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Closing the loop: Reconnecting human dynamics to Earth System science

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Abstract

International commitment to the appropriately ambitious Paris climate agreement and the United Nations Sustainable Development Goals in 2015 has pulled into the limelight the urgent need for major scientific progress in understanding and modelling the Anthropocene, the tightly intertwined social-environmental planetary system that humanity now inhabits. The Anthropocene qualitatively differs from previous eras in Earth's history in three key characteristics: (1) There is planetary-scale human agency. (2) There are social and economic networks of teleconnections spanning the globe. (3) It is dominated by planetary-scale social-ecological feedbacks. Bolting together old concepts and methodologies cannot be an adequate approach to describing this new geological era. Instead, we need a new paradigm in Earth System science that is founded equally on a deep understanding of the physical and biological Earth System – and of the economic, social and cultural forces that are now an intrinsic part of it. It is time to close the loop and bring socially mediated dynamics explicitly into theory, analysis and models that let us study the whole Earth System.

Keywords

coevolutionary dynamics, complex adaptive networks, Earth System analysis, Earth System modelling, human agency, planetary boundaries, safe and just space for humanity, sustainable development goals

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Introduction

By pushing Earth's climate and biosphere out of the dynamics of the Holocene (Steffen et al., 2015a) humanity is at risk of moving our planet outside a safe operating space for humanity by altering important feedback loops, potentially producing abrupt and irreversible systemic changes with impacts on current and future generations (Steffen et al., 2015b).

From the start, Earth System science has recognized that humans are an important component of the contemporary system (Mooney et al., 2013; NASA, 1988). Integrating natural and social science perspectives on the Earth System has been a key aim of a suite of research initiatives over the past decades (e.g. AIMES, IHOPE, International Human Dimensions Program and Future Earth). Despite these efforts, key characteristics of the Anthropocene – human agency, global social and economic networks and important feedback interactions between human systems and planetary processes – have not been *dynamically* represented or otherwise resolved in existing Earth System and integrated assessment models.

Capturing these dynamics in a new generation of Earth System models should allow us to address a number of critical questions about socio-ecological turbulence in the Anthropocene, such as: Could transnational social movements such as the push for divestment from fossil fuels tip the socio-economics of carbon emissions? How is climate change science processed in world cultures and traditions other than those of the secular West? How are climate tipping events such as in the West Antarctic Ice Sheet interlinked with social and political transitions?

The biggest challenge in answering such questions is to understand human activities and social structures as the least predictable, but at present also the most influential component of our planet in the Anthropocene. This would, finally, contribute to closing the loop in theory, analysis and models of Earth System analysis (Future Earth, 2014; Schellnhuber, 1998, 1999).

To meet this challenge, Earth System analysis requires significant progress in three key areas forming the systemic substratum that many pressing, real-world sustainability questions have in common (Figure 1).

First: How best to represent human agency?

There is a long tradition of philosophical, anthropological, sociological and psychological research on the nature and degree of human agency, i.e. to what extent are humans free to act and what is the structure of the factors that constrain them. This has produced a wide variety of schools of thought, ranging from assumptions of substantial freedom of choice to behaviour within social norms and economic rules (Ajzen et al., 1991), to no agency at all (e.g. physics-based theories of social macrodynamics; Garrett, 2014, 2015). Here, we are primarily motivated to understand how this broad spectrum of (socially and structurally differentiated) human agency and behaviour can be appropriately included and evaluated in Earth System models. Our starting assumption is that we need to go substantially deeper than the common scenario approaches used in current Earth System modelling, where the dominant underlying social narrative is driven by macroeconomic optimization paradigms. These approaches, whilst computationally efficient, will necessarily exclude a wide spectrum of behaviours. Consequently, we call for new narratives of global change based on the fundamental *dynamics* following from different assumptions about human agency, and within such analysis for differentiation by social groups.

Second: What are the system-level effects of social networks?

The social is networked. Social interactions are mediated via information, trade, political and infrastructure networks. Such networks can change over time via adaptive, anticipatory and preference

