

Review of manuscript titled “Towards modelling the World-Earth System: A Systematic Literature Review of the State of the Art and Ways Forward”

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I am pleased to review this manuscript [1] and commend the authors for their valuable and timely systematic review of the literature. I also appreciate their choice of an open review format. The authors conclude that “high fragmentation and segregation of the field seems to currently inhibit cross-community interactions and learning” and I strongly agree with this conclusion and hope that the open review process can begin to facilitate an urgently needed cross-community discussion and reorientation of the field.

The review suggests that future research should focus on four priorities and I will organize my comments around these four priorities but start with an overview to frame my subsequent comments. As shown in Figure 1, our globally connected, planetary-scale problems form a coherent family or class of Anthropocene challenges [2-4]. Building on this unified and massively complex planetary-scale problem, it appears obvious that we need to break it up into several pieces, study the pieces separately, and then put them together again to address the problem. We can think of this as a “system of systems” perspective, as shown in Figure 2, where we have broken up the problem into an initial system of 20 Anthropocene systems.

For a unified and massively complex planetary-scale problem, it appears obvious that we need to understand what caused the problem and what gave rise to the current form and function of the system of Anthropocene systems. This includes understanding the prevailing causal coherence across scales because we need to coordinate multiple interventions across multiple scales to address the planetary-scale problem and the resulting perturbations will cascade across all Anthropocene systems and scales. We can think of this as an “evolutionary” perspective, as shown in Figure 3, where we take advantage of the deep evolutionary trajectory and coevolving nature of Anthropocene systems, helping us to understand how the systems generally increased in complexity and became more tightly connected and how the ensuing family of Anthropocene challenges emerged as a result of the coevolutionary mechanisms.

Finally, for a unified and massively complex planetary-scale problem, it appears obvious that we cannot break it up into tens of thousands of pieces and study them all separately in different research groups and disciplines and research communities and cultures and nations and cities around the world (which is essentially the current situation) and then imagine that we can somehow bring all these pieces back together again in a coherent and scientifically falsifiable fashion. Based on our recent critical reviews [2-4] as well as these common-sense arguments, it should be clear that the global scientific community urgently needs a more viable approach to frame and address the family of Anthropocene challenges.

The evolutionary, system-of-systems perspective led us to propose five elements in our evolutionary, system of systems (evoSoS) convergence paradigm [4]: (1) Causally coherent,

scientifically falsifiable **theoretical framework** characterizing a system of Anthropocene systems within a planetary-scale meta-ecosystem; (2) Cross-scale, modular, hierarchical, dynamic **conceptual models** of the Anthropocene systems that are based on a common language and that reconcile disciplinary ontologies; (3) Common **computational frameworks** that build directly on the conceptual models and that are agile, extensible, and scalable; (4) Coherent **decision-support system** used to interact with conceptual models and computational frameworks, enabling effective integration of a wide range of stakeholder perspectives spanning multiple scales and organizational levels; and (5) Comprehensive **educational pedagogy** to train a new generation of Anthropocene systems integrators to develop and implement the paradigm.

Conceptually separating the first three elements means that we can work on them separately, as is usually done in science, and will need to be done in a global research community, with a theoretical framework that leads to conceptual models that are subsequently used for simulation. We have proposed that the systems modeling language (SysML) can be used as an initial common language that reconciles disciplinary ontologies and that hetero-functional graph theory (HFGT) can be used as the computational framework that can build directly on the conceptual models (expressed in SysML), in an agile, extensible and scalable fashion [2-4].

Building on the preceding overview, I will provide some additional comments on the four research priorities proposed by the authors.

The first priority is to “broaden the representation of socio-cultural processes and actor types beyond households and consumers, explicitly including institutions, governance systems, and their interactions.”

