Reviewer comments on:

Unresolved: Deciphering the Biosphere's Role in the Earth System

By Wolfgang Lucht, Katherine Richardson, Jørgen Bendtsen, Boris Sakschewski, and Johan Rockström

Overall comments

This is a well-written and fascinating manuscript that aims to deepen understanding of the interactions between the biosphere and the other parts of the Earth system and to integrate that knowledge into a more comprehensive assessment of biosphere integrity in planetary boundaries. To do this, it proposes a multidisciplinary approach to deciphering these relationships, which I hope might also extend to geologists/palaeontologists, with their knowledge of how the biosphere has sustained itself over billions of years and how it has overcome many planetary-scale disruptions not unlike the one being caused by some humans (those who are hyper-consumers) at present.

In reading this manuscript, I did really wish to see a discussion of the technosphere as the main driver of biosphere change (both of functional and genetic loss). A good start point here is Peter Haff's seminal 2014 paper which clearly addressed the unsustainable relationship of the technosphere with the other spheres of the Earth system.

See: https://pubs.geoscienceworld.org/gsl/books/edited-volume/1761/chapter-abstract/107650441/Technology-as-a-geological-phenomenonimplications?redirectedFrom=fulltext

Haff's (2023) comment that no system (the technosphere) can sustain an accelerating regime of energy use indefinitely' is of central importance to the discussion here, because as it grows, the biosphere seems to suffer. See also:

https://philarchive.org/archive/HAFTXX

I also wondered about the notion of 'two biospheres', a marine and a terrestrial sphere, as that may be ignoring the deep subsurface biosphere as a third component of this structure? That deep biosphere may not be predicated on the energy of the sun, but it is necessary to integrate it into a broader understanding of how the biosphere interacts with the Earth system (including across geological timescales), for example, it is clearly interacting with the geosphere.

I have made a number of specific comments on the text as following.

Specific comments (apologies there are lot of comments, but then this is an interesting manuscript)

Abstract, lines 33-4: perhaps my following comment is encapsulated by what you call 'biogeophysics', but I think the range of disciplines needed to consider the biosphere should also include Earth scientists, especially palaeontologists who have a knowledge of how the biosphere has evolved across Earth time. This should become a central tenet of thinking about Planetary Boundaries, enabling direct comparisons between contemporary and past biosphere change, notably to include intervals of positive change (enhanced biodiversity, productivity, biomass) versus negative change (reduced biodiversity etc.).

See Wong Hearing, Williams, Zalasiewicz in press (for Proceedings B of the Royal Society)

Available as a preprint here: https://www.biorxiv.org/content/10.64898/2026.04.10.715592v2

This provides an evaluation of how past biosphere change can be used to inform contemporary change, through the medium of planetary boundaries.

Introduction, line 38, these are good references, but the primary understanding of how the biosphere interacts with the other spheres of the Earth system must surely be Vernadsky, and that should be cited here too.

His work is also relevant to the following few paragraphs of the introduction.

I see that Vernadsky is quoted in section 2 of the manuscript.

Line 55, I'm not sure that the statement 'Considerable focus has been directed towards understanding the co-evolution of species (Gomulkiewicz et al., 2007; Carmona et al., 2015), but much less on biosphere-geosphere co-evolution' is wholly correct. Planetary scientists and geologists have been doing this for a long time and there is a huge literature, see for example the comprehensive Royal Society volume at:

https://royalsocietypublishing.org/rsfs/issue/10/4

'The origin and rise of complex life: integrating models, geochemical and palaeontological data'

I would say another prime example in this context is this paper:

https://www.nature.com/articles/s41579-024-01044-y

'Co-evolution of early Earth environments and microbial life'

Section 2, A short history of the idea of the biosphere as part of planetary mechanisms

Lines 171-2, The definition 'the Earth system behaves as a single, self-regulating system comprising physical, chemical, biological and human components', is an interesting one, given that the human component seems not to be self-regulating, and arguably along with the technosphere is overwhelming the capacity of the other components to self-regulate too. Here and elsewhere a consideration of the technosphere's role is important, as Peter Haff put it: 'no system can sustain an accelerating regime of energy use indefinitely'

Haff, P.K. 2023. Technosphere. In: Wallenhorst, N. and Wulf, C (eds). Handbook of the Anthropocene. Springer Nature, Switzerland

Available at: https://philarchive.org/archive/HAFTXX

Perhaps some mention of the technosphere is essential, when thinking about how the biosphere is utilised in the planetary boundaries context, not least because arguably the technosphere is the main driver of functional and genetic biosphere loss. The mass of the technosphere now exceeds that of the biosphere and some authors speculate that information flows in the technosphere may also soon (within a century) come to exceed those of the biosphere.

See: https://pmc.ncbi.nlm.nih.gov/articles/PMC10532900/

Some discussion of the technosphere's role within the Earth system should therefore be a central tenet of the manuscript.

Lines 193-4, but it may be possible to measure functional biosphere integrity by comparison with past major episodes of biosphere change, and thus to get some sense of the pace and degree of change at present (for which see the Wong Hearing et al. paper mentioned above).

