sub-models often simply coupled in an integrated model environment.	Regional to global scale with decadal to sub-decadal timescales.	Somewhat reduced data and computing requirements.	Top-down usually lacking feedback or emergence (some EMICs can simulate tipping points and abrupt changes). Social subsystem often reduced to profit optimization or simple heuristics.	Scenario results are aimed at input into policy processes; models used for ex-ante assessment.	Limited as above. EMICs tested against palaeo-climatic records (e.g., ice core data).
Agent-based social –(ecological) and cellular (social)-ecological models	Agent-based models (ABM), Land use change models	High potential but not frequently implemented.	Generally local to regional scale and relatively short timescales with often annual resolution.	Rule based. Strongly variation in data and computational needs. Strongly relying on either theory or empirical data.	System level dynamics often emerge as a consequence of low level interactions and feedbacks.	Limited application, but examples of participatory use exist.	Either based on ability to reproduce pattern and dynamics or particular empirical data. Increasing focus on validation of system behaviour.
Simple toy social-ecological models	Conceptual models, games	Highly variable but high potential.	Any scale	Mostly low. No use of empirical data.	Able to simulate complex dynamics but with over-simplified assumptions.	Low potential. Learning tools.	Mostly not applicable.

Models are considered a manifestation of our scientific knowledge (or lack thereof) and our technical capacity in terms of modern computational science. Based on progress in both fields in recent decades, models have been advanced to represent our increasing understanding of the Earth system. Major advances have been made in including the increased understanding of atmospheric processes in climate and weather models (Hazeleger et al., 2015), the role of international trade policies in economic models of trade flows between world regions (Hertel, 2011) and in representing social interaction and governance in multi-agent models of local to regional socio-ecological systems (Filatova et al., 2013). Increases in computing performance have facilitated the ever-increasing addition of detail and complexity within models. At the same time, the increasing complexity of these models, often focused on specific aspects of the Earth system, has limited their applicability to support policy processes that require the integrated analysis of multiple aspects of the Earth system at the same time, (e.g. the interactions between climate, water availability, agricultural production, trade and food security).

Reduced-complexity models such as integrated assessment models have been developed to capture a broader aspect of the Earth system dynamics, either by using simplified representations of the different Earth system components or by facilitating the exchange of information with more complex models. van Vuuren et al. (2012) proposed the coupling of integrated assessment models that represent human-environment interactions with more detailed Earth System models that simulate the biophysical processes in vegetation, water and atmosphere. Integrated assessment models are able to address feedbacks between system components. However in many cases, a simple, hierarchical, flow of information between model components is assumed and many underlying drivers of the system are exogenously defined by scenario assumptions or specialized models. Feedback between impacts and the underlying drivers of changes in socio-ecological systems are seldom addressed.

Examples of coupled analysis with integrated assessment models include the analysis of shifts in agricultural production calculated by General Equilibrium Models of the agricultural economy on production patterns and subsequent emissions of greenhouse gases from agriculture under scenarios of assumed economic growth (Hertel et al., 2014). Feedbacks as a result of climate change on the economy are often ignored in such assessments; these would necessarily require dynamic feedback between different models or model components (Dellink et al., 2014). Most integrated assessment models distinguish between the “environmental” and the “social” subsystems of the overall socio-ecological system, and the connections between the two are conceived simply. Moreover, due to lack of quantitative understanding of the social system most models reduce the social system to economic modelling assuming rational decision-making. In reality the environmental and social “subsystems” do not exist independently. We have to deal with one single, massive system in which environmental and societal dynamics coexist and impact upon each other in multiple dimensions and ways, and at a multitude of scales. The early World3 models attempted to simulate continuous, emergent paths using a large number of contemporaneous feedback loops. Integrated assessment type-models do not simulate the path to a defined scenario but rather 'calibrate' the modern system to the boundary conditions for a given scenario based on the projection/modelling of major drivers (e.g. climate, population, land use, global economy etc.). Some of these approaches seem to prioritize the modelling of the drivers over the definition and operation of interactions within the socio-ecological system. We increasingly acknowledge the fact that socio-ecological systems are interacting, adaptive entities governed by feedback mechanisms – and use this in a number of ways to inform management (e.g. through resilience theory). Implementing feedbacks in integrated models is not necessarily technically challenging. Packages such as STELLA, Vensim and Netlogo afford the user the ability to design and find numerical solutions for complex models that feature multiple elements and interactions. What limits such activities is typically model validation and interpretation of results. Such difficulties not only limit the predictive capabilities, but also constrain the assessment of the ways in which resilient solutions and adaptations to changing conditions can best be achieved.

Socio-ecological models are built based on our understanding of real-world systems, grounded in physical laws for the biophysical components, and economic theory and observations for the socio-economic system components. It is likely that as socio-ecological systems change through time new interactions produce new system properties, conditions and states through the process of emergence. Social systems are fundamentally adaptive systems. Human behaviour can and indeed does change over time and such changes can be a result of impacts from biophysical processes that humans have previously interacted with. Since we are concerned about the future of these systems it follows that any research approach should try to capture emergent or evolutionary changes through time if it is to provide potentially realistic and useful findings. Hence, the use of direct cause-and-effect explanations through multivariate statistics of available datasets has to be tempered with the knowledge that the way a system responds to a potential driver is likely to change with time because the network structure and interactions are unlikely to stay constant. When considering new climate-driven river regimes, the next global financial crash, the long-term vulnerability of deltas, or future lake tipping points, the responses in the system that we see are at least partly contingent on the system's history. Major events such as disasters are difficult to predict, but possible to represent with current models, particularly when the focus is on average responses rather than extreme values (Kaufman, 2012). Socio-economic responses after such events may render the behavioural assumptions of the models invalid.

