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Ocean deoxygenation: Everyone's problem

Causes, impacts, consequences and solutions

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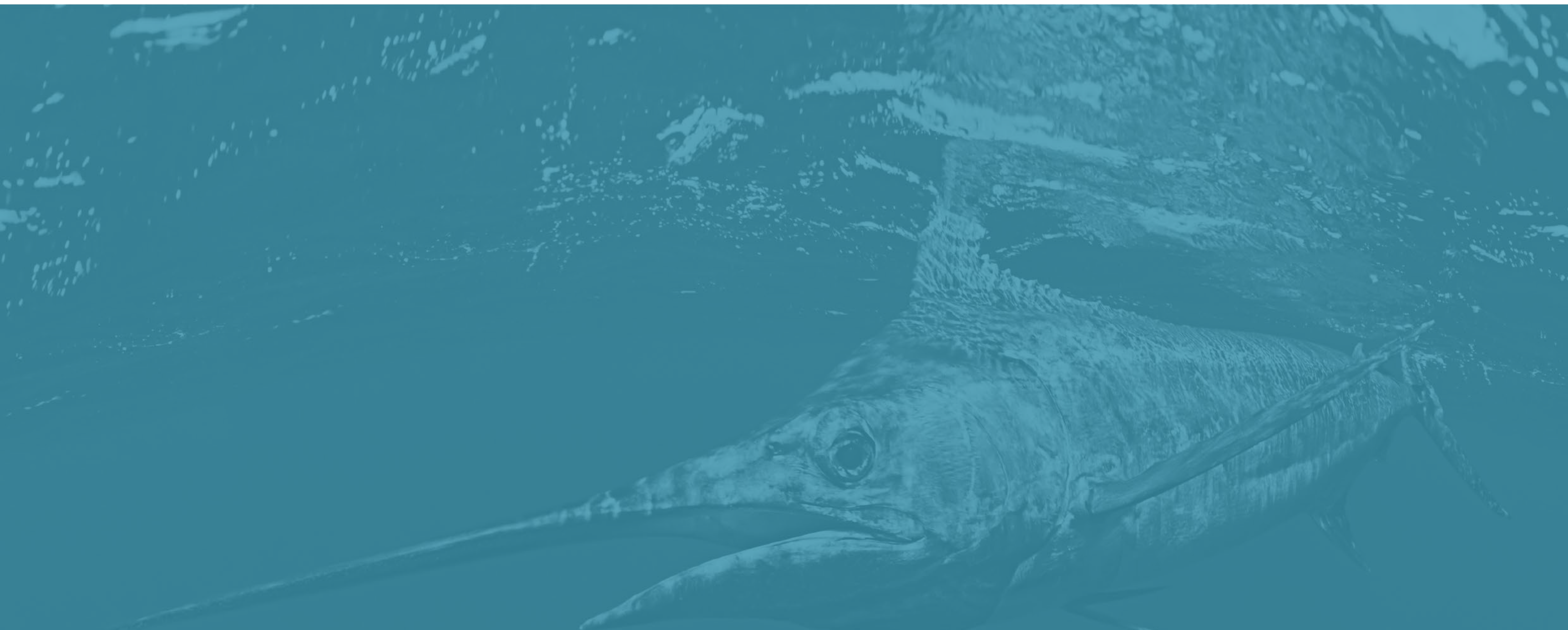
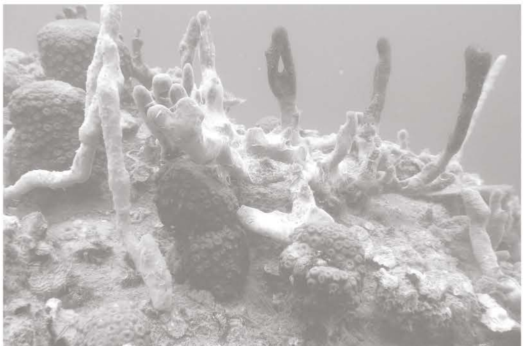


11. What can we do? Adaptation and solutions to declining ocean oxygen

Denise Breitburg, Daniel J. Conley, Kirsten Isensee, Lisa A. Levin, Karin E. Limburg and Phillip Williamson



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Intergovernmental Oceanographic Commission
Sustainable Development Goals

What can we do? Adaptation and solutions to declining ocean oxygen

11

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Summary

- The oxygen content of the open ocean and coastal waters has declined since the middle of the 20th century, and is expected to decline further during the 21st century as a result of climate change and increased nutrient discharges. Consequences of this ocean oxygen decline include decreases in biodiversity, shifts in species distributions, displacement or reduction in fisheries resources, and changes in biogeochemical cycling.
- Fossil fuel combustion and agriculture contribute to both global warming and over-enrichment of waters with nutrients. Sewage – biomass in untreated sewage and nitrogen and phosphorus in both treated and untreated sewage effluent – is also a major contributor to oxygen depletion in coastal waters.
- Nutrient reduction strategies that have been most effective have utilized legal requirements, set specific targets, and have employed monitoring to detect problems and responses to management strategies. A range of potential solutions to nutrient reduction exists and can be tailored to local needs and economies.
- Reducing the rate of oxygen decline in the global ocean, and minimizing the contribution of climate change to deoxygenation of coastal waters, requires a dramatic climate mitigation effort, primarily through global reduction in greenhouse gas emissions due to human activities. Restoring oxygen lost over the past century on less than millennial time scales will likely also require reducing atmospheric greenhouse gas concentrations to levels lower than the present, through active greenhouse gas removal.
- Continued and enhanced efforts to quantify trends in deoxygenation and project future oxygen conditions, to understand deoxygenation effects on biological, biogeochemical and ecological processes, and to incorporate deoxygenation in development of fisheries and other management strategies are needed.
- Governance at scales ranging from local jurisdictions to international bodies such as the United Nations plays important roles in identifying the problem of deoxygenation, and in mitigation and adaptation efforts to reduce deoxygenation and its negative consequences.

- Solutions to ocean deoxygenation, and development of adaptation strategies in its presence, depend on sound and sufficient science. The international scope of scientific collaboration on this issue is notable; scientific working and expert groups can help facilitate communication among different stakeholders, and support decision makers to take measures required to stem increasing deoxygenation at local, regional and global scales. Further progress is needed, however, in the science of ocean deoxygenation, especially to improve predictions of future conditions and impacts on human welfare.

11.1 Introduction

Declining oxygen in the world's ocean, including its coastal waters, is one of the starkest examples of degradation of ocean ecosystems caused by human activities (Breitburg et al., 2018) (Figure 11.1). Since the middle of the 20th century, the open ocean has lost an estimated billion metric tons of oxygen, and the volume of water in which oxygen is completely lacking[1] has increased 4 fold (Schmidtko et al., 2017). Much of this oxygen loss is attributable to global warming through its effects on oxygen solubility, stratification, ocean circulation and respiration rates (IPCC, 2019; Oschlies et al., 2018). Over a similar period of time, more than 500 estuaries, semi-enclosed seas and other coastal water bodies have reported first instances or expanded areas of dissolved oxygen concentrations at or less than 2 mg L^{-1} or 63 µmol L^{-1} (hypoxia) as a result of an over-supply of nutrients from agriculture, aquaculture, human sewage and the combustion of fossil fuels (Breitburg et al., 2018; Diaz & Rosenberg, 2008; Isensee et al., 2015). Inaccessibility of information, and lack of monitoring, has likely led to an undercount of such systems, particularly in developing nations. Numerical models project that continued warming and increasing human populations will increase the severity of the problem of oxygen decline in both the open ocean and coastal waters (e.g. Cocco et al., 2013).

