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Earth System Dynamics
Discussions

Interactive comment on "Earth System Economics: a bio-physical approach to the human component of the Earth System" *by* Eric Galbraith

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I thank Anonymous Referee 1 for taking a look at the manuscript, and for providing some general comments which point to ways in which the manuscript can be improved.

The comments identify a number of misunderstanding that show the manuscript did not provide sufficient clarity on three main issues: 1. the rationale underlying the main focal points of the approach, 2. examples of potential applications of the approach, and 3. the fact that this primarily describes a strategy for further work, rather than a final destination. Below, I discuss these three main issues, and follow this with a point by point response.

Main issues

First, the rationale behind the approach was not sufficiently clear, and apparently gave the impression of arbitrariness.

The central feature of the approach is its focus on physical quantities. This is motivated by the fact that much of the predictive success of natural sciences lie in their ultimate recourse to physical variables, which allow interdisciplinary pathways to diverse insights whether starting from biology, physics or chemistry. For example, the conservation of mass, momentum and energy play essential roles in many branches of Earth System Science, from atmospheric circulation to ice sheet motion and sea level rise. Ecosystem and biogeochemical models benefit from the understandings of living processes as molecular interactions writ large.

The fact that many social sciences have, as their fundamental principles, concepts like beliefs and values, with no obvious relationship to biology, physics or chemistry, forms a brick wall for interdisciplinary scientific inquiry (e.g. Bouchaud, Nature 2008). Values and beliefs are emergent characteristics, not physical quantities. Connecting emergent behaviours with their underlying physical properties is vital to advance scientific understanding. The pursuit may not yield plentiful results immediately, but is a direction with great potential.

In addition, the ESE approach aims to construct understanding based on conserved variables. Most centrally, the use of time: there is no question that all humans have 24 hours per day, and it is therefore perfectly conserved. The use of conserved variables helps to greatly constrain possible outcomes.

Second, I did not provide examples of questions that can be successfully addressed with the ESE approach, which was an important oversight in the manuscript. Some examples of the avenues of research that can benefit from this approach include:

- Historical dynamics. How did physical Earth system constraints contribute to aspects of human developments such as the neolithic transitions, and the development of long-distance trade? What emergent societal features have been most important in

determining the interactions of humans with their environments?

- The long-term spatial and temporal dynamics of human interactions with ecosystems and consequences for biodiversity, from early mass extinctions to current biodiversity loss and future extinction threats.

- The elucidation of mechanistic linkages between subjective well-being and the bio-physical consequences of societal features. How can we optimize human lived experience within physical constraints, including climate impacts?

- Understanding the direct spatial and temporal coupling between industrial material flows, human activities and waste production. Essentially, resolving the whole human system as an integrated part of global material cycles.

Most of these complex problems have been addressed to some extent by other means, but the ESE approach can provide an unprecedented large-scale perspective, leading to a new set of answers and opening new avenues for mechanistic insight.

Third, the manuscript is primarily attempting to lay out a path towards further progress, rather than reporting on results (although some results are included). I understand this to be consistent with the stated aims of ESD to publish articles that discuss "ways how [various Earth System interactions] can be conceptualized, modelled, and quantified". The model is included as an illustration, intended to help the reader see how the pieces could be fit together in a working example. I should also have emphasized the fact that it is a 'zero-D' model, i.e. with no spatial resolution, though the intention would be to typically implement ESE models on a global grid. The process of first documenting models in a zero-D format is common in Earth System domains such as ocean biogeochemistry.

I plan to address these communication-related issues, as well as the points raised below, by a thorough revision of the manuscript.

Point by point response:

The Author proposes the "new" modelling approach that combines earth and economic systems. Let me start with general impression. The Author takes bits and pieces from differ- ent fields of science and tries to arrange them into one coherent model.

I entirely agree. The aim was to provide a framework within which to integrate various branches of natural and social sciences, made tractable by focusing on a certain critical aspects.

However the Authors decisions are very subjective, unsystematic and the overall model /approach makes an impression of being unnecessarily complex and very chaotic.

I am disappointed to hear that the impression was one of chaos. As emphasized above, the guiding principles are to focus on bio-physical features that can open up insights from other branches of science, and provide predictability through recourse to principles of conservation. In revision I will attempt to improve the presentation to make this more clear.

The different variables sets represent different levels of abstraction for example things and connectome. Whereas the latter is unmeasurable and very loosely connected with the rest of the model.

I would characterize this differently. Both Things and connectomes are real entities, and can therefore both, in principle, be measured by physical means. Connectomes are, in fact, being measured - this is on the forefront of neuroscience research (e.g. Van Essen et al., Neuroimage 2013; Smith et al., Neuroimage 2019). That is not to say that the current ability to measure and quantify connectomes is similar to our ability to measure Things - it remains highly rudimentary by comparison, and the main value of recognizing the role of the neural underpinning remains conceptual at this early state of development, rather than providing much predictive power. But I would say that the referee's criticism of unmatched abstraction is far more appropriately applied to models that combine the physical Earth system with non-physical general equilibrium models of the economy, which is what the majority of existing human - Earth coupling

approaches do (e.g. IAM models).