I agree that this is the most important priority. As emphasized in our recent reviews [2, 4], a theoretical evolutionary framework founded on an understanding of how Anthropocene systems coevolved and became increasingly interconnected, is crucially important when relating Anthropocene systems to human cognition, communication, and the resulting human behavior, because it was the evolution of the human brain, combined with the evolution of culture and technology, that drove the evolution of the Anthropocene. The way we think, the way we communicate, and the way we make decisions and transform decisions into behavior, all influence, and are influenced by the coevolving geophysical, biophysical, sociocultural and sociotechnical systems in which our lives are entwined. Unfortunately, the interdependent relationship between human behavior and context has largely been ignored, but the evoSoS convergence paradigm enables the integration of behavioral science – including the physical, social, and evolutionary contexts that shape perception, deliberation and inferential reasoning – with the geophysical, biophysical, sociocultural and sociotechnical context in which the behavior occurs [2, 4].

As we have emphasized [2, 4], a major coordinated initiative is needed to develop cross-scale models of sociocultural systems, and their causally coherent connections with other Anthropocene systems. While all causal influences are clearly not equally important, human behavior influences, and is influenced by, the globally connected system of Anthropocene systems. An outline of a more generic model of a sociocultural system has been proposed [2, 4], with social dynamics that involve individuals, groups, and groups of groups, providing a way to

scale these interacting systems coherently. Indeed, there is growing recognition that a complex systems approach is required to represent the multiscale, multidimensional, dynamic and interacting nature of sociocultural systems. To be successful, however, we must overcome the fragmented nature of research on human behavior enabling a more coherent integration of sociocultural systems and their causally coherent connections with other Anthropocene systems (see Figure 2) [2, 4].

Human behavior is profoundly complex and is not conceptually tied to specific Anthropocene systems. If all we have is myriad context specific models of human behavior, how can we coherently combine them when representing a coevolving system of Anthropocene systems. We clearly need to include cognitive, communication, education, economic, legal and governance systems (see Figure 2) as we frame and address Anthropocene challenges, but current models and approaches for these systems are seldom based on a causally coherent evolutionary framework. In addition, there is growing concern about ideologically driven research and the replication crisis. The only credible way forward is to focus on scientifically falsifiable research, but this requires a causally coherent theoretical framework, otherwise falsifiability is difficult to establish, and the results cannot be applied to other systems and disciplines. Finally, cultural norms and institutions generally emerge as a function of sociocultural group dynamics, and there are no generally accepted values that apply universally across all cultures. We need only think of the current global situation where polarization is rapidly evolving in many parts of the world, with interactions (cultural evolution) among individual leaders and their followers strongly influencing and being influenced by the coevolution of other Anthropocene systems with alarming global ramifications. This is by no means an exhaustive argument, but it illustrates some of the profound difficulties we face as a global scientific community when trying to include sociocultural processes to more reliably address Anthropocene challenges, as elaborated in our recent reviews [2, 4].

The second priority is to “explore more diverse bidirectional feedback and their interplay, shifting attention beyond climate change towards a broader set of planetary boundaries.”

I also agree with this priority, but adding bidirectional feedback is not easy unless we have a causally coherent, scientifically falsifiable theoretical framework characterizing a system of Anthropocene systems within a planetary-scale meta-ecosystem. I also agree that attention needs to shift beyond climate change and believe that a broader set of planetary boundaries is consistent with the family of Anthropocene challenges outlined in Figure 1.

The third priority is to “develop modelling approaches that can explicitly represent the emergence coupling of social and biophysical tipping dynamics and their cross-scale interactions - for example through hybrid formats combining agent-based and system dynamics approaches. At the same time, no model should aim to be a jack-of-all-trades: model complexity should be guided by the research question and grounded in existing empirical and theoretical knowledge across disciplines and approaches, spanning social sciences, and psychology, environmental sciences and physics, as well as place-based and context focused research and global system thinking.”

