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# *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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Thanks again to Referee 1 for the further constructive comments. As part of the Final response, I provide more details on how I plan to address them in revision. These are presented point-by-point below, with Referee 1's comments in italics.

*Thank you very much for your accurate and comprehensive reply. Let me refer to some of the issues raised by you. I will also try to make some points in my initial reply more precise. I really missed the detailed and comprehensive discus- sion of the framework design principles. When building interdisciplinary models (which normally are based on the already existing theories and approaches and the focus is set on selecting the optimal combination) there is a possibility of many alternative model frameworks. The*



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*central question is which theories are selected from relevant scientific discipline and why. Alternatively, which theories have been considered but finally not selected and why?. My impression was that you focused more on justify- ing single theories (building blocks of your model), whereas, in my opinion, it is their selection process, guidelines and the additional features of the model resulting from their simultaneous application of these theories that are crucial.*

I appreciate the interest in understanding the underlying motivations for the model construction, and agree that a framework such as this cannot be understood without also understanding the guiding principles. I therefore agree that the manuscript should be revised to discuss the rationale and aims more explicitly, in a way that will lead more naturally to the proposed approach.

*Please also discuss potential application areas of you model and its limitations.*

Thanks for the suggestion - I agree that there should be a more thorough description of the potential application areas of the model, as detailed in my prior response (the second of the Main Issues). In addition, I agree it's a good idea to highlight limitations. Most importantly, the population-level approach is not the best one for exploring motivations and mechanisms of societal change, which could be thought of as the 'why' and 'how' of behaviour. The ESE approach is focused on the more readily quantified 'what'. This will be better explained in the revision.

*I still think that specifying these application areas where you expect that your model may deliver additional, new insights comparing to the existing approaches would be beneficial for your pa- per. One specific issue that remains crucial. Namely human behaviour modelling. As you correctly notice there is some "wall" between natural and social sciences.*

I am glad to hear you agree with the existence of this wall, which is really the single most important motivation for the current work.

*On one hand there is a critique that the social sciences are too abstract. On the other natural sciences are precise but not really able to explain more complex aspects of human behaviour other than satisfying basic needs as e.g. food consumption.*

I partly agree with this characterization, but I would add that natural scientists do not (by definition) work on humans. I think the existence of the natural-social 'wall' creates cultural barriers between natural and social scientists that are detrimental to progress on the shared frontier, which is where sustainability/environmental crises lie. ESE is offering one approach to help chip away at the wall.

*Let me share some personal views from the perspective of social scientist. There is nothing wrong with being abstract, different levels of abstraction are commonly used for example in computer science. They are also used in natural sciences. For example mechanics behind pendulum movements have abstract description. The fact of actual physical shape of pendulum is ignored, so as the fact that it consists of particles, particles con- sists of atoms and so forth. The problem with connectome, neurons, synapses is not that they are abstract per se but that we cannot (at least at the current scientific level) connect it with observed human behaviour. These mechanism are abstract, rather guessed.*

Thank you for this perspective. In general, I agree. Some writers refer to symmetry-breaking between levels of organization (e.g. Anderson, Science 1972; Longo and Montevil, Progress in Biophysics and Molecular Biology 2011) whereby systems undergo fundamental changes in operation between scales, or phases, that prevent the 'lower' level of organization from being used to inform the 'higher'. In fact, this is why the ESE approach focuses on the population level: populations can behave in ways that are not predictable from the behaviour of individuals; there is a symmetry breaking between individuals and populations.

But even though the underlying levels of organization may not be useful for direct prediction, it can be highly informative to bear in mind that the underlying physical fabric

exists, and to be aware of its physical nature. This is why it is useful to know how photosynthesis converts $CO_2$ to glucose when considering the global biosphere. It is not that one would dream of calculating the biosphere from the motion of individual carbon atoms, but that the understanding of the physical basis provides mechanistic insight, such as pointing to the interactive links between atmospheric water vapour and $CO_2$ concentrations through stomatal conductance.

*For me using explicitly abstract social norms provide much better explanation of human behaviour than having the physical connectome in the model and then assuming/guessing some abstract mechanisms how it may influence our behaviour*

I agree that abstract social norms can indeed be very useful, and I am sure they will continue to dominate work in this area. Here I am suggesting an alternative and complementary approach, which is not actually opposed to the representation of features such as social norms in a highly parameterized way.