In addition, I should highlight that the connectome is not the only neural feature that could prove of use, it is used here only for the illustrative framework and model. In revision I will make this distinction more clear.

No evidence is provided that modelling connectome provides any value added to more traditional measures as technology, social capital etc.

I think this comment reflects a miscommunication of the aim of the manuscript. The proposal is to work towards a biological / chemical / physical basis for the understanding of the human system, including the all-important neurological features, especially as they pertain to our interactions with the remainder of the Earth system. This is intended to complement - not replace - traditional measures of technology, social capital etc.

There is a well known statement "All models are wrong but some are useful". I doubt whether this approach and example presented in the paper in particular give more insights than any of the traditional economic/demographic models that take the limited resources into account.

Indeed, this aphorism is one of my favourites. I would point out that the paper is mostly proposing a conceptual approach, rather than a specific model - the model discussed in the latter half of the manuscript is not intended to be a full realization of the approach, but an aid to understand it. The referee's comments indicate that this was not well communicated, and I will attempt to improve it. Further works using the approach are currently underway, with one example under review (Zhu et al.,) and provide numerous novel insights due to the embedding in a spatially resolved, realistic Earth system model.

Occam's razor principle should definitely be applied here. The Author should provide such an example that provides the evidence that the proposed approach is superior to

the existing modelling approaches and not just any example.

I would never attempt to prove that the ESE approach is superior to all existing modelling approaches. Instead I would point to an essay by Truran (2013) who, in discussing Box's aphorism, writes 'It may be necessary to create a model that takes a totally different perspective in order to improve upon currently accepted models.' Given the predicament of the current human-Earth system, it seems that the new insights that could be provided by a different perspective make it worth pursuing. In the revision I will provide a list of examples for specific problems to which this approach is likely to provide new insights.

Moreover it is not clear why the Author claims to be able to explain the complexity of the human being behavior with very simple somatic and neural variables.

Please note, I had no intention of claiming to explain the complexity of human behaviour. Rather, I am attempting to explicitly acknowledge the fact that human behaviour emerges from the physical reality of human minds, their interactions with each other, and their interactions with their bodies and the environment. Furthermore, the model illustrations do not attempt to explain human behaviour, they test the sensitivity of particular physical outcomes to the assumptions, and identify likely hypotheses that could be further tested, such as one set of dynamics that could produce golden ages.

The example with hunger is the oversimplification when taking into account that the food expenditures constitutes only a fraction of all expenditures. How should this approach be any good to explain such phenomena as values, norms, cooperation, altruism and so forth.

I would say that the provision of food is the most essential and immediate aspect of human interactions with the rest of the Earth system, regardless of how much of household spending it happens to represent in modern western societies. Hunger is also one of the most straightforward human responses to predict, which is why it was chosen as the focus for this illustrative model. The illustrative model does not, in any way, attempt

to explain values, norms, cooperation or altruism - rather, these are assumed to contribute to the outcomes in an unresolved way, through their emergent effects on the r and k parameters.

Not to mention that the problem of dividing the time into leisure and wok is the classical example studied in microeconomics books.

Agreed, this is a classic example, but in practice sees remarkably limited application in economics. It has been historically relegated to a niche of microeconomics, and is not generally applied as a universal mechanistic principle. Time use statistics are widely collected by governments, but often using very limited sets of categories, and are not widely used in social sciences. Gershuny and Sullivan (2019) provide many arguments for the need to consider time allocations more broadly in social sciences, beyond the simple division into leisure and work - well aligned with the intention for the ESE approach.

The model is mostly unjustified. The economics part is based on one handbook from 1890 and one article. It is even visible in the economic terms used by the Author e.g. things instead of goods and so forth. Contrary to IAM models, mentioned by the Author that are based on classical economic growth models and have theoretical backgrounds this model is mostly unjustified.

I interpret 'unjustified' here to mean unsupported by sufficient references to the literature. In fact, there are so many relevant works that could be cited that I can't possibly cite all of them, although I agree that I did not cite enough in this initial submission. I will add to the reference list in revision.

Finally, I would explain to the referee that I purposefully chose 'Things' rather than 'goods' so as to prevent a reader from assuming that the two are directly equivalent. The definition proposed for 'Things' is a strictly physical one, as the sum of all constructs physically maintained by human activity. 'Goods', on the other hand, are usually defined by the fact that they are wanted by people (they have value), and are often

conflated with services (which would mostly fall under Activities in the ESE approach). This distinction is not designed to be difficult, but so as to hew as closely as possible to the biophysical reality, which is the most important aspect of the ESE approach.

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