Severely oxygen-depleted waters, and those in which oxygen is completely lacking, represent habitat that is unusable by most multicellular marine organisms that are important to marine food webs and fisheries. Instead, these areas host rich microbial communities that alter biogeochemical cycles, increasing production of toxic compounds and greenhouse gases, and reducing the supply of biologically available nitrogen in regions of the ocean where nutrients can be in short supply. Even less severely oxygen-depleted waters alter distributions, growth rates and disease in marine organisms. The combined effects of oxygen decline with those of other anthropogenic stressors — warming, acidification and population-level and food web-effects of fisheries, for example — can be more severe than effects of oxygen decline alone. Oxygen is fundamental to multicellular life and to many microbes, and when in short supply, it can greatly alter the functioning of marine ecosystems, with the potential to negatively affect human wellbeing.

How do we move forward, given the magnitude of the problem of ocean oxygen decline? The first step is to raise awareness of the issue among policy-makers and within civil society. Increasing awareness and understanding of ocean[2] oxygen decline is a major goal of this report, as well as of several other recent publications (e.g. Breitburg et al., 2018; GO_2NE, 2018; Isensee et al., 2015; Levin & Breitburg, 2015; Limburg et al., 2017). Although the problem of low oxygen caused by nutrients and sewage in coastal waters has been recognized for over a century, progress in correcting the problem has generally been slow except where solutions also address issues that create a direct threat to human health (e.g. discharge of raw sewage into waterways). The magnitude of the effect of global warming on ocean oxygen content is only recently becoming understood (Levin, 2018). It is important to raise the profile of oxygen decline within the larger conversation on the effects that increasing greenhouse gas (GHG) emissions are having on the global ocean. Improved understanding of the economic consequences of oxygen decline, lost ecosystem services and effects on human well-being may contribute to this effort.

In the remainder of this chapter, we discuss the way forward – the steps and strategies needed, as well as opportunities to stem the loss of ocean oxygen, and especially in nutrient-enriched coastal waters, to

1 The designation of an area as 'anoxic' or 'completely lacking in oxygen' is based on detection limits of instrumentation used to measure oxygen and the presence of biogeochemical processes that are inhibited by oxygen. As instrumentation improves, we are finding that some areas classified as anoxic contain nanomolar concentrations of oxygen, but these are levels that are too low to support most multicellular organisms and many microbes.

2 We use the term 'ocean' or 'global ocean' to include the open ocean, and coastal water bodies such as semi-enclosed seas, estuaries, and similar systems. 'Open ocean' refers to areas where the influence of local watershed processes is secondary or undetectable.

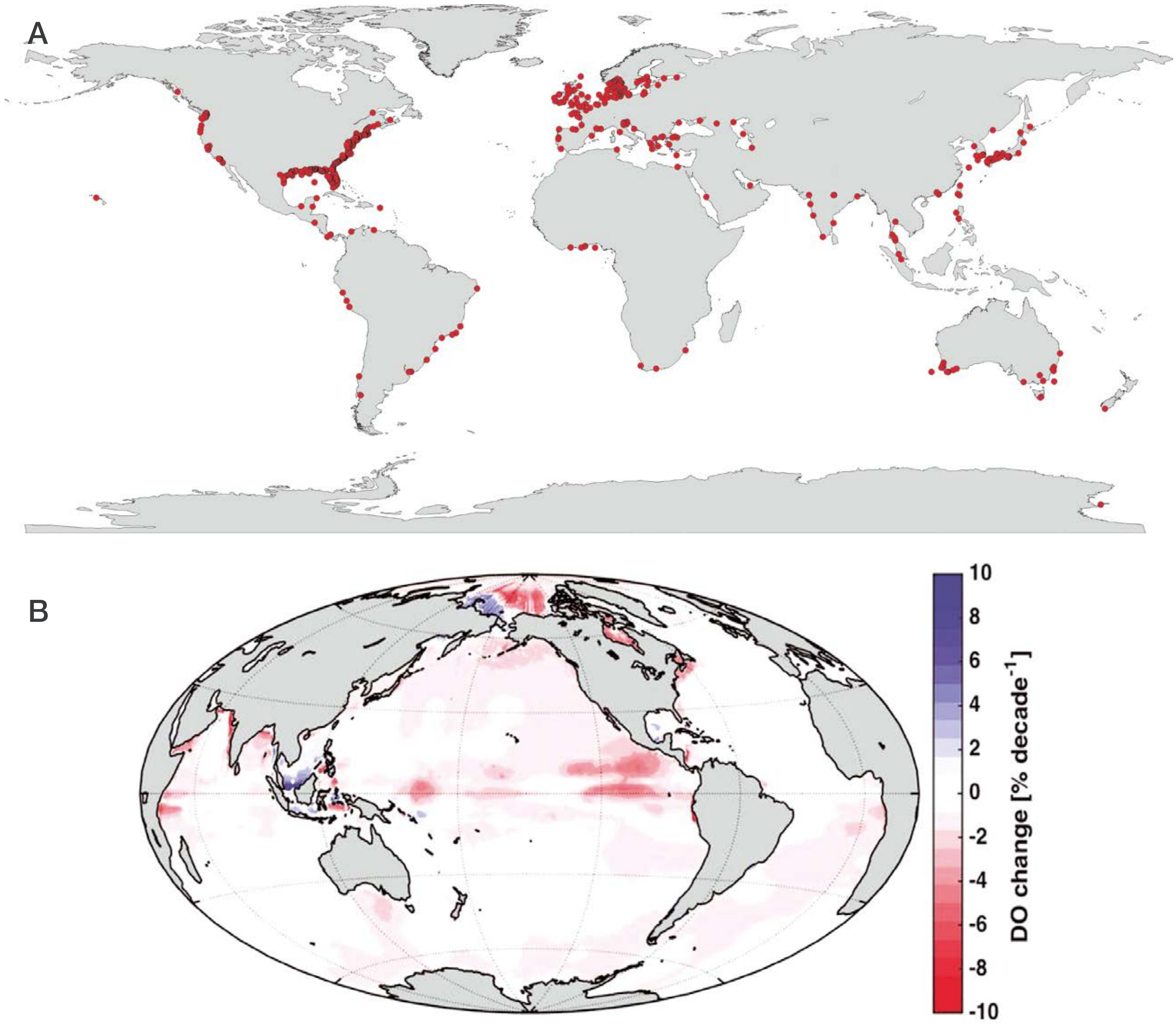


Figure 11.1 Oxygen has declined in both (A) coastal waters and (B) the open ocean since the middle of the 20th Century (reproduced from Breitburg et al., 2018). (A) Coastal waters that have reported oxygen concentrations <2 mg L^{-1} (63 µmol L^{-1} or 61 µmol kg^{-1}) (red dots) (Diaz & Rosenberg, 2008; Isensee et al., 2016). Most systems shown in this figure reported their first incidence of low oxygen after 1960. (B) Estimated change in oxygen content of the global ocean in percentage decade^{-1} since 1960 (Schmidtko et al., 2017). Red tones denote oxygen declines, and blue tones increases.

restore this vital resource to healthier levels. Addressing deoxygenation will require action on multiple fronts, with mitigation and adaptation actions at the global, regional, national and local levels, and thus engagement of a broad range of stakeholders.