Validation of a model is good modelling practice, but is seen as an extremely complex challenge for integrated and complex system models (Parker et al., 2002). Procedures for evaluation and validation are rarely rigorously applied to the global-scale integrated assessment models used to inform major global assessments due to the lack of consistent time series of empirical data. Guidelines for structuring the assessment process of integrated assessment models have been proposed (Bennett et al., 2013). They include not only the evaluation of final model outputs but also the appropriateness of the model for its particular use and the chosen model structure and specification (Jakeman et al., 2006). Model validation often proceeds on the basis of model calibration so that it is able to reproduce phenomena for which there is reliable empirical data. A physical example of model validation would be a General Circulation Model's ability to reproduce historical weather data over a certain period of time. The central assumption, is that if the model output is within a sufficiently small error margin to empirical data, then the model's skill in producing predictions will be high. However, the equifinality thesis (Beven, 2006) is an important guard rail against ascribing excessive confidence in a model's predictive skill. Equifinality is the principle that the outcome of a system can be achieved in more than one way—there many routes up to the top of the mountain. In a modelling context, equifinality should warn us against assuming that because a model is able to produce output that fits empirical data, it's structure and parameterisation is the most appropriate with respect to either understanding the processes and dynamics of the target real world system, or that the model will produce useful predictions when certain assumptions or starting conditions are altered. The need to evaluate the structure of the model has especially been argued for by agent-based modellers that have replaced strongly simplified representations of human decision making by more diverse and complex decision making structures and interactions between decision makers (Messina et al., 2008; Rindfuss et al., 2008). Rather than be driven by questions such as: what will this system do in the future, agent based models may strive to understand why social systems produce currently observed behaviour. While sometimes coming at the cost of predictive ability over the short time periods used for standard model validation, these models may shed more light on the system response to changes that are outside the range of change on which the models have been calibrated (Castella and Verburg, 2007). Alternative ways of model validation and evaluation may not come at the cost of assessing accuracy and precision (or truth and repeatability) of models. The ability of a model to simulate reality, and the probability of getting consistent output are a key feature of any useful model. At the same time, the need for validation and sensitivity analysis and lack of appropriate validation data should not constrain the development of novel approaches that are not easily validated based on available empirical data. Models should not solely be judged based on their capacity to reproduce short-term patterns (Cooke, 2013). As science grapples with systemic or holistic analyses the idea that everything we need to know is 'measurable' and 'testable' is becoming a barrier to understanding socio-ecological systems. Not only are there critics of rigorous significance testing, but the lack of data (length, resolution) may often preclude the direct mathematical/statistical analysis of real world systems.

4. Modelling the Anthropocene: directions for a new generation of Socio-Ecological Earth System Models

4.1. Reconciling epistemologies

A number of challenges remain in the modelling of socio-ecological systems. First among these, and relatively rarely touched upon, is the fact that the data brought together in many models have been collected by different disciplines, and different schools within each discipline concerned, and often for different purposes. They have been collected with different questions in mind, different disciplinary epistemologies, different methods and techniques. This is both a current and a growing problem, as ever-limited research funding forces us to rely on historical data. We need to develop the practice of systematically extending the meta-data commonly included in databases, to include (1) the questions the data were trying to answer, (2) the methods and techniques used in collecting and in analysing them, (3) the sampling, units of observation, and units of analysis associated with the data, (4) the working hypotheses involved in the research, and (5) a statement about the epistemological status of the information derived from the data.