I again agree that we need modelling approaches that can explicitly represent the emergence coupling of social and biophysical tipping dynamics and their cross-scale interactions, but caution that system dynamics has significant limitations compared to SysML and HFGT [5]. Indeed, the proposed World-Earth Model Design Principles are necessary but not sufficient. For example, tipping dynamics are only reliable if we are sure that we have identified the dominant mechanisms that cause the tipping, but the approach will lack credibility if the models are not causally coherent and if many of the important systems are ignored. Another major limitation is the need to reconcile disciplinary ontologies [3, 4]. The five elements of our evoSoS convergence paradigm are what we currently believe to be sufficient, but these could be revised with further research. In addition, the five elements are expressed in relatively abstract form. For example, they do not specify the nature of the causally coherent, scientifically falsifiable theoretical framework characterizing a system of Anthropocene systems within a planetary-scale meta-ecosystem. Neither do they identify the specific Anthropocene challenges, systems and scales, although initial examples are provided in Figures 1, 2 and 3. Similarly, the specific common language and modeling framework are not mentioned in our five elements, but we believe that SysML and HFGT have great potential [3, 4]. For example, the methodology is currently being deployed by CSIRO's [National Energy Analysis Centre](#) to coordinate Australia's clean energy transition.

The fourth priority addresses “the high fragmentation and segregation of the field which currently inhibits cross-community interactions and learning. Fostering scientific exchange between the research communities could help to increase the understanding of global Anthropocene social-environmental dynamics from the combination of different perspectives.”

As already emphasized, I appreciate this valuable and timely systematic review of the literature as well as the open review format and hope that the open review process can begin to facilitate an urgently needed cross-community discussion and reorientation of the field.

Finally, my comments so far have focused on proposed “ways forward”, but with regard to the details of the systematic literature review itself, it would be useful if brief sections could be added that cover stakeholder engagement and pedagogical approaches (see elements 4 and 5 of our evolutionary, system of systems (evoSoS) convergence paradigm [4]). These are both crucial topics which can either severely inhibit or strongly facilitate the coherence and integration of the field. Perhaps most important, a common language that reconciles disciplinary ontologies provides essential support for the five elements of our evoSoS convergence paradigm, including theoretical framework, conceptual models, computational framework, decision-support system [6], educational pedagogy and team science [7] and the required communication, coordination, capacity building and collaboration that are essential for success [4].

Societal challenges of the Anthropocene
Stabilize carbon emissions
Manage the nitrogen and phosphorus cycles
Reduce waste in a circular economy
Adapt to climate change
Prepare for and manage pandemics
Upgrade adaptive infrastructure for urban populations
Feed a growing global population sustainably
Clean the world's oceans (plastics and dead-zones)
Supply human needs for energy sustainably
Provide healthy living environments
Prepare for and respond to multiple disasters
Improve governance of the global poly-crisis

Figure 1. A family or class of globally connected **Anthropocene challenges** [2-4] which share similar characteristics. The challenges all emerged based on the same set of causally coherent evolutionary mechanisms. The challenges are all complex and systemic with causes, interactions and consequences that cascade across all **Anthropocene systems** and all **Anthropocene scales**. The challenges all require the close integration of stakeholder perspectives at multiple scales through participatory approaches. Furthermore, each one of the challenges depends on most of the coevolving Anthropocene systems shown in Figure 2, meaning that the challenges are both interdependent and dynamic, and cannot be framed and addressed individually. The continuing coevolution of Anthropocene systems must be taken into account when framing and addressing the challenges, which is frequently done in terms of resilience, sustainability, risk, equity, planetary boundaries, doughnut economy, One Health, One Earth and many others.