11.2 Solutions to slow and reverse oxygen decline

11.2.1 Warming-induced deoxygenation and eutrophication share common causes

Causes of global warming-driven and nutrient-driven oxygen decline are closely intertwined (Seitzinger & Phillips, 2017) (Figure 11.2). Combustion of fossil fuel and agriculture are major contributors to both problems. Fossil fuel combustion, the major source of GHG emissions, also produces nitrogen oxides that are deposited onto land and directly into coastal waters, where they stimulate primary production and, ultimately, oxygen decline (Seitzinger & Phillips, 2017). Atmospheric deposition of iron and fixed nitrogen also stimulates primary production in the open ocean and may worsen oxygen decline in oxygen minimum zones (OMZs) (Ito et al., 2016). Agriculture, strongly associated with eutrophication of coastal waters, is estimated to be the source of 13% of global anthropogenic GHG emissions (FAO, 2014; including energy use in agriculture). Methane and nitrous oxide emissions associated with livestock production, comprised approximately 22%

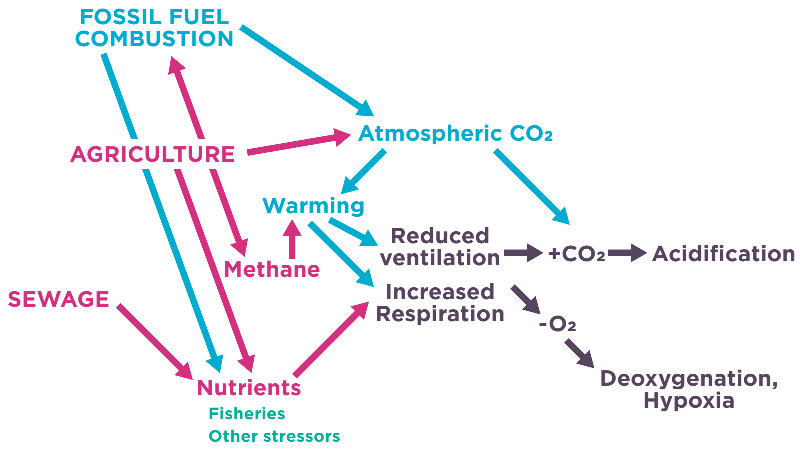


Figure 11.2 Linked causes and mechanisms of oxygen loss. Not shown are pathways for some greenhouse gasses such as N_2O, or feedbacks, including the potential for deoxygenation and warming to increased production of greenhouse gases such as nitrous oxide and methane. Red = major pathways for nutrient sources and effects; blue = major pathways for warming and CO_2 enrichment; green = other stressors that can increase respiration, for example by altering food webs.

of total non-CO_2 GHG emissions (in CO_2 equivalents) in 2010 (Caro et al., 2014). The boom in agriculture, made possible, in part, by the invention and use of synthetic fertilizers (Figure 11.3), and transportation systems that enhance food distribution, have provided the tremendous benefit of feeding the growing human population. A side effect, however, is that agricultural fertilizers, and the sewage from livestock and humans, also fertilize coastal waters, increasing oxygen demand in these systems. Ensuring food security and adequate nutrition for the human population while minimizing the negative effects of agriculture on the environment is a challenge that must be met.

11.2.2 Nutrient management

Reducing nutrient and carbon loads to coastal waters is the basic action required to slow and reverse oxygen depletion in eutrophic coastal waters, and is a focus of policy goals ranging from local municipalities to Goal 14 of the United Nations 2030 Agenda for Sustainable Development (Table 11.1; UN General Assembly, 2015). An important first step for governments is to set environmental quality objectives, as well as specific water quality criteria, to guide the process (Bricker et al., 1999; Ferreira et al., 2011; GO_2NE, 2018). The most effective efforts have utilized legal requirements (Andersen et al., 2017) and set specific targets. Aquatic monitoring programmes that provide a comprehensive picture of environmental conditions are essential to nutrient reduction efforts. They are needed to detect large- and small-scale changes indicative of degradation, as well as positive responses to nutrient management. A focus on data collection and management, with coordinated assessments and analyses, is also necessary to evaluate progress and to adaptively modify nutrient-reduction actions. Finally, long-term financial support for implementation of actions required to reduce nutrients and sewage inputs, for research to develop and identify the most effective actions, and for environmental monitoring to track progress must be established.

Figure 11.3 Stock of synthetic fertilizer ready for applying to crop © Photo-Loci / Alamy stock photo.

Figure 11.4 Boston Harbour © Terry Mathews / Alamy stock photo.

Evaluating cost effectiveness of the various possible actions to reduce nutrients from both point and non-point sources is a critical step needed to move beyond broad strategies. Both societal equity and the magnitude of nutrient reduction that is often required mean that reductions must come from the range of sectors contributing to the problem, including atmospheric deposition, industrial sources, wastewater treatment plants and agriculture. Reductions in nutrient loads from advanced wastewater treatment plants with both phosphorus and nitrogen removal have been clearly demonstrated to lead to improvements in water quality in diverse locations. Estuaries with heavy urban biochemical oxygen demand that had severe oxygen depletion in the past have also seen remarkable improvements in recent decades, such as Boston Harbour, MA, USA (Tucker et al., 2014) (Figure 11.4), the urban region of the Delaware estuary, USA (Sharp, 2010), and the Thames River Estuary, UK (Tinsley, 1998). Conditions in the Thames recovered from anoxia (zero oxygen) to >10% oxygen saturation through implementation of primary treatment of wastewaters, with a resulting 10-fold increase in fish species richness (Tinsley, 1998). The Thames example shows that even primary sewage treatment, the removal of biosolids, can result in a large improvement in systems currently receiving raw sewage (Figure 11.5).

Numerous measures can be taken to achieve sustainability in nutrient cycling to protect the environment and reduce the anthropogenic deoxygenation of coastal, shelf and ocean waters. Human-derived nutrients originate from four main sources: nutrients contained in waste from septic systems and wastewater treatment plants, fertilizer run off, livestock manure, and atmospheric deposition primarily of nitrogen from the burning of fossil fuels. Within the agricultural sector, improved manure management, more efficient fertilizer use, and other changes in crop production can make substantial contributions to reducing nutrients reaching coastal waters. Manure management to reduce nutrient losses to both the atmosphere and aquatic environments includes (i) effective manure handling, (ii) manure transport to other areas, and (iii) adjustment of livestock density (Oenema et al., 2007). Technical solutions to treat manure are becoming increasingly common to reduce its environmental impact (De Vries et al., 2015). To achieve sustainable agriculture, maximum limits on the amount of plant-available nutrients added to different crops, scaled to the optimum needed, can greatly reduce nutrient losses from agricultural fields (Kronvang et al., 2008). Implementing cost effective measures to reduce nutrient loads from agriculture is a major challenge but is needed to minimize the food system's environmental burden (Davis et al., 2016; Sharpley et al., 2015).