This challenge is particularly relevant in the current context, to merge natural science (systemic) models with social-science theory, towards the creation of socio-ecological models. In many instances, the contribution of the humanities and (some) social sciences, such as anthropology, cannot easily be integrated into such models. This may be a question of scale, where the data collected by the social sciences is so detailed that it is difficult to generalize from them, and the disciplines concerned have, therefore, focused on individual case studies and instances rather than systemic approaches to distil generalities. It may be a question of profound differences between the epistemologies of the [universalist] natural sciences that have promoted modelling and those of context-based social sciences. The latter have emerged in most countries as a response to specific situations, and have therefore developed methodological and technical as well as epistemological biases that are specific to the communities that carry these disciplines and the issues they are interested in. In particular, many build their analyses and interpretations 'bottom up', around individual cases, rather than using the systems framework as an integrative tool. Over the last twenty years, some of these differences have been stressed in terms of opposing non-positivist humanistic social sciences and the positivist approaches of the natural sciences, thus limiting the involvement of a significant sector of the social sciences in (complex) systems perspective used in socio-ecological system models. This dichotomy, however, is slowly given way to a more multiform, dialogic conception of science in which a diversity of approaches, anchored in different traditions, propose different trajectories forward that are based on the different values and epistemologies of the cultural and scientific traditions involved (Tengö et al., 2014). From that perspective, Castree and colleagues have made an appeal to build a bridge between the GEC modelling sciences and those that directly study the everyday human experience under different conditions (Castree et al., 2014). Often, the argument against that is that this moves science (and in particular sustainability science) away from its 'objective', a-political position and that this will in the end reduce the credibility of the work done and the conclusions arrived at. Once one realizes that science may 'objectively' be answering certain questions, but those questions are themselves subjective, culturally and socially determined, that argument loses much of its attractiveness. Whether we like it or not, our science is socially, culturally and politically anchored. Stirling (2010) proposes to link the different disciplinary traditions by constructing building specific 'values-means-ends' packages. "These are proposals about possible technical and behavioural pathways framed by different, although equally legitimate, conceptions of the 'good society'. In turn, these yield their own definitions of what 'problems' need to be addressed in the first place and what kinds of evidence can speak to them" (Castree et al., 2014). Models can be used as tools to support the design and evaluation of such pathways. In a more traditional manner models can evaluate the impacts and consequences of pathways using scenarios or quantifications of the problems to be addressed. However, in this mode, most current models are likely to fall short as the pathways may include behavioural changes violating many of the assumptions embedded in model structures. Agent Based Modelling (ABM) is a well-established methodology for modelling purely biophysical and socio-ecological systems (Grimm et al., 2006). In ABM human's either at individual or community level can be represented as agents that behave in accordance to a set of rules. Agents interact with and affect biophysical aspects of their environment. Algorithms that allow rules to change over time can capture adaptive elements of human behaviour. Insight into such behavioural changes can help test the system response to such behavioural changes. Alternatively, models may be used in ways that we characterized as goal-oriented modelling in section 2 of this paper. Here the goals are set by the alternative conceptions of a good society (or 'good Anthropocene') and models are used to explore a range of pathways towards those, either by backcasting or by the simulation of a range of scenarios and options to identify which of those bring us closer to the stated conceptions of a good society. Evolutionary computation approaches such as Genetic Algorithms (GA) have been shown to be effective in finding optimal solutions in high dimensional search spaces (Holland, 1992). An example GA approach would involve a 'population' of different scenarios being evaluated in terms of ability to produce desirable outcomes. Small changes or 'mutations' to successful scenarios allow incremental search towards optimal solutions. When normative visions and goal setting are combined with objective simulations based on our understanding of system functioning we can identify the leverage points, problems and barriers to achieving such vision. Although pleas have been made to use models in such ways, few actual examples are available in the literature (Castella et al., 2007; Seppelt et al., 2013). Besides providing options towards solution-oriented use of models such approaches provide options to combine positivist and non-positivist approaches and may thus assist in the process of reconciling epistemologies.

4.2. Moving beyond conceptual models

Much research effort is devoted to the description of socio-ecological systems in terms of causal frameworks or systems diagrams that conceptualize the interactions between different system components. There are many examples of conceptual frameworks which have successfully supported interdisciplinary research, for instance serving as platforms for theoretical integration and multi-scale collaborative research (Ostrom, 2011) or collaborative global assessments (MEA, 2005). There is no doubt that their development is an essential part of any research approach. But our view is that they are granted too much importance in terms of their role in understanding how a system works, in forming a basis for modelling or even in deciding the sequence of research steps. Some causal frameworks (e.g. DPSIR) seem to have gained elevated status as 'official' models in certain quarters, yet can be quite deficient (e.g. using overly rigid definitions) (Maxim et al., 2009; Svarstad et al., 2008). Conceptualizing the real world is important, but we perhaps should remember that more often than not we are simply producing lists of key elements with probable links, and emergence tells us that these may all change through time. Frameworks and conceptual models should be treated as first steps in creating hypotheses that could be tested via a suite of tools and methodologies: they have limited value in their own right because they are the means to an end.

Similar considerations apply to 'integrated modelling platforms'; there are many such frameworks claiming to be easily applicable to many problems/re-usable (Bazilian et al., 2011). In practice the re-use of these frameworks is very limited (Granell et al., 2013). Such structures can be useful in particular instances, but should not enforce a standardized research approach; the questions to be answered with the models are variable and dynamic. Too often, the same integrated assessment modelling approaches are used as a standard approach to make global-scale assessments, irrespective of the question: climate change, biodiversity decline, or the general state of the environment. Although such models may have a generic set-up, they are often not well suited for addressing a specific problem or question and we should avoid defining our research questions by the structure of a (conceptual) model rather than focusing on the societal questions as these are emerging. The tail should not wag the dog! Any model building or application should start with a clear rationale for the choice of a particular model approach or system conceptualization based on the questions and hypothesis of interest. Overall, the design of conceptual models and the structure of modelling frameworks should be used as a tool to structure our current understanding of the system, rather than as a way to develop theory on socio-ecological systems. Both conceptual and operational models should easily adapt to new understanding and different applications rather than being fixed to a conceptual model that has become a paradigm.