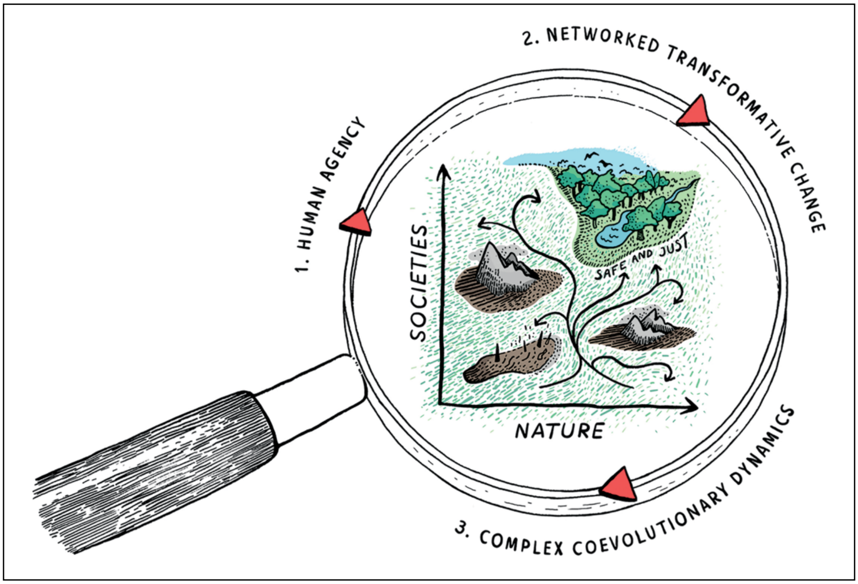

Figure 1. Closing the loop. Understanding and modelling the Anthropocene, the tightly intertwined social-environmental planetary system that humanity now inhabits, requires addressing human agency, system-level effects of networks and complex coevolutionary dynamics. The loop sheds light on a coevolutionary view of Earth System dynamics (Schellnhuber, 1998, 1999) in the Anthropocene including multiple development pathways, obstacles (mountains), dangerous domains (spikes) and the sought-after safe and just space for humanity (oasis).

formation processes. The dominant existing conceptualizations of Earth System loops – essentially using the same rigid box-and-arrow wiring diagram developed by the Bretherton Committee (NASA, 1988) – are no longer fit for purpose when the magnitude, direction of flows, and even composition of the components of the socio-environmental system are changing. Transformative phenomena such as the Great Acceleration (Steffen et al., 2015a) cannot be fully understood without digging into the network structure of the Anthropocene such as the wide-ranging teleconnections that emerge in land use change (Seto et al., 2012) and are the essence of digital communication between people. Earth System analysis needs to recognize that values and norms shape human behaviour, leading to changes in Earth System functioning with feedbacks to behaviours, values, and norms. This is a coevolving social-environmental network with an indisputably very rich structure.

Third: What tipping points and complex dynamics arise from social-environmental loops?

Even simple nonlinear systems can surprise us with our mostly linear thinking; even more so highly complex systems such as the Earth's climate. It is to be expected that social-environmental networks that feature myriad feedback loops will exhibit a wide range of complex behaviours. From observational records and modelling we know that there are several global-scale tipping elements in the climate system (Lenton et al., 2008; Schellnhuber et al., 2016). Even richer complex dynamics are expected and observed in the social sphere on comparably fast timescales (Bentley et al., 2014), particularly when interactions in the Anthropocene alter and strengthen feedbacks between biogeophysical and social processes. Research and assessments ignoring the loops between and within these two spheres will inevitably overlook critical phenomena such as emerging multi-stabilities and tipping points. Models that allow for a systemic view that classifies potential pathways and identifies critical parameters, management options, windows of opportunity and dilemmas (Heitzig et al., 2016) represent important additions to studies more focused on quantification and prediction of individual trajectories.

A complex systems view of the Anthropocene

Effects that may arise even in simple systems due to complex dynamics may be illustrated for the case of a deliberately elementary representation of decarbonization in the energy sector. A dirty (CO_2-emitting) and a clean (e.g. sustainably renewable) energy technology compete while their market penetration can be influenced by a managing agent through subsidies. This is a hugely simplified case of the more general problem of multiple technologies, multiple economic incentive systems, non-economic values and, particularly, of a large number of interacting networked agents with different objectives and means. However, already this simple case system reveals non-trivial effects not usually taken into account in integrated Earth System modelling (Figure 2):

(i) A rich landscape of possible pathways exists that are sensitive to parameter settings and initial state. The cost-optimal pathway, an example of the imposition of a utility to be optimized (a very common practice in the analysis of such problems), is but one pathway toward a desired state and gives a rather incomplete picture of the dynamical landscape in which a manager is to operate. Closing the loop requires socio-ecological systems analysis. What is more, what is considered 'desirable' can differ among networked agents and potentially lead to conflict. Closing the loop means better inclusion of plurality of worldviews, priorities and objectives.
(ii) Large areas of parameter space form basins of attraction: pathways within these basins approach an end state that could have desired properties, but could also be an undesired state, underlining the importance for a manager to understand the structure of the dynamical landscape. Closing the loop means considering agency that is more multi-dimensional than single-purpose optimization, i.e. to follow broader concepts that allow potential access to a larger subset of trajectories.
(iii) Pathways toward a desired end state do not always initially lead in the direction of this state but can counterintuitively follow less obvious dynamical routes (which presents a problem to politics measured as short-term success). Along these lines, some paths that lead to desired end states have to temporarily traverse intermediate states with undesired properties (the situation must get worse before it will get better). Closing the loop requires a broader temporal perspective which may challenge short-term thinking in governance and policy making.
(iv) Pathways optimizing a given utility may display the phenomenon of 'optimizing to the edge', i.e. they tend to follow the edge of domains bordering undesired states, rendering them vulnerable against fluctuations that may tip them into neighbouring, less favourable domains of attraction. Closing the loop informs notions of desirability by explicit consideration of the resilience of trajectories.