Section 3, Energy enables ecological work

Line 207 is not really correct, the first metazoans evolved about 570 million years ago, for which there is now a substantial record, and it seems that those early animal communities may have been closely co-evolving with climate state, see:

https://pubs.geoscienceworld.org/gsa/gsabulletin/article/doi/10.1130/B39047.1/734976/Ediacaran-coupling-of-climate-and-biosphere

There is a much deeper record of multicellular life on Earth, going back before 1 Ga, so I think the word 'substantial' needs to be measured here.

Line 245 and hereabouts, relating to disruptions to the biosphere, again it would be worth looking at Wong Hearing et al., as cited above

Section 4, Two biospheres or one (or perhaps three?)

Line 296, I would question the statement that **'**Only a small number of life forms have evolved to survive on the very limited amount of energy originating from below Earth's crust or from utilizing geochemical gradient'. Perhaps as much as 15% of the biomass (70 Gt C) of Earth's biosphere lies below the surface in the Earth's upper crust, and so it should be considered an important part of the biosphere.

See: https://www.pnas.org/doi/10.1073/pnas.1711842115

You may also wish to consider a third biosphere then, that of the deep subsurface, as discrete from both your marine and terrestrial biospheres. It is clearly interacting with the geosphere, and so must be considered in any holistic model of how the biosphere interacts with the other spheres of the Earth system.

Line 336, it should be Holocene Epoch (with a capital)

Lines 340-1, is it true that the overall effects of the marine biosphere are less direct on the Earth system, given that the biological pump in the oceans is a major control on Earth's carbon cycle, and that marine phytoplankton are a key part of this? You come back to this again later in the manuscript, on lines 388-89, where you talk about the deep oceans as a large carbon sink. This is also contributing to maintaining atmospheric and oceanic oxygen-levels, which is a significant positive-feedback to maintaining the biosphere (notwithstanding that much of the organic carbon buried on the continental shelves and the oceans has a continental source).

There is a useful review here:

https://www.sciencedirect.com/science/article/pii/S001282522200071X

And there are the concomitant effects on oceanic and atmospheric CO2 and its feedbacks through climate, that you also discuss.

So, I would accept your comment (lines 340-1) that the feedbacks manifest more slowly, but I'm not sure they are less direct? I think this is better framed in lines 412-414, where you state 'That the marine biosphere must first alter ocean chemistry before the effects of its activity can influence Earth system state means that its Earth system impacts are, in contrast to the terrestrial biosphere, usually only apparent over long time scales'

There is a related point to this, where you talk about the relative (negative) impacts of some humans on the marine and terrestrial realms, and argue that the impact is more immediate on the terrestrial biosphere (lines 426-7). This might, however, be an underestimation of the growing impacts of ocean

deoxygenation (something not really considered by planetary boundaries), that is directly caused by humans, which may very significantly impact the marine biosphere. Some have argued, very cogently, that this effect may resemble that of significant mass extinctions in the past, and over a very narrow near-future timeframe. In this context, I would refer you to this work:

https://www.science.org/doi/10.1126/science.abe9039

This will certainly reverberate to the planetary level, to build on your point on line 430, even if impacts on fisheries might not.

Section 5 Thought experiment: loss of the biosphere

I wasn't quite sure what this section intended to be, but it would be good if it focussed on different trajectories of the biosphere, and how more positive scenarios might be achieved, rather in the way that IPCC predicts different climate futures. Again, for a perspective on this, see the Wong Hearing et al. paper cited near the beginning of this review. At the moment I found this section rather nihilistic.

Line 459, but it might be possible to get some indication of the degree of loss, and of the ability of the biosphere to recover from this loss, by looking at past major biodiversity loss evident in the geological record.

Line 490, worth citing Benton et al. 2022 here, showing how terrestrial biodiversity massively increased following the evolution of angiosperms in the Cretaceous, for which see:

https://nph.onlinelibrary.wiley.com/doi/10.1111/nph.17822

Line 505, comment 'Generally, one can expect the time scales of adjustment to change on land to be notably shorter than in the oceans', I think you need to underpin this by key references. And see comment about the impact of de-oxygenation of the oceans relative to your comments on lines 506-7.

Lines 515-17, and I think here the role of the technosphere in changing patterns of production and consumption in the biosphere is also very salient to the discussion.

Section 6 Modelling planetary functions of the biosphere

I have no comments on this section

Section 7 Understanding Earth as a living planet remains a core challenge for Earth system science

Opening paragraphs. Indicate how you are using the Anthropocene, here I would guess in the sense of a mid-20th century start date (for which you could quote Waters et al. 2016, as already cited). Even though the biosphere integrity boundary of planetary boundaries was exceeded in the 19th century, Steffen et al.'s Great Acceleration graphs clearly show how patterns of consumption, including of the biosphere, have become completely unsustainable in the latter part of the 20th century, and this would also loop back into a consideration of the technosphere's role here too.

Line 650, collaboration also needs to include geologists/palaeontologists, whose knowledge of past major disruptions to the biosphere are relevant to considering rates and degree of change at present, and who have datasets that are germane to useful comparisons, thereby giving some sense of forward trajectory. Again, I would encourage you to look at the paper by Wong hearing et al., cited at the start of this review.

Mark Williams, August 2026