4.3. Modelling safe and operating spaces

A significant development in recent global environmental change research has been the concepts of planetary boundaries and safe operating spaces for humanity (Rockstrom et al., 2009; Steffen et al., 2015). The concepts focus primarily on identifying the critical limits or thresholds for major biophysical variables that steer the climate, biosphere and hydrological systems that underpin social wellbeing. For planetary boundaries, the approach has relied mainly on expert judgment based to some extent on earth system models and supported with time-series of global conditions, such as temperatures. At regional scales, identifying the proximity to critical limits has been attempted using a formal definition of system behaviour observed in time-series (Dearing et al., 2014) but the predictive value is low. In contrast, some large-scale climate models appear to show sufficient skill to simulate the conditions under which future critical transitions may occur. For example, the shutdown of the North Atlantic thermohaline circulation (Hawkins et al., 2011) as a result of salinity changes caused by the melting Greenland ice cap. This is one of a number of potential climate-related tipping points that have been identified (Lenton et al., 2008). But modelling safe operating spaces in the Anthropocene to a level that can inform policy thinking will require information about the desirable and undesirable development paths for humanity at a range of spatial scales. For global scale climate conditions, such paths are represented in global climate models by representative concentration pathways (RCPs) for greenhouse gas emissions, but these do not map on to specific combinations of population, economics and ecology. At regional scales, integrated assessment models are often not configured with appropriate feedback mechanisms to generate system instability or critical transitions. Therefore there is a gap between over-simplified toy models that can simulate complex social-ecological change at global scale (e.g (Motesharrei et al., 2014) and global climate models that can capture complexity but only for the climate system. To inform the discussion on safe and operating spaces, there is a need for a new suite of models that moves away from the conventional approach of driving models in the light of particular scenarios forward in time, and instead focuses on stable and unstable social-ecological dynamics associated with alternative development pathways.

We envisage models that could be driven by combinations of different social and biophysical variables representing different socio-economic paths. The models would simulate continuous, emergent phenomena with metrics for system instability, for example the time at which the system shows heightened sensitivity to impacts or when the system begins to break down. This would also afford us the opportunity to conduct early warning signal analysis of model output. The models should be capable of simulating total social collapse (or at least producing dynamics that are moving model output into regions significantly beyond any particular stable state) but the warning signs of transitions are the rationale boundaries. Such simulations would enable a definition of the boundaries for 'safe operating spaces' within model parameter space and by extension the proximity of modern real world systems to future boundaries. Inclusion of social preferences and norms in the social-ecological pathways would allow definition of 'safe and just operating spaces' (Dearing et al., 2014; Raworth, 2012). Thus, we would not only include social processes in Anthropocene models in a response to epistemological concerns – humans have to be in the machine in order for it to function correctly and so give us reliable knowledge about nature – but also to enable the use of models to inform normative discussions. Explicitly including social processes in Anthropocene models allows us to quantitatively explore notions of justice and fairness in the context of a global civilization.

4.4. Feedbacks and emergent properties

In building the kinds of models we need for the Anthropocene, we lack the systematic integrated, trans-disciplinary and in depth knowledge of the feedbacks between the different parts of socio-environmental systems. This lack of knowledge can be attributed to the long, relatively independent history of most of the disciplines involved. At the same time, feedbacks are often intractable—in the sense that they cannot easily be observed or measured. In designing (conceptual) approaches to address feedbacks between the natural science components of models and social science modules, the issue of scales comes to the foreground. The natural, earth and life sciences have in the context of GEC essentially gathered information at local and regional scales and synthesized it to develop models to predict patterns globally. For example, local measurements of nutrient export by numerous rivers in combination with watershed properties are synthesized to develop models that predict nutrient export by rivers around the world (Billen et al., 2013). Global models often focus on predicting general patterns at regional scales, but are not designed to address dynamics at local scales (Verburg et al., 2013). The social sciences and humanities have gathered their information, and synthesized it, at the local scale. Much decision-making and action are at the local scale, and requires ex-ante assessment. At the same time the necessary local scale information is often not available, and there can be cross-scale feedbacks that require models that incorporate those scalar issues. There is thus a need for ways to downscale (provide higher resolution) environmental information, and to upscale the information on societies. The former is complex enough, but inroads are being made in that domain. The latter is much more difficult and probably demands substantive methodological development beyond simple statistical aggregation. Progress has been made in synthesizing the results of local studies worldwide through meta-analysis which aims to find general patterns across cases and the role of context in specific case-study results (Magliocca et al., 2014). However, in the effort of making case-study results comparable, a lot of the richness and specificity of the research is removed leading to a high level of abstraction. Examples of the use of meta-studies to inform global scale models are still scarce, but there is a lot of potential (Alkemade et al., 2009; Magliocca et al., 2015).

When producing representations of real-world systems, we are motivated to abstract away complexities in exchange for tractability. Significant model complexities arise via feedback loops. A affects B which affects C which affects A. The challenge is to incorporate such feedbacks while keeping models computationally tractable and where possible transparent in terms of providing insights and understanding of the processes responsible for model behaviour. All models face two central challenges. First, model structure – what are the important processes to capture? Second, parameterization – how are processes represented mathematically, what are the functional relationships between model components?

