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OPINION

Why aquatic deoxygenation belongs in the planetary boundary framework

Erica M. Ferrer[1☯], Ariel K. Pezner[2☯*], Yassir A. Eddebbar[3], Denise Breitburg[4], Sean Crowe[5], Véronique Garçon[6], Marilaure Grégoire[7], Stephen F. Jane[8], Peter R. Leavitt[9], Lisa Levin[3], Kevin Rose[10], Douglas Wallace[11]

1 Department of Ecology and Evolutionary Biology, University of California Santa Cruz, Santa Cruz, California, United States of America, **2** Climate Change Cluster, University of Technology Sydney, Broadway, New South Wales, Australia, **3** Scripps Institution of Oceanography, University of California San Diego, La Jolla, California, United States of America, **4** Smithsonian Environmental Research Center, Edgewater, Maryland, United States of America, **5** Departments of Microbiology and Immunology and Earth, Ocean, and Atmospheric Sciences, The University of British Columbia, Vancouver, British Columbia, Canada, **6** Centre National de la Recherche Scientifique, Institut de Physique du Globe de Paris, Paris, France, **7** MAST-FOCUS, Department of Astrophysics, Geophysics and Oceanography, University of Liège, Liège, Belgium, **8** Department of Applied and Computational Mathematics and Statistics, University of Notre Dame, Notre Dame, Indiana, United States of America, **9** Institute of Environmental Change and Society, University of Regina, Regina, Saskatchewan, Canada, **10** Department of Biological Sciences, Rensselaer Polytechnic Institute, Troy, New York, United States of America, **11** Department of Oceanography, Dalhousie University, Halifax, Nova Scotia, Canada

☯ These authors contributed equally to this work.
* arielpezner@gmail.com

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Aquatic systems under the planetary boundary framework

In an epoch dominated by human activities, Planetary Boundaries (PBs) have emerged as a powerful overarching framework for tracking global environmental change [1]. In this framework, PBs constitute limits to processes and stressors that threaten a sustainable "Holocene-like" Earth, including: Climate Change, Novel Substances, Stratospheric Ozone Depletion, Atmospheric Aerosol Loading, Ocean Acidification, Disruption of Biogeochemical Flows, Freshwater Change, Land System Change, and Loss of Biosphere Integrity [Rockstrom et al., 2009]. Since its inception, the PB Framework (PBF) has been widely adopted by both scientists and policy makers, with several notable iterations, expansions, and updates [2]. Application of the PBF to marine and freshwater ecosystems has been relatively limited, however, as PBs are disproportionately weighted toward terrestrial and atmospheric systems [3]. Of the original nine PBs, only three specifically apply to aquatic systems – Ocean Acidification (OA), Freshwater Change, and Disruption of Biogeochemical Flows – and appropriate thresholds for OA as a boundary are still being refined [4].

Given that water covers 70% of the planet, monitoring changes to aquatic ecosystems is of paramount importance and should be included under a PBF. However, one major threat to both freshwater and marine systems remains overlooked within the PBF: Aquatic Deoxygenation.

Aquatic Deoxygenation (AD) refers to the contemporary, human-driven loss of dissolved oxygen in aquatic environments, and is a lesser known but highly detrimental consequence of human disruptions to climate, land-use, and nutrient-cycling [5]. Most forms of life require oxygen to function, and the cycling of nutrients is tightly coupled

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to oxygen concentrations. Thus, AD poses widespread and potentially irreversible threats to planetary integrity via its impacts on freshwater and marine habitats, biological productivity, biodiversity, and ecosystem services.

Concern for the impacts of AD on aquatic ecosystems has grown over the past decade [5,6], culminating in a recent proposal to add AD as the 10th boundary [7]. Here, we discuss why deoxygenation belongs in the PBF and outline next steps towards integration in the PBF.

Aquatic deoxygenation: A key planetary boundary

AD functions as an integral PB, linking terrestrial, aquatic and atmospheric systems [7]. It spans broad spatial and temporal scales [5], interacts with all other PBs [8], and has the capacity to cause global biological crises.

Globally, oxygen content has declined precipitously across aquatic ecosystems over the last half century. Human-caused deoxygenation is not a new issue for coastal bays and freshwater systems, particularly those subject to anthropogenic runoff driving local deoxygenation. However, on a global scale, anthropogenic warming is also leading to massive oxygen declines in ecosystems far from the direct impacts of human activities. For instance, observations and models suggest that the ocean's oxygen content has decreased 1–3% since 1970, with models projecting an additional 3.2-3.7% loss by 2100 [9]. While a ~ 3% loss may seem small, this equates to 961 tera moles of oxygen lost per decade, equivalent to the amount of oxygen ~320 million people breathe in a lifetime. Meanwhile, *in situ* data collected from lakes [10] and rivers [11] suggest equally perilous rates of decline in freshwater systems. This ubiquitous deoxygenation will likely increase the frequency, duration, and severity of extremely low oxygen events in normally well-oxygenated ecosystems [12], which can co-occur with marine heatwaves and acidity extremes in the form of dangerous "compound" events [13]. Extreme events like these can be acute (lasting a few hours or days) or chronic (persisting for decades), and can span areas from single ponds to entire oceanic shelves.

Given their vast reach and scale, AD events can seriously disrupt aquatic health. AD can lead to fish kills and harmful algal blooms that cost millions of dollars in lost tourism revenue, reduced property values, fishery and aquaculture closures, and human health challenges [14]. Looking towards the end of the century, deoxygenation in conjunction with warming may also drive massive extirpations of marine life [15].

Towards a truly comprehensive planetary boundary framework

Given the effects that deoxygenation can have on the integrity of ocean and freshwater systems, we argue that AD represents an immediate and urgent threat to planetary health. We therefore call upon the PB community to include Aquatic Deoxygenation as a boundary in the next update to the framework. Without it, the PBF will risk overlooking serious Earth system degradation.

We also call on scientists to critically explore how AD fits within the PBF, increase communication across disciplines, and engage with policymakers and governments to find effective solutions that mitigate AD and its potential damages. Specifically, scientists must identify appropriate limits for AD within the PBF, given the spatiotemporal complexities and species-dependent thresholds of hypoxia [7,8]. Towards this, scientific discussions are needed to bring together relevant experts to work in tandem on this issue.

Likewise, scientists must also work closely with stakeholders to identify and assess the threat of AD to ecosystems, people, and economies. Progress on these fronts demands broader engagement on monitoring and addressing the threats of AD on aquatic life, including two-way interactions with fisheries, aquaculture, maritime industries, Indigenous knowledge holders, and environmental advocacy groups. Collaborative scientific forums, industry partnerships, and public-private initiatives can unlock new solutions while ensuring that AD is recognized as a critical planetary challenge integrated into most major climate and sustainability frameworks.

Finally, we call for additional monitoring, experimentation, predictive modeling, and mapping to identify deoxygenation causes and progression, measure its interactions with other PBs, and expand global capacity to respond to its effects. Innovation in observations (e.g., BGC Argo float program) and near-term predictive modeling is essential to anticipate and mitigate the effects of AD, and expanding global capacity through equitable access to knowledge, technology, and infrastructure will empower all nations, particularly those most vulnerable, to respond effectively.

Addressing Aquatic Deoxygenation (AD) requires bold, interdisciplinary collaboration and engagement beyond traditional scientific circles. By introducing AD as the 10th PB while also mobilizing diverse expertise and resources, we can protect ecosystems, sustain economies, and build a more resilient and sustainable Earth system.

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Author contributions

Conceptualization: Erica M. Ferrer, Ariel Katharine Pezner, Véronique Garçon.

Project administration: Erica M. Ferrer, Ariel Katharine Pezner.

Writing – original draft: Erica M. Ferrer, Ariel Katharine Pezner.

Writing – review & editing: Erica M. Ferrer, Ariel Katharine Pezner, Yassir A. Eddebbar, Denise Breitburg, Sean Crowe, Véronique Garçon, Marilaure Grégoire, Stephen F. Jane, Peter R. Leavitt, Lisa Levin, Kevin Rose, Douglas Wallace.

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