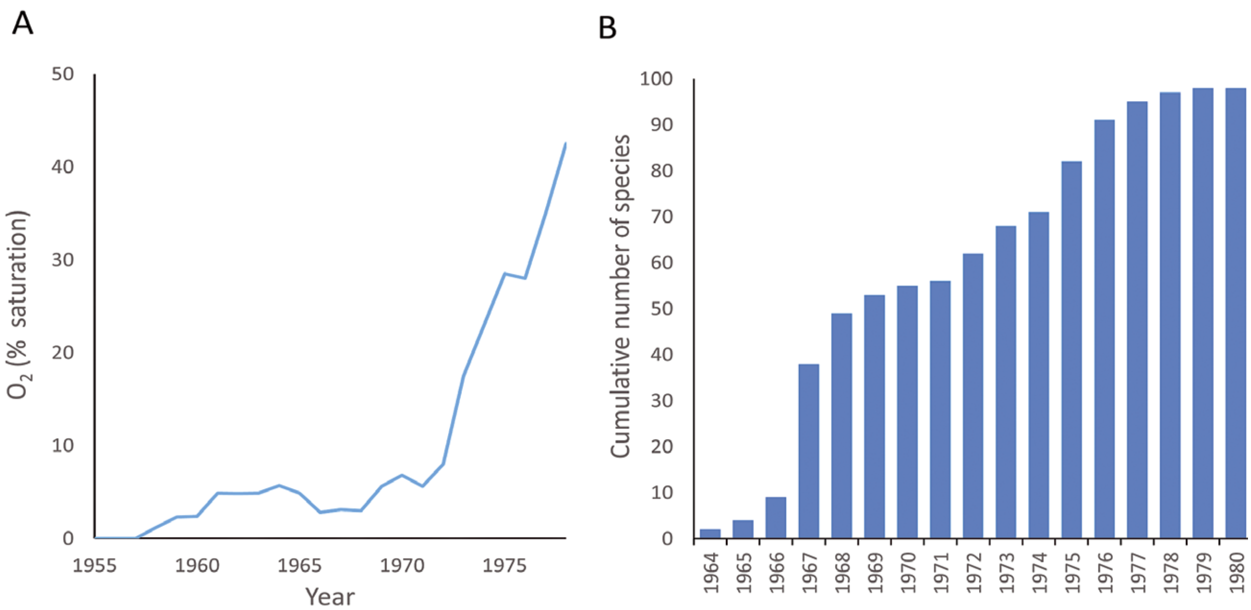
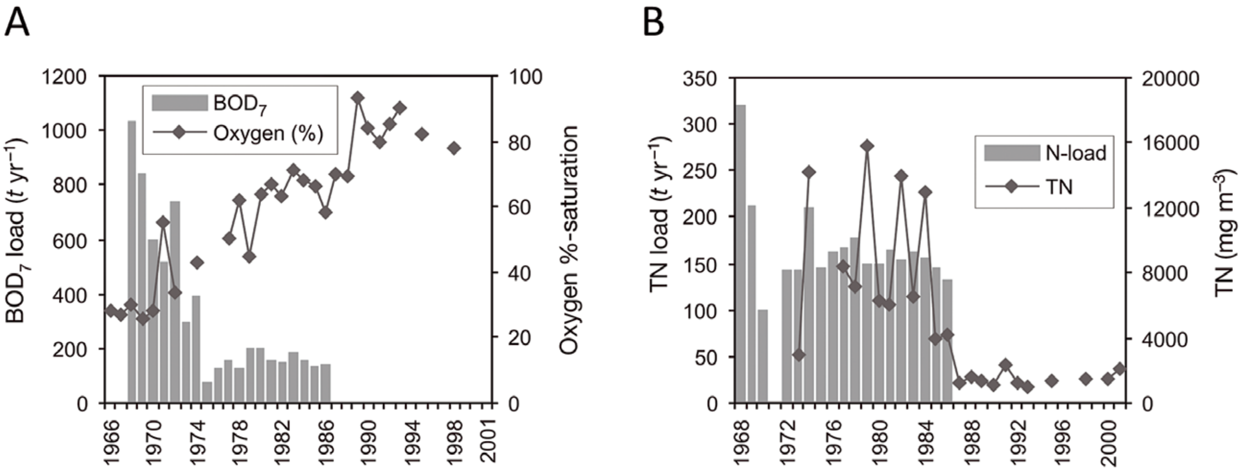


Figure 11.5 Recovery of (A) dissolved oxygen in the upper Thames River Estuary, UK, and (B) fish populations in the cumulative number of fish species recorded in the Thames between Kew and Gravesend. Conditions improved from anoxia (zero oxygen) to >10% oxygen saturation and a 10-fold increase in fish species richness through implementation of primary treatment and offshore shipping of sewage sludge in the early 1960s. Further improvements in sewage treatment during the 1970s resulted in large further improvements in dissolved oxygen and fish species richness (Tinsley, 1998). (A) adapted from Kemp et al. (2009); (B) adapted from Andrews (1984).



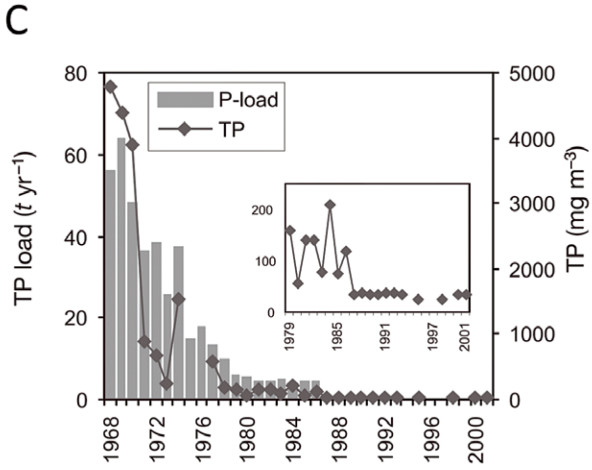


Figure 11.6 Trends in water quality variables and annual loading into Laajalahti Bay, Gulf of Finland (Kauppila et al., 2005). Reducing urban wastewater discharges and chemical removal of phosphorus in sewage treatment plants led to greatly improved oxygen conditions in this estuary. A) near-bottom summertime oxygen % saturation and load of organic matter (BOD); B) surface wintertime concentration and load of total nitrogen (TN); C) surface wintertime concentration and load of total phosphorus (TP).

Effective environmental monitoring and assessment systems have been established regionally and nationally during the late 20th century, e.g. Australia (http://www.ozcoasts.gov.au/indicators/introduction.jsp), Chesapeake Bay, USA (U.S. Environmental Protection Agency, 1996), and San Francisco Bay, USA (Cloern et al., 2017). Progress in nutrient reduction has, however, often been slow. An exception can be found in Denmark where measures have included large changes in agricultural practices and significant improvements in sewage treatment (Kronvang et al., 2008), resulting in approximately 50% reduction in nitrogen and 75% reduction in phosphorus discharges to Danish coastal waters (Rieman et al., 2016). Nearly three decades after the first mitigation measures were implemented, most key ecosystem components (chemical and biological variables) show evidence of a healthier coastal ecosystem, demonstrating the importance of nutrient reductions and the impact on coastal communities. However, the Danish experience also demonstrates the complexity of the problem of deoxygenation in coastal waters: frequent stratification and higher water temperatures have counteracted the expected positive effects of reduced nutrient inputs on bottom water oxygen conditions (Riemann et al., 2015) and further nutrient reductions are needed to meet dissolved oxygen goals. Clearer benefits of nutrient reduction to oxygen content have been seen in Laajalahti Bay, an estuary in the Gulf of Finland near Helsinki (Figure 11.6). Decreasing organic matter and nutrients from urban wastewater has led to dramatic increases in near-bottom summertime oxygen saturation (Kauppila et al., 2005).