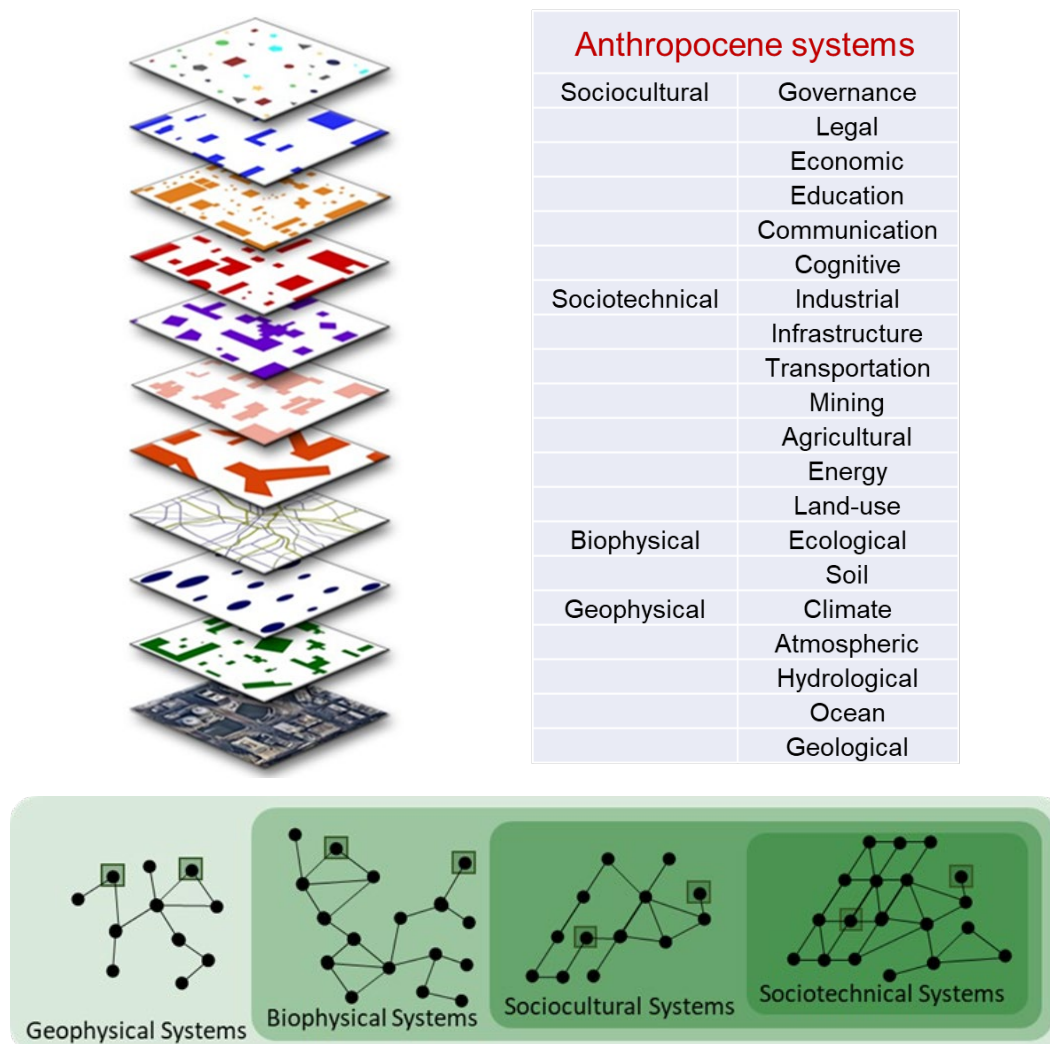


Figure 2. An initial list of 20 globally connected **Anthropocene systems** [2-4] is shown on the right. The image on the left provides a visual representation of a system of Anthropocene systems with the “real world” on the bottom, and 10 interdependent systems layered above. The image on the bottom illustrates the primary Anthropocene systems within a coevolving, nested, evolutionary ensemble of geophysical, biophysical, sociocultural and sociotechnical systems [2, 4].