The overwhelming number of possible feedbacks in complex systems can cause our models to become overly complex 'Integronsters' (Voinov and Shugart, 2013). Feedbacks make models extremely sensitive to error propagation in which small deviations in initial parameters can lead to large system-wide changes, especially in the case where the feedback is reinforcing itself. Such sensitivity to initial conditions can give rise to deterministic chaos. At the same time, feedbacks are difficult to measure in reality and parameterization of models is therefore extremely difficult (Verburg, 2006). The challenge is to identify those feedbacks that are important for the system dynamics and that have the possibility to change system outcomes. Those feedback mechanisms that enable the propagation of positive impacts of measures are also important. Many of these are found in the societal system, such as environmentally friendly behaviour and emerging environmental governance systems. More complexity is added as result of the emergence of new feedback loops. The emergence of new feedback loops is particularly difficult to either elicit or model, but from an ex-ante perspective, in particular when dealing with systems that have important societal components, it is highly relevant.

In this perspective, the choice of either connecting (existing) modular models through the most important feedback mechanisms or the integral approach of building models of the system as a whole using a single formalism, depends on the strength of the interactions between the different parts of the system and the needs to describe the single system components in great detail. The one approach is not by definition superior to the other, but the linkage of individual modules comes at the risk of an imbalance between the representation of specific elements of the system and the interactions between the system components (Voinov and Shugart, 2013). Studying feedbacks mechanisms per se instead of choosing the individual components of complex systems as basic study objects will enrich our knowledge on the mechanisms involved, their relative importance and possible impacts on system functioning. Models will remain an essential tool as a computational laboratory to further explore and test our understanding of such feedback mechanisms in different contexts.

Another way forward relates to our representation of socio-ecological systems in models. Most often, the units of simulation are directly connected to the variables of interest, e.g. we model land cover change or carbon sequestration. However, these units of simulation are part of larger systems in which the socio-economic and natural aspects are connected. When these systems change, the relations between the variables we model is changing and such system change, or regime shift, is difficult to capture. Regime shifts are well-known in many socio-ecological systems and receive increasing attention in GEC research (Müller et al., 2014). Although such shifts are normally expected to decrease system predictability (Müller et al., 2014) an alternative approach to modelling is to build models that, in their architecture, model transitions between systems instead of changes in the system components. An example is the approach of Van Asselen and Verburg (2013) that use land systems, as defined by specific types of interactions between humans and the natural environment, as units of simulation and, therefore, simulate changes between systems rather than trying to deduct system changes from the underlying variables.

4.5. Connecting local and global dynamics

In the both the debate on different epistemologies, and the discussion of feedbacks, different scales and scalar interactions play important roles. The Anthropocene is characterized by global scale changes in the Earth system function, emerging from local changes in human interactions with the environment. The emerging global challenges translate into impacts on local realities and most solutions to manage these have to be implemented at local scales. This brings about the challenge to represent such cross-scale dynamics in modelling tools. It should be emphasized that, in theory at least, upscaling and downscaling have no inherent strengths and weaknesses—both are important, both are useful, and the only criterion that seems to make sense is the context in which they are applied. We need to ask more often: “When does this particular approach apply, to which data, at which scale, and in response to which question?" rather than talking about strengths and weaknesses in general terms, as if these are inherent in the models and approaches.

In general terms, if we are to address policy-relevant issues in our approaches, we will need to provide a higher spatial and temporal resolution in our models accounting for the scales at which policy making operates. This can be seen clearly in the ongoing shift in the politics of climate mitigation and adaptation. Prompted by the fact that for a long time, the climate and earth sciences were the primary disciplines to study greenhouse gases and their consequences at the global level, the efforts of the UN were directed at finding global solutions to these challenges. But in doing so, they did not take into account that this involved different cultures, different societies and different economies. What was proposed was a uniform solution, a united effort of burden sharing to avoid irreparable damage to our environment. If, on the other hand, the challenge is seen not as an environmental one but as a societal one, then it is clear that not all societies can deal with this in the same manner. The current trend (based on the Lima protocol) of allowing different societies to define their contributions is, from that perspective, much better (but, of course, more difficult to enforce, which in itself points to the fact that this issue cannot be solved by force but requires changing mindsets and motivating people). So, to use models to assist in finding potential solutions to these challenges requires the capacity to represent the local societal dynamics in the context of global processes. Such an approach will also increase the usefulness and possibilities to interpret global model results by people in the different regions. Current large scale assessment models are not often taken very seriously by people in the region because they generate information that is simply not useful at the level.

The concept of telecoupling which describes how local socio-ecological systems are globally connected through processes that operate at a global level (e.g. the global trade system) is useful in this respect (Liu et al., 2013). Representing this concept in models requires structures that go beyond the current tendency to represent local system dynamics by uniform and aggregate rule-sets as is common in most integrated assessment models. Similarly models representing local socio-ecological system dynamics should not simply assume global conditions exogenous to the system analysed as the sum of local responses may feedback on the local system. A few ways have been proposed to better incorporate these multi-scale issues in large-scale models. Most of these, reviewed by Ewert et al. (2011) for agricultural systems, are based on the linking of models operating at different scales in a top-down manner in which local dynamics are simulated in response to higher-scale model dynamics (e.g. Raworth, 2012) (Fig. 2). Bottom-up interactions and feedbacks can conceptually be implemented in such coupled model systems but are only infrequently operationalized due to the complex and iterative interactions between models that would become necessary. Alternative approaches of capturing cross-scale dynamics by a more explicit representation of the scalar dynamics in a single approach have been given much less attention (Ewert et al., 2011; van Wijk, 2014). Some have warned that cross-scale dynamics are probably highly a-symmetric: where the importance of effects going up in scale (from land user up to global trade flows and climate change) are likely to be relatively weak, the feedbacks from the global processes down to local land users are very strong (e.g. price changes, regulations, subsidies, etc.) (Giller et al., 2008). However, while we agree on the a-symmetry of these cross-scale dynamics these are strongly depending on the process characteristics and societal context.