One of the major challenges for reducing hypoxia is that deoxygenation is driven by multiple factors. In diverse ecosystems such as Chesapeake Bay and the Baltic Sea, river- or inflow-induced stratification, respectively, and nutrient load are highly correlated with hypoxia (Hagy et al., 2004). Wind speeds and directions during summer are key secondary variables explaining interannual variability in hypoxia and anoxic volumes (Carstensen et al., 2014; Testa et al., 2017). It is also increasingly recognized that there is a legacy of excess external nutrient loading from the last century in the sediments of many coastal and shelf ecosystems that contributes to continued eutrophication despite large-scale nutrient reductions. The legacy of a higher sediment respiratory demand following eutrophication has been shown for other coastal systems (Turner et al., 2008) whereby repeated hypoxic events lead to an increased susceptibility of further hypoxia and accelerated eutrophication. Nutrients previously buried in the sediments can be returned to the water column

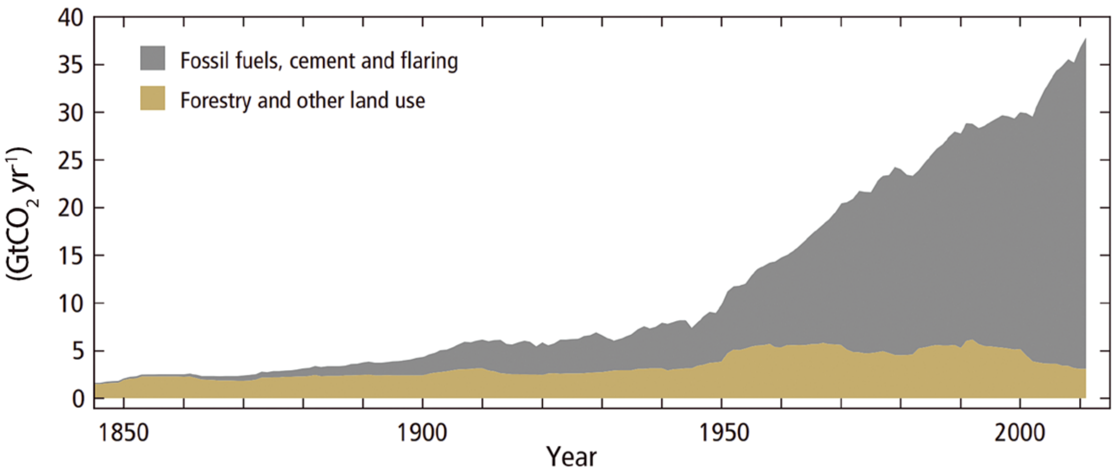


Figure 11.7 Global CO_2 emissions have increased more than 10 fold since 1900 (modified from IPCC, 2014).

causing an increase in eutrophication (Conley et al., 2009a).

Geoengineering has been suggested as a complementary measure to nutrient reduction strategies to reduce coastal hypoxia. However, two such efforts carried in the Baltic Sea demonstrate the mixed success and potential for unintended negative consequences of this approach. In both of these cases, oxygen-rich surface water was pumped into the deep water to enhance the burial of phosphorus. Pumping surface water downward in Sandöfjärden, Finland expanded the bottom area below the pycnocline, and the basin went from hypoxic to anoxic because of the warming of bottom water (Rantjärvi, 2012). In By Fjord, Sweden, pumping increased oxygen concentrations and induced deep-water renewals by inflowing water from an adjacent estuary (Stigebrandt et al., 2015). Reduced phosphorus regeneration from sediments was observed, but the long-term benefits of this effort are uncertain. More research is needed on the potential for implementation of sea-based measures and their long-term efficiency in order to better understand their impacts. Important issues including costs, legality, financial liability and, not least, potential environmental impacts, must be addressed before implementation occurs (Conley et al., 2009b).

11.3 Reducing the threat of global warming

Reducing the rate of oxygen decline in the global ocean, and minimizing the contribution of global warming to deoxygenation of coastal waters, requires a dramatic climate mitigation effort, primarily through global cessation of greenhouse gas (GHG) emissions due to human activities (IPCC, 2014, 2018). Restoring oxygen lost over the past century on less than millennial time scales will almost certainly require reducing atmospheric GHG concentrations to levels lower than the present, through active GHG removal (IPCC, 2014, 2018). Both approaches (emission reductions and active removal) are likely to be necessary to achieve the objectives of the United Nations Framework Convention on Climate Change (UNFCCC, 1992): '...stabilization of GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system'. An international commitment to achieve global net zero emissions by 2100 — in order to keep global temperature increase "well below 2 °C" — was made through the 2015 Paris Agreement (UNFCCC, 2016), but national mitigation commitments are currently insufficiently aggressive to achieve that goal (Hansen & Sato, 2016). Human activities have caused an estimated 1 °C increase in global temperatures above pre-industrial levels, and current estimates indicate that global temperatures are now increasing at a rate of 0.2 °C per decade (IPCC, 2018).

Global anthropogenic GHG emissions increased by an order of magnitude during the 20th century, and nearly doubled between 1970 and 2010 (Edenhorfer et al., 2014) (Figure 11.7). Energy production is the largest contributor to global greenhouse gas emissions (72% in 2013; Figure 11.8). Thus, the goal to decarbonize the electric grid through renewable energy, and fully electrify the energy supply, can be considered as joint priorities. However, the pace of those transitions is not currently on track to meet the goals of the 2015 Paris Agreement (REN21, 2019). Growth in global energy consumption averaged 1.5% per year between 2006 and 2016. During that time, the contribution to total energy consumption from all renewables, combined

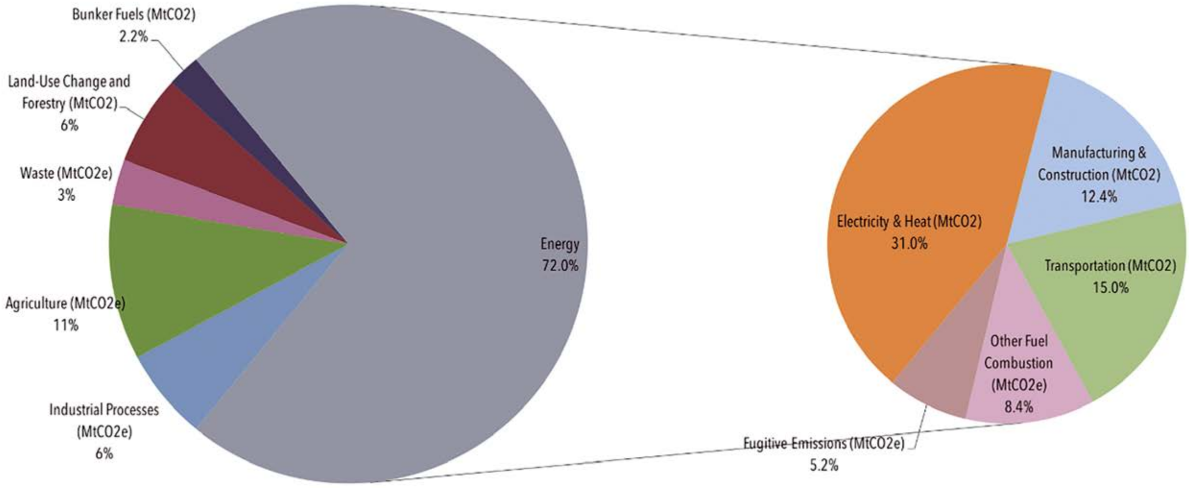


Figure 11.8 The largest global sources of greenhouse gas emissions are electricity and heat, transportation, manufacturing, and agriculture. (Center for Climate Change Solutions, 2017).