I realize that the point about using parameterizations to capture unresolved phenomena did not come across clearly (manuscript section 2.1). Basically, I agree that using more abstracted quantities is a good first step, when direct physical quantities are not available for key features (e.g. the connectome). The key distinction aimed for here is that these are conceived of as representing physical quantities, so that future research can link them to other scientific insights, and ultimately replace the abstract quantities with explicit physical ones. In that sense, this is a very long-term goal for aspects such as social norms. Nonetheless, I am confident that it could ultimately be achieved for many important features of the human system, and provide many novel insights.

*(I read and tried to understand the physiology of hunger and satiety and it is far away from the mechanism used in your model) .*

I am not completely clear on what aspects of the mechanism this refers to, however I will add references and details to explain the approach used, which is loosely based on cognitive decision models (e.g. Ratcliff and McCoon, 2008) expressed at the popu-

lation level.

*The first one can at least be examined using survey, interviewed etc. Now my impression is that a connectome is kind of hid- den variable in your model with all disadvantages of such an approach. Some variable sin IAM are abstract as labour, capital, damage function,... but these variables can be easily operationalized labour – workers, capital – machinery, buildings and so forth. Also Cobb-Douglas (or CES) production function is abstract but one can easily image the production processes it represents and also estimate the necessary parameters based on the real empirical data. So that eventually it can be used for modelling, fore- casting the real phenomena.*

Again, I entirely agree that the classical economics approach is useful, and IAMs have been extremely successful. Yet, the 'wall' between social sciences and natural sciences persists, and many environmental problems continue to become worse. Thus, the incentive for new approaches.

*Using your (non abstract) approach one would need to explicitly model all existing machines, map all the production processes and so forth. Not realistic.*

I agree this would be unrealistic, and it was not at all the intention. On the contrary, ESE is intended to pursue a simple, aggregated approach. And I realize that I should have more strongly emphasized the role of non-physical parameterizations to capture essential processes that cannot be directly represented, in the same way that cloud parameterizations are used to capture unresolvable aspects of cloud physics. These parameterizations are always unsatisfying, but the fact that they can ultimately be replaced by more physically-grounded mechanistic understandings identifies a direction for progress. Resolutely abstract variables, on the other hand, resist connection to complementary scientific insights, and reinforce disciplinary silos.

*In my opinion the role of social sciences in your model should be described more clearly and justified in a more comprehensive way.*

Thanks for the suggestion, I will add description accordingly, as well as a new conceptual figure. At the same time, this article is not intended to provide a thorough review of social sciences, so I will try to address this while remaining concise.

*Secondly, why do you think that modelling connectome and using it for explaining the human behaviour makes sense. It is really not clear for me. The argument that it is exists (is physical) is not convincing for me. We do not model the movements of each particle in the pendulum to understand its behaviour.*

As explained in the $CO_2$-photosynthesis example above, there is no intention to model each movement of each particle, or in this case every synapse of every neuron, as will be made more clear in the revision. Rather, the long-term goal is to set a course for understandings that are based on physical principles and can be continually improved through physical observation and connections to other branches of science.

*Thirdly why do you think that somatic variables are that important. Of course age, gender yes but these are already used in economic modelling. On the other hand physical strength, muscle mass are mostly irrelevant due to machines applied in the production process.*

Somatic variables would be potentially representative of human health, food consumption, and physical comfort. There are entire fields devoted to these (including medicine, nutrition, occupational health) so they would appear to be important to many people. The emerging field of global health pursues similar aims, but with different conceptual tools, and without the mechanistic linkages to other features of the human and non-human systems.

*I still think that you should provide more convincing example. Now in natural science there is a whole family of predator-pray model that could easily provide simple and elegant explanation to the same problem as in your example by just using constrained resources, energy, metabolism rate etc. Similarly analogous also simple model are used in economics.*

I appreciate the referee's sentiment, and agree it would be great to have a more convincing example – the challenge is to do so without overwhelming the reader. In light of both referees' comments, I have been considering how the model might be improved in order to provide a better illustration of the general idea. For one, I will de-emphasize the connectome: although this has tremendous long-term promise, I agree that it is of little direct utility at present. Instead I will add detail regarding the construction and maintenance of Things (which I am considering renaming 'Artifacts' after Fischer-Kowalski). I would note that the model does indeed have aspects of a predator-prey model, but does not try to explicitly identify the prey, since it includes all food sources and its biomass is not necessarily depleted by predation (which is standard in Lotka-Volterra style predator-prey models). But in the end, this model is bound to be somewhat disappointing to a modeling enthusiast, because it is only an illustration squeezed into a conceptually-focused overview paper. A fully-developed model is beyond the scope of what can be accomplished here, but the first such paper has already been submitted elsewhere (Zhu et al., under review).

Again, many thanks to the referee for the constructive engagement with the paper.

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