To achieve a better integration of local socio-ecological system dynamics in models the representation of human agency and decision-making is an essential component (Rounsevell and Arneth, 2011; van Wijk, 2014). In most global scale models human agency has been reduced to simplified, rational choice algorithms for the individual level which are applied to the average conditions over a large geographic area. Alternative approaches to the inclusion of human agency in large-scale models have been suggested (Rounsevell and Arneth, 2011; Rounsevell et al., 2014). One approach is based on the representation of individual decision making by outscaling of agent-based models (i.e., representing all individual agents also for large scale applications) using the merits of enhanced computational capacity (Lysenko and D'Souza, 2008). The advantage of this approach is that the local dynamics are represented at the scale of the decision makers. For large-scale applications this approach is highly demanding in terms of data and computational capacity. Agent-based models that are representing individual decision-making are, therefore, not often applied beyond the level of small regions. Some efforts to go beyond these small scales are currently underway, such as a project to construct a national-scale agent based economic model in which macroeconomic dynamics emerge as a consequence of the interaction of large number of individual agents and interactions (Farmer and Foley, 2009; Klimek et al., 2015).

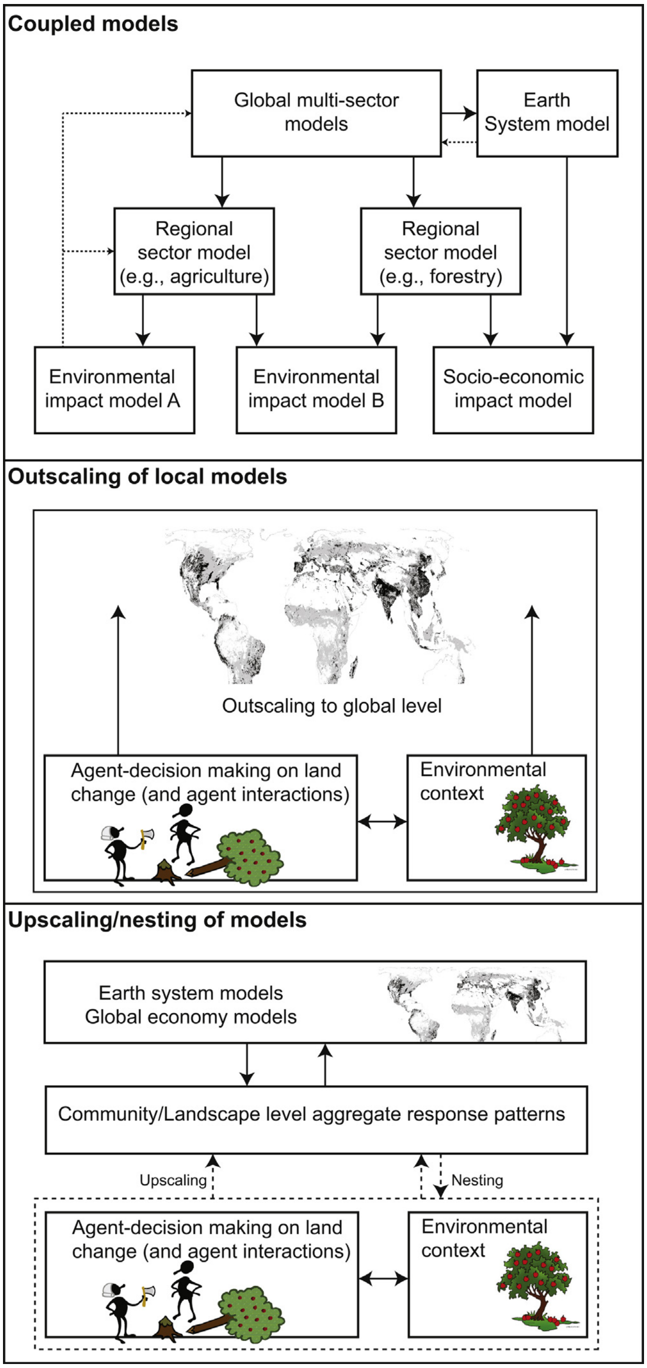

Fig. 2. Alternative approaches of modelling multi-scale processes.