(including both traditional biomass and modern renewables) increased only slightly more, by 2.3% annually (REN21, 2019). Eighty per cent of global energy was still generated from fossil fuels in 2017, with less than a 1% decline in contribution to total energy production in the decade 2005-2015 (World Bank – IEA Statistics, 2018). Progress in reducing GHG emissions from heating and cooling, and from transportation, the largest power consumption contributors other than electricity generation, has also lagged (REN21, 2019).

Somewhat more encouraging is the trend to a decarbonized future within sectors and within individual nations and regions. Despite continued subsidies for fossil fuel consumption (estimated at US$300 million in 2017), 2018 marked the fifth consecutive year that global investment in new renewable power capacity exceeded US$230 billion. The contribution to total energy consumption by modern renewables, dominated by wind, solar, and hydropower (Figure 11.9), increased by 4.5% per year between 2006 and 2016, a rate more than three times that of total energy consumption (REN21, 2019). China, currently the largest producer of GHG emissions, also has the highest annual investment in new renewable power and fuels, and a near-complete phase-out of fossil fuels by 2050 is planned in several European countries (France, Norway, Sweden and the UK) in order to meet legal net-zero emission targets (Climate Home News, 2019).

As noted above, global warming can be slowed either by reducing emissions, or by the active removal of greenhouse gases from the atmosphere, also known as

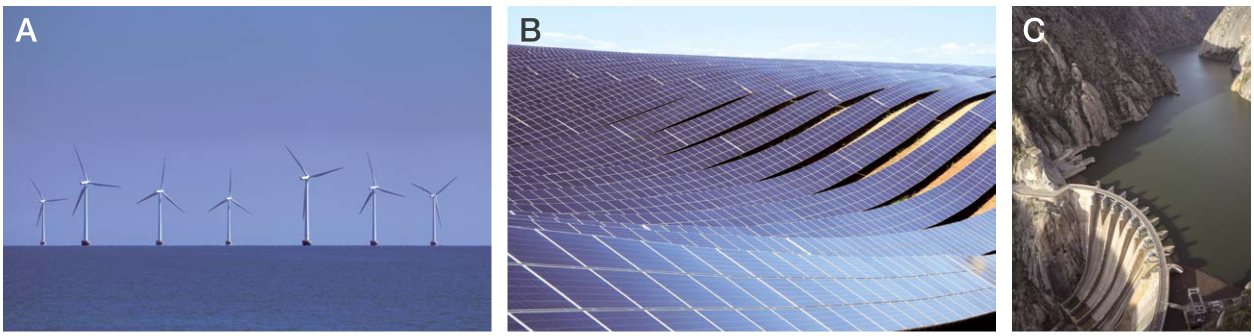


Figure 11.9 (A) Offshore wind turbines in the Baltic Sea © Arterra / Alamy stock photo (B) Large solar panel farm in France © Helene Roche /Alamy stock photo (C) Hydro-electric dam on River Ducro, Spain ©M Afoto / Alamy stock photo.

sink enhancement or negative emissions, as well as by reducing emissions.

Within scenario-based integrated assessment models, bioenergy with carbon capture and storage (BECCS) and increased forestation are the techniques most commonly considered for CO_2 removal (Fuss et al., 2014). A wide range of other approaches have also been proposed (CBD, 2016; Minx et al., 2018); those, that involve ocean-based CO_2 removal and have recently been assessed by Gattuso et al. (2018). For all methods, the feasibility of large-scale removal is contentious, either for technical, environmental or governance reasons (Smith et al., 2016; Williamson, 2016). Nevertheless, IPCC (2014) considered that 'warming caused by CO_2 emissions is effectively irreversible over multi-century timescales unless measures are taken to remove CO_2 from the atmosphere'.

Other proposed climate interventions involve sunlight reflection methods (SRM), also known as solar radiation management. Sunlight reflection methods include stratospheric aerosol spraying, marine cloud brightening and increasing the albedo of the land or ocean surface. Although they are theoretically capable of reducing global temperatures, high uncertainty and risk are involved (Sillmann et al., 2015), with low public and political acceptability (CBD, 2016). The potential implications of different carbon removal and SRM techniques have been considered by several studies in the specific context of ocean acidification (Gattuso et al., 2018; Keller et al., 2014; Williamson & Turley, 2012). However, those considering effects on ocean oxygen (other than direct temperature effects) are more limited. One widely discussed approach, iron fertilization, would exacerbate mid-water and seafloor deoxygenation (Williamson et al., 2018).

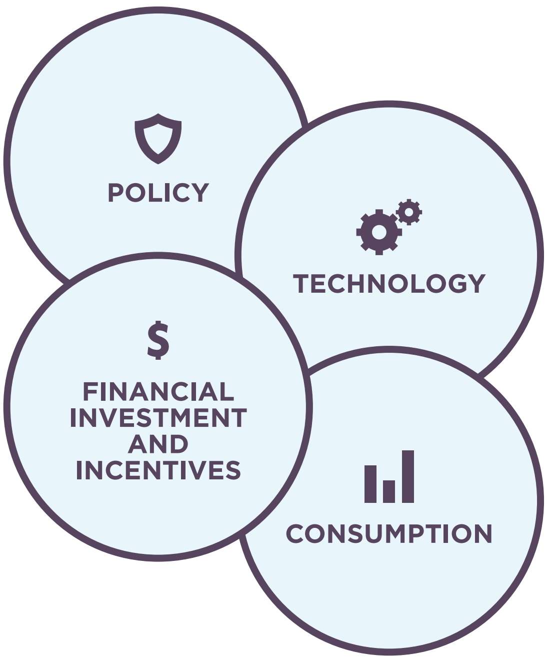


Figure 11.10 Success in addressing global warming requires major emphasis on policy development and implementation, technology development and transfer, economic investment and incentives, and patterns of consumption.

Solving the problem of global warming clearly requires strong commitments in four areas- policy, technology, finance and patterns of consumption (Figure 11.10). Nations will need to adopt very ambitious policies that go beyond those aimed at limiting warming to less than 2 °C if the goal is to halt and reverse ocean deoxygenation. The much smaller increment in warming that occurred between the mid-20th century and present was sufficient to contribute to substantial ocean oxygen decline (Schmidtko et al., 2017). The global ocean is projected to lose 2% of its Year 2000 oxygen content under RCP 2.6, the scenario that is projected to keep global temperature rise below 2 °C (Bopp et al., 2013). The acceptability of a 2% decline in global ocean oxygen is a societal question, not a scientific one, but limiting oxygen loss to 2% would likely cause far less environmental harm than oxygen loss projected for GHG scenarios that result in more severe warming.

Continued rapid advances in technology and future innovation can provide the promise of cleaner energy and healthy societies (Nuttall, 2017), and ambitious development and implementation are key to meeting goals to limit global warming. Development and implementation of policies and technology will require direct investment as well as financial mechanisms that increase the cost-effectiveness and encourage public acceptance of the transformative changes that are required. Both policies and financial resources are also required to ensure justice and equity in the face of changes that will occur.

The good news is that all actions taken to reduce emissions of CO_2 and other greenhouse gases, through the Paris Agreement, other policy instruments and financial incentives, will help to mitigate ocean deoxygenation. Efforts taken at national, regional and local levels all contribute to solutions (Table 11.1).

Table 11.1 Examples of governance actions that address ocean deoxygenation.

Governance Unit	Entities	Mitigation	Adaptation
Local/State	Climate Action Committees, local promulgation of European Climate-ADAPT programme	City commitments to reduce C emissions (e.g. Climate action plans)	Wetland restoration, fisheries management, nutrient reduction programs, green infrastructure
Larger region within a nation	West Coast Acidification and Hypoxia Panel - unified management actions	Carbon Cap and Trade	Coordinated science priorities, fisheries management
National	National Ocean Policy, Clean Air and Water Acts	Regulating CO_2 as a pollutant, Nutrient legislation, water quality limits, Blue carbon initiatives, Carbon Cap and Trade	Research and development programmes, Ecosystem-based fisheries management policies, National Sanctuaries/Protected Areas
Regional/ Transnational	UN - Regional Fisheries Management Organizations	EU Water Framework Directive	Oxygen-sensitive fisheries management for Vulnerable Marine Ecosystems (VMEs), fishing grounds
International	UNFCCC UN General Assembly	Paris Agreement (CO_2 emissions), 2030 Agenda Sustainable Development Goal 14.1	Classification of oxygen as an essential ocean variable for Global Ocean Observing System (GOOS) (science)

11.4 Adaptation in the face of oxygen decline

Given that the ocean has already lost substantial amounts of oxygen (IPCC, 2019; Levin, 2018; Schmidtko et al., 2017), and that many regions and ecosystems will continue to experience deoxygenation, it is beneficial to consider adaptation strategies that may help preserve fisheries and other ecosystem functions and services in affected and adjacent waters. Options include adaptive, ecosystem-based management of fisheries, spatial planning to create refugia that enhance ecosystem resilience, actions that reduce local stress on ecosystems, capacity building and socio-ecological shifts that ameliorate impacts on people. An additional category involves observation, monitoring and mechanistic studies that can improve understanding of hypoxia impacts in space and time and will facilitate management and adaptation.

Where deoxygenation occurs, it can be critical to integrate the oxygenation regime into fisheries management through spatial restrictions that protect oxygen-stressed populations, and through closures and landings limits that reduce overfishing on species vulnerable to direct and indirect negative effects of low oxygen (e.g. Roberts et al., 2012). Because different fish and invertebrate life stages can vary in their vulnerabilities to low oxygen, it may be possible to achieve protection of populations by regulating size limits, gear type, or fishing locations to reduce pressure on the most vulnerable stage or ontogenetic phase. Regulations that require avoidance of particular fishing depths or time periods could reduce fishing pressure in hypoxia-stressed locations (e.g. McClatchie et al., 2010) or seasons, and during episodic hypoxia events.

Spatial planning and the creation of protected areas are increasingly being used to enhance ecosystem resilience in the face of climate change (Le Cornu et al., 2018; Micheli et al., 2012). The effectiveness of area-based spatial management under climate change has been questioned (Johnson et al., 2018). But proactive efforts exist; climate-informed spatial management has incorporated ocean acidification (Queiros et al., 2016), sea-level rise and warming (Le Cornu et al., 2018). All major climate stressors have been modelled for deep seabed mining conservation applications (Dunn et al., 2018), as well as for deep-ocean fisheries management in relation to vulnerable marine ecosystems (FAO, 2019); modelling of potential interactions between deoxygenation and other stressors could inform management and policy. Creation of no-take marine reserves with flexible boundaries that take into account changes in hypoxia distribution, and flexible timing to accommodate hypoxic seasons or events could reduce fishing stress and physical disturbance (Micheli et al., 2012). Hypoxia-induced habitat loss for cowcod (*Sebastes levis*), for example, was a consideration incorporated in management and closures in the US Channel Islands (McClatchie et al., 2010).

Habitat restoration has rarely been considered as an adaptive measure to protect species stressed by low oxygen. Creation or restoration of new nursery, spawning or feeding habitats could facilitate recruitment and contribute to population resilience, while providing additional ecosystem-scale benefits (Petr, 2000). In general, steps that relieve sources of mortality other than low oxygen exposure may help protect populations in systems with hypoxic waters (Breitburg et al., 2009).

Enhanced scientific capacity to monitor oxygen, detect hypoxic events, characterize their spatial and temporal dynamics, and place these in a broader oceanographic and anthropogenic context will aid adaptation to ocean deoxygenation by improving mechanistic understanding, modelling skills, and predictive power. Monitoring networks can facilitate quick-response capabilities. The ability to rapidly assess the consequences of episodic hypoxia for habitat structure, recruitment, and other effects can facilitate rapid, adaptive management decisions and could reduce further impacts on habitat, facilitate recolonization, and aid recovery. Open data access allowing the incorporation of local information in regional and global oxygen syntheses will advance these goals (Breitburg et al., 2018). Improved understanding of thresholds or tipping points as a function of region or ocean basin is needed to inform management practices (Chu & Gale, 2017; Chu & Tunnicliffe, 2015). The Argo float programme (Figure 11.11) has offered unprecedented synoptic and regional views of oxygen in the open ocean (Martz et al., 2008; Takeshita et al., 2013), and local, national and regional monitoring programmes have done the same in coastal waters. A combination of raised awareness, technology transfer, and instrumentation training to build capacity in developing countries is needed. Additionally, development of inexpensive, easy to maintain and simple to deploy, continuous oxygen monitoring tools and platforms will enable engagement of more countries and regions. Creative use of fishing vessels, ferry lines, shipping infrastructure, and smart cables could be considered.

In addition, although still in the developmental phase, there is growing evidence that fishes themselves can be "mobile monitors" of their habitats and that