This illustrative list of phenomena arising even in this simple example suggests that dilemmas in governing complex systems such as the global human–environment system (Heitzig et al., 2016)

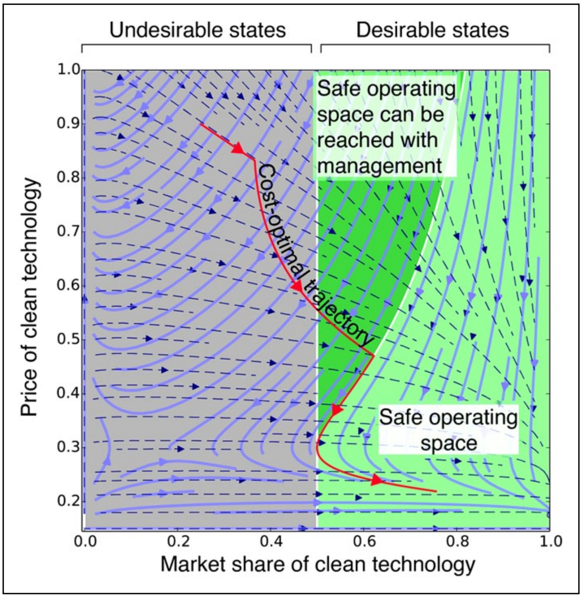

Figure 2. Complex dynamics arising from a conceptual model of decarbonization transformation. Mapping of trajectories in a dynamical system model of an energy market with competing dirty and clean technologies that can be influenced by subsidizing the clean technology (management). Business-as-usual trajectories without management (solid lines) as well as pathways with management (dashed lines) are shown. In this example, a market share of the clean technology larger than 50% is normatively considered as desirable. Background colours indicate state space regions such as the *safe operating space* (*shelter*, light green), where trajectories can remain in the desirable domain without management, or the region from which the *safe operating space* can only be reached through desirable states when applying subsidies (glade, dark green), following Heitzig et al. (2016). A typical cost-optimal pathway as generated by integrated assessment models is indicated by the red line.

require particular insight into three aspects of such dynamic landscapes. First, at issue is to what extent human intervention can alter the pathways upon which societies and the environment develop, i.e. what agency different types of agents have to manoeuvre on the landscape of trajectories, and what the instruments are to achieve this. Second, since humans act collectively as social groups on environmental processes and these are equally characterized by hierarchical interconnectedness, the macroscopic effects of coevolving complex networks on dynamic pathways have to be explored. And third, the topology of these dynamic landscapes has to be discovered as opposed to dissecting thin policy slices – this will require complex systems analysis, particularly regarding separation of domains of attraction, regions with steep gradients and faults, and critical dependence on key parameters.

Conclusion

We have shown how a simple model that explores trajectories towards decarbonization can produce complex behaviour and multiple outcomes, highlighting issues of agency over paths and of resulting complexity in the dynamical landscape of accessible paths. As such, this analysis demonstrates the utility of taking a complex systems, coevolutionary approach to dilemmas of the Anthropocene. This example highlights the first and third key area identified above. It is to be expected that further complexities would arise by factoring in the collective effects of social networks on multiple agents and their interactions.

If science is to provide robust and useful input into this and other dilemmas that arise as a consequence of the transition to the Anthropocene, then Earth System models must embrace wherever possible these three areas: representation of socially differentiated agency, social-economic networks and complex coevolutionary dynamics. This would produce useful models of the Anthropocene (Donges et al., 2017; Verburg et al., 2016).

We see examples of such approaches emerging. For example, theory and models of biogeophysical dynamics in the Earth System are well established, and recently developed adaptive network approaches (Gross and Blasius, 2008) offer a flexible framework for modelling social-environmental regime shifts and transformations in an emergent and dynamic way without static prescription of scenarios, including phenomena such as social learning, segregation, norm and value change, and group dynamics such as coalition formation (Auer et al., 2015; Schleussner et al., 2016). Our vision for Earth System analysis calls for a synthesis of these so far disconnected phenomena within a complex systems framework.

The Paris climate targets (UNFCCC, 2015) and United Nations Sustainable Development Goals (UN SDGs, 2015) are examples of humanity's ambition to remain within a safe operating space at the same time as continuing to increase the wellbeing of the global population. Earth System science should play a critical part in this endeavour. To do so it must connect the behaviour and impacts of humans to biophysical processes and seek to understand the resulting very rich dynamics. We have existing tools and approaches to study such phenomena. Such analysis offers significant potential to augment existing models and methodologies and so help humanity chart a course towards a desirable Holocene-like Anthropocene.

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