An alternative approach is the upscaling of local dynamics through the identification of aggregate response patterns that are based on the scaling of local responses. Instead of representing the behaviour of individuals the agency (aggregate behaviour) of communities is captured while still retaining the differential characteristics of these communities based on their composition and socio-cultural context (Dobbie et al., 2015). Upscaling may also be achieved through nesting detailed models at individual level within a more aggregate model to derive aggregate responses. This approach to scaling local human decisions and responses is comparable to the approach taken in the more physical Earth system Models of Intermediate Complexity (EMICs). EMICS use a combination of techniques (selection of processes to be represented; representation of aggregated responses rather than simulating individual underlying processes) to capture those processes that are essential to capture the Earth System dynamics of interest (Weber, 2010). At the same time, the increasing global connectedness of locations (telecoupling) does not rule out that a lot of decision making by individuals is still place-based and responsive to local conditions. While food, energy and information can be transported worldwide, humans rely on many ecosystem services that are provided regionally (clean water, regulation of flood risk) or locally (recreation opportunities, cultural services). Model approaches that aim at capturing both the regional and global processes as well as the local responses to environmental and socio-economic change have to go beyond coupling existing models. This will likely require new model architectures with a strong focus at capturing these multi-scale responses of human to environmental change.

4.6. Co-designing models

While models are mostly used as tools for researchers aimed at expanding the mental capacity to explore system functioning, the concept of the Anthropocene also provides new perspectives and demands on modelling in terms of the interactions between the users and creators of models and society as a whole. Fig. 3 provides an overview of the different ways in which science and society may interact in the context of the design and use of models. Co-design and co-production of research has become important in global change research (Cornell et al., 2013). This also has repercussions to modelling. Co-design of research questions may change the nature of the questions and, therefore, have consequences for the suitability of the modelling tools available. While many modelling tools are built from the perspective of exploring system function they may not be able, or not optimally designed to answer questions that emerge from the interactions between researchers and stakeholders. Research models need to be transformed into operational models and choosing the right model for the question at hand becomes even more important (Kelly et al., 2013). Apart from co-designing models to better address societal questions co-design should also involve data-gatherers and non-modellers in the design process. This way, model design can be better matched to available data, and data collection to the model needs. Moreover, there is room for fruitful interactions with non-modellers in the efficacy of modelling and for modellers to use appropriate input data, better interpret and understand model output to jointly gain greater insight into social-environmental dynamics. van Delden et al. (2011) describe a possible workflow for better connecting models and stakeholders in a decision support context while Hamilton et al. (2015) discuss the differential roles of stakeholders and modellers.

Beyond embedding modelling tools in the co-design process there are also opportunities for co-production of knowledge with models. Citizens can contribute information to models on those aspects that are difficult to measure with traditional observatories. Citizen observatories or crowd sourcing have the potential to contribute information on individual decision making or local environmental conditions that is not available in census data or spatial datasets, but essential for representing the socio-ecological system or parameterizing the models. Such data may be used to design model structure, as well as parameterize or validate models (Enenkel et al., 2015; Magliocca et al., 2015; See et al., 2015). Citizens can thus contribute to model implementation and validity, but at the same time they may benefit from the information by being provided with updated information on their environment, thus ensuring an interactive flow of information and true co-production of knowledge. A close interaction between scientists and stakeholders is also found in companion modelling approaches. Bousquet and Le Page (2004) describe ways in which models have been used as a platform for negotiation between stakeholders on natural resource management. Stakeholders jointly build the model and analyse alternative management options, thus achieving joint learning and actionable knowledge of the socio-ecological system they are part of.

Co-production approaches are used in decision support systems in which the algorithms are updated with stakeholder input during the process (Eikelboom and Janssen, 2013; Vonk et al., 2005). However, often the models embedded in these systems are highly linear and simplified, lacking some of the important processes that characterize Anthropocene dynamics. Thus, decisions taken based on such processes may disregard potential feedbacks and externalities. In that respect, there is the risk that stakeholder involvement can drive model simplification in order to aid transparency to the extent that important processes are disregarded. In spite of the advantages of simple models such approaches may limit progress in capturing complex system dynamics (Evans et al., 2013). Some models are completely based on stakeholder perceptions, such as models based on fuzzy cognitive maps (Kok, 2009). These build on the implicit assumption that stakeholders have the best information on system function and a formalized representation of that information in a model enables us to explore future system dynamics. In spite of the richness of stakeholder knowledge, there is a risk of including bias due to stakeholder perception of system function or an oversimplification of dynamics that may cause undesirable system outcomes if policy and management decisions are based on these.

4.7. Model architectures

Most models are written to be stand-alone. Such software defines and initializes variables and arrays, reads in input data, runs the program to generate realizations according to its discretized algorithms, writes out its output, and ends the run. The disadvantage is that investments in re-designing all model components make the development of new models extremely expensive. This is one of the

