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Ocean deoxygenation – a climate-related problem

Many take for granted low oxygen as “just another water-quality issue”. Excessive loads of nutrients from non-point and point sources, including sewage, enter aquatic ecosystems where they increase biological oxygen demand and promote eutrophic conditions that can lead to periods of hypoxia or anoxia (in coastal areas somewhat misnamed as “dead zones”).

Global warming is now gaining attention as exacerbating the problem, leading to oxygen loss in larger regions of fresh, brackish, and marine waters. Not only does warmer water hold less dissolved oxygen than colder water, but the warmer upper layers are less dense and thus are more stratified, reducing ventilation of deeper water layers. Accelerating ice melt at the poles and increased freshwater runoff into some coastal areas further act to stratify ocean waters because fresh water is less dense than salty water. High atmospheric inputs of nutrients and wetland loss from sea-level rise intensify coastal eutrophication. Oxygen minimum zones (OMZs), naturally occurring hypoxic waters 100–1000 m deep, are expanding.

Globally, the oceans have lost an estimated 77 billion tons of oxygen – approximately 2% since 1960 (Schmidtke *et al.* 2017; *Nature* 542: 335–39) with more loss projected into the 21st century. Reinforcing feedbacks include phosphorus release from anoxic sediments that stimulate primary production, drawing down oxygen as the organic matter created is decomposed. Indeed, this effect of warming will necessitate more stringent nutrient reduction measures than ever. Furthermore, expanding OMZs have the potential to alter denitrification and anammox processes, with subsequent production of N₂O, a potent greenhouse gas (GHG). This could further exacerbate atmospheric warming, although the magnitude of this feedback is currently the subject of study.

Why is ocean deoxygenation not understood as a climate-change impact? Ocean deoxygenation in a climate-change context has received relatively little attention as compared with ocean acidification, yet they are strongly linked to each other and to rising levels of CO₂ in the atmosphere. Part of this lack of attention could be due to the impression that low oxygen is a problem we’ve been aware of for over 100 years, and that until recently, it was difficult to measure changes in oxygen content at the scale of the world’s oceans. Although such measurements are still problematic, new instrumentation and initiatives are emerging to coordinate accurate, reliable oxygen data collation and analysis. Additionally, oxygen loss in the open ocean is largely an effect of warming, and thus is one step removed from GHG emissions.

What is at stake if we ignore this? One reason we should care about deoxygenation is global reliance on marine protein. Marine fisheries (total economic impact \$225–240 billion per year; Dyck and Sumaila 2010; *J Bioecon* 12: 227–43) are considered critical to the welfare of millions. Anoxic waters are harmful to most fish and shellfish, but even hypoxic waters (generally defined as <2 mg of dissolved oxygen per liter of water) reduce the metabolic scope for growth, and consequently limit the ability of animals to forage, avoid predation, or fend off diseases; at the same time, warmer water raises oxygen demand. This may explain why Baltic Sea cod have become smaller and exhibit poor condition, although crowding into reduced habitable space may also have led to competition for food (Casini *et al.* 2016; *Roy Soc Open Sci* 3: 160416). There will be winners and losers in fisheries and aquaculture. Deoxygenation effects will hit some areas harder than others, and fish may flee low oxygen zones, aggregate, and then be caught in locations that are more habitable. Deoxygenation is a consequence of climate change that direct fisheries management can do little to control, but adaptive practices can help.

Food security and associated livelihoods are the obvious ecosystem services at risk, but others include biodiversity losses and cultural amenities such as tourism. It will also be much more difficult to manage nutrients effectively.

We are concerned that the scientific community and the many stakeholders in society at large are mostly unaware that spreading low oxygen zones constitute a global climate-change issue – one that includes international waters. Sorely needed measures to reduce GHGs take on the added importance of helping maintain oxygenated waters, biogeochemical balances, and healthy aquatic ecosystems. We encourage ecologists to engage with stakeholders to promote policies that mitigate (eg restore coastal wetlands to absorb more nutrients), conserve (eg reduce fishing pressure on hypoxia-sensitive species), and keep “eyes on” the problem (implement monitoring systems), while recognizing the linkages to other climate-related pressures. We advocate a holistic approach linking warming temperatures, oxygen, and other stressors.



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