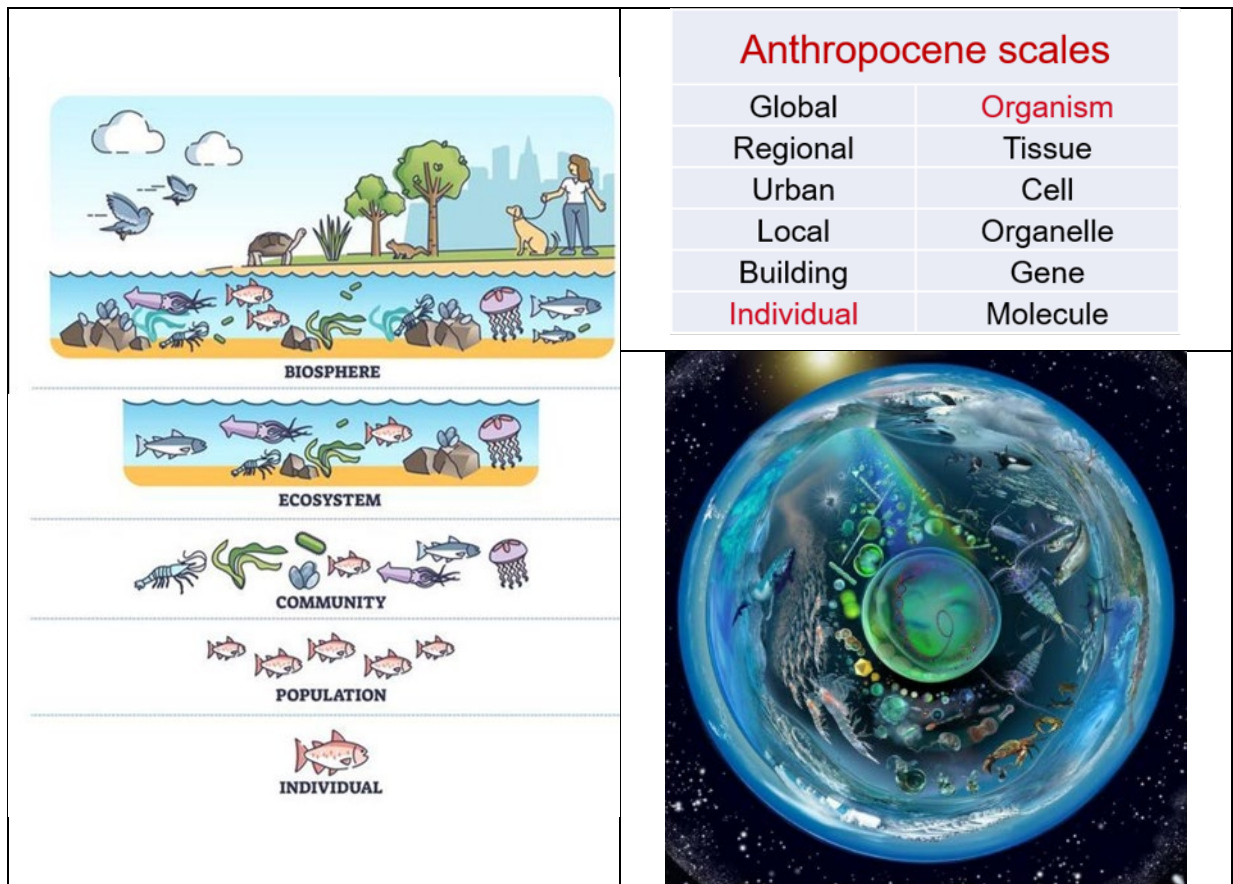


Figure 3. To frame and address the globally connected **Anthropocene challenges**, we need to coordinate interventions in thousands of cities and hundreds of nations around the world, and these interventions need to be made in multiple **Anthropocene systems** and at multiple **Anthropocene scales**. These potentially include interventions at the global scale, but certainly include regional, urban, local, building and individual scales. As we focus on the health of humans, animals and ecosystems, then the scales within individual organisms become increasingly relevant [4]. In general, however, the perturbations that result from these interventions will cascade out across all systems and scales, meaning that we need to understand causal coherence across scales. The only way to establish this causal coherence is to take advantage of the fact that all the Anthropocene systems coevolved, keeping in mind that they continue to coevolve [2, 4].

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