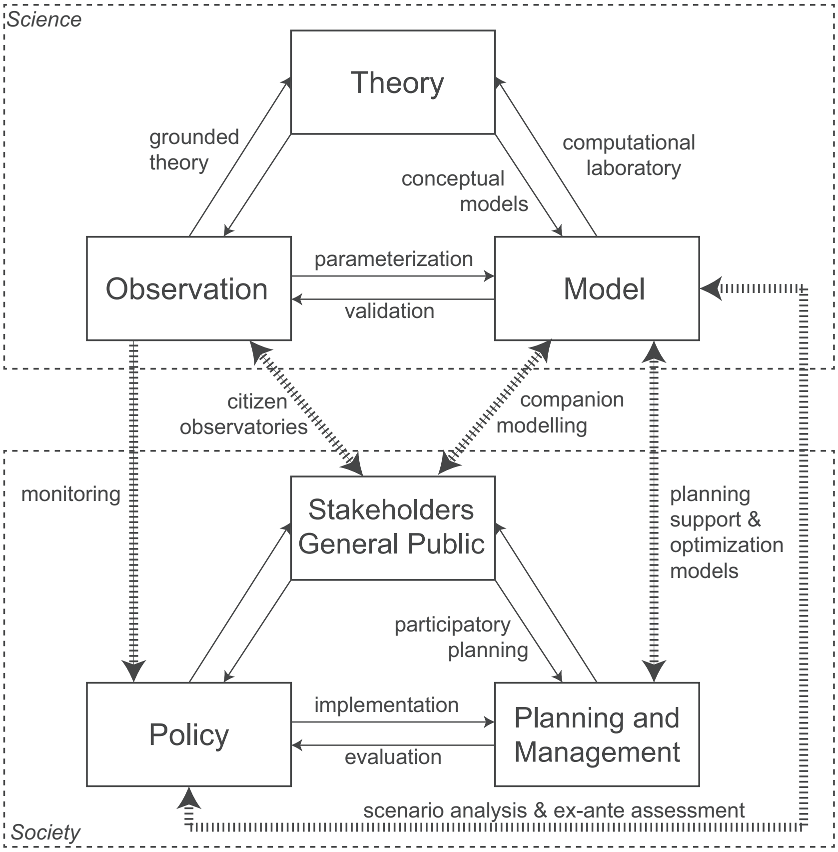

Fig. 3. Overview of different interactions between science and society related to modelling.

reasons why there are relatively few different integrated assessment and Earth System models. To tackle the challenges outlined in this paper a diversity of approaches is needed, which is hampered by the costs of building such approaches from scratch. Component-based modelling brings about the advantages of "plug and play" technology. Models wrapped as components become functional units that once implemented in a particular framework can be coupled with other models to form applications. Frameworks and architectures additionally provide the necessary services such as regridding tools, time interpolation tools, and file-writing tools. A model component can communicate with other components even if they are written in a different programming language (Syvitski et al., 2013).

Most earth-surface dynamics models advance values forward in time on a grid or mesh and have a similar internal structure: an initialize step, a run step, and a finalize step. Virtually all component-based modelling efforts employ this Basic Modelling Interface or BMI specification (Hill et al., 2004; Peckham et al., 2013; Syvitski et al., 2013). The interface identifies entry points into software components to provide a calling application with the level of control over the components that is necessary for two-way model coupling.

Plug-and-play component programming benefits both model programmers and users. Using a framework, a model developer can create a new application that uses the functionality of another component without having to know the details of that component. Models that provide the same functionality can be easily compared to one another simply by unplugging one model component and plugging in a similar model. Users can more easily conduct model inter-comparisons, or build larger models from a series of components to solve new problems. Modelling frameworks allow automated coupling of models and data from different contributors, but this implies that semantic mediation or matching is required. To ensure that one model's output variable is appropriate for use as another model's input, a precise description of the variable, its units and certain other attributes are required. Standardized names avoid domain-specific terms and abbreviations, are based on a set of rules or conventions and are designed to eliminate ambiguity.

Plug and play modelling with its use of standards, interfaces and semantics offers insight on how Anthropocene models might be developed and coupled, suitable for investigations on our human footprint on the global, regional and local environment. Hurdles of the past few decades such as incompatible computer languages, or computational platforms (e.g. laptops versus high-performance computing clusters or even distributed and cloud computing), and problems of scale beyond simple nesting approaches, have become greatly reduced. Focus, then, returns to model development and creative application. However institutional momentum also remains a hurdle. Large research institutes are the purveyor of large 'Earth System' models—monster codes nearly impossible to break up into smaller components, and requiring state-of-the-art computational platforms offering Petaflops to Exaflop, and under the purview of a master(s) of the code. Smaller institutions, less tied up in these expensive workflow systems, will likely lead the way in plug-and-play Anthropocene modelling.

5. Conclusions

Models play different roles in scientific investigation and management of Anthropocene dynamics. Disciplinary history, different epistemologies and the dominant role of conceptual models have caused the typical characteristics of Anthropocene dynamics to be underrepresented in operational models. While integrated assessment models currently dominate model-based explorations of Anthropocene dynamics they are not fully equipped to represent emergent patterns, regime shifts and cross-scale dynamics. Rejection of modelling due to the above-mentioned failures is not productive. Advancing beyond the obstacles starts with the recognition that modelling is a tool like any scientific method and not a goal in itself. To advance our understanding and develop models that are capable to support solution-oriented research for Anthropocene problems novel system representations that focus on the representation of feedbacks between socio-ecological systems across different scales and the representation of human processes such as environmental decision making, adaptation to climate change and migration need urgent attention. A pluralistic approach that tests different alternative model structures is required as no single approach will be capable of fully covering the complexity of socio-ecological system dynamics. At the same time, each approach has its own inherent strengths and limitations and is capable to support certain uses and address some of the different questions and challenges posed by the Anthropocene.

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