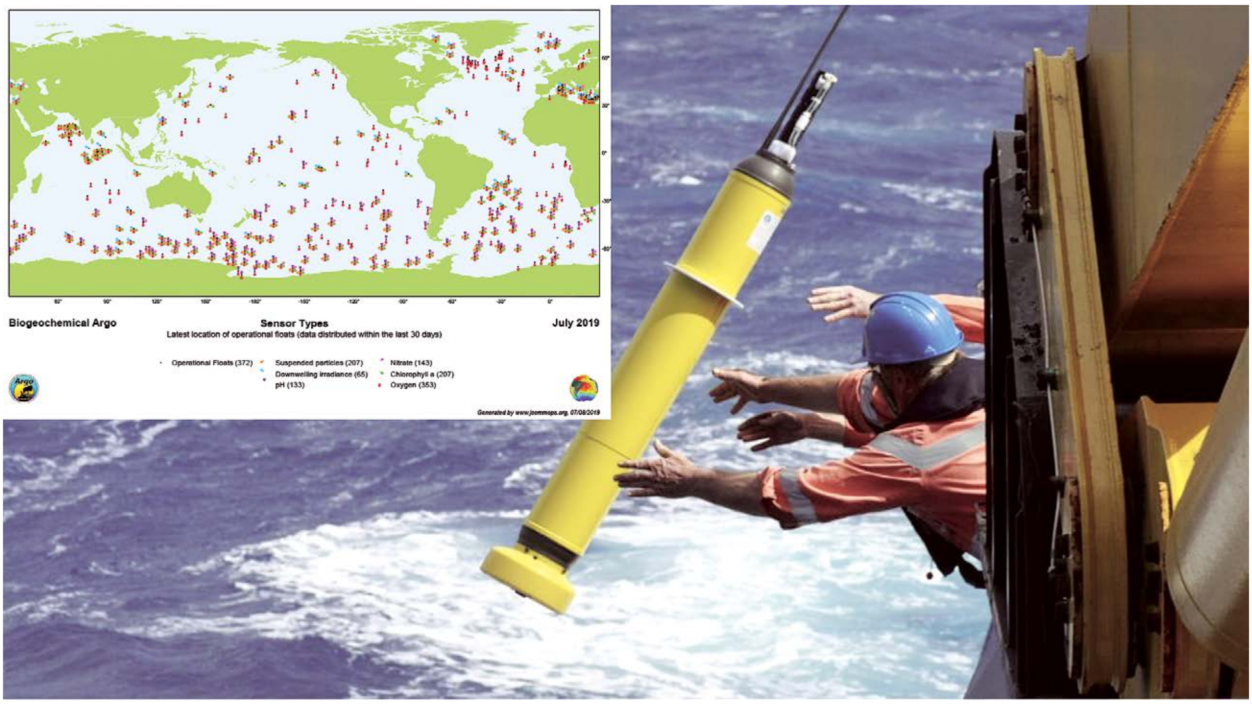


Figure 11.11 The deployment of an Argo Float in the Indian Ocean. Map showing the locations of 372 operational Argo floats equipped with biogeochemical sensors, of which 353 have an oxygen sensor in July 2019. Argo floats freely drift in the ocean at a parking depth of 1,000 m, and perform vertical profiles of temperature, salinity, oxygen and other parameters every 10 days between 2,000 m depth and the sea surface. (Sources: Map JCOMMOPS; photo: CSIRO *https://blog.csiro.au/bio-robots-make-a-splash-in-the-indian-ocean/*; images and figure legend from GO_2NE, 2018).

lifetime exposure to hypoxia can be tracked through geochemical proxies in fish otoliths (ear-stones), the small, calcified structures that form part of the hearing and balance system (Limburg et al., 2011, 2015). Because otoliths grow throughout life and lay down annual increments like tree rings, they can record the chemistry of waters in which fish develop, and chemical proxies can be developed from the trace elemental composition of otolith rings. In combination with age information derived from ring counts, it is possible to generate powerful chronologies of hypoxia experienced directly by fishes (Limburg et al., 2011) that can aid in the management of species and populations sensitive to the effects of hypoxia (Figure 11.12).

There are also important scientific-sociological linkages to consider in developing adaptation strategies to minimize the negative effects of oxygen decline. Deoxygenation is most likely to impact local economies, livelihoods and food security in areas where either artisanal or subsistence fisheries rely on vulnerable resources, aquaculture facilities are susceptible to hypoxia, or tourism relies on vulnerable ecosystems (Breitburg et al., 2018). Hypoxia-induced mortality in aquaculture (San Diego-McGlone et al., 2008) can compromise livelihoods or harm human health (Cayabyab et al., 2002). A lack of human mobility to track resources or move to unaffected areas for economic, cultural or other reasons, may mean that adaptation requires shifting sources of food, jobs and income. Linking governance actions across sectors (environment, fisheries, labour and other ministries or agencies) and jurisdictions (watershed, coastal, marine) would be key to effective integrated management of hypoxia for ecosystems and people.

11.5 Governance and collaboration

Locally designed and implemented actions can be successful at mitigation of low oxygen conditions, and for adaptation to locally degraded conditions, where the cause of deoxygenation and the affected water body fall within a single jurisdiction. But this is rarely the case even for the problem of excess anthropogenic nutrients, and is even less likely for deoxygenation caused by global warming. Collaborative efforts among governance units within nations are required where watersheds, airsheds and fisheries management units cross jurisdictional boundaries of villages, cities and provinces. Even where manifestations of problems are geographically confined, larger economic and political boundaries influence options for solutions. At large scales, regional and broader international collaboration in science, policy development and implementation are critical to solving, mitigating, and adapting to the problem of ocean deoxygenation.

International and regional scientific collaboration and cooperation are key to building capacities, to raising awareness, to improving management strategies and to informing policy decisions. The complexity, severity and geographic extent of problems like ocean deoxygenation requires that the best science from across the globe on a wide range of topics be used, and that there is a continued effort to build scientific capacity in both developed and developing nations. The IPCC and its working groups, with hundreds of members, authors, reviewers and editors from nations throughout the world is a model of the efforts that can be marshalled to address problems at a global scale. Scientific understanding and collaboration are proving

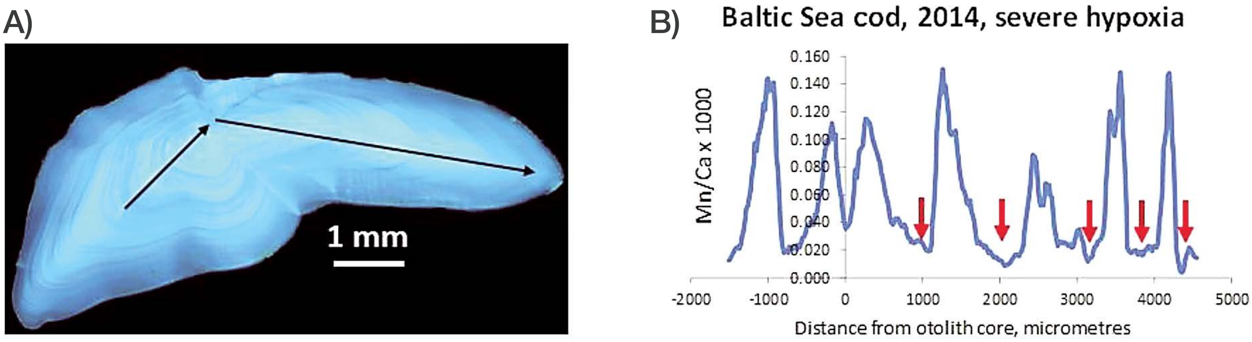


Figure 11.12 (A) Otolith cross section and (B) Mn/Ca ratios of a Baltic Sea cod, *Gadus morhua.* The peaks in Mn/Ca on the graph correspond to seasonal hypoxia exposure. Baltic cod exposed to increasing amounts of hypoxia, as shown in the chemical signature in their otoliths, experience a decline in body size (Limburg & Casini, 2018). The incidence of hypoxia exposure in these fish is increasing over time, with greater exposure during the current decade (2010s). Foregone biomass (losses from hypoxia exposure) is yet to be calculated for the entire population, but for three-year-old cod, those exposed to high levels of hypoxia (> 75% of the year), weight is estimated to be 64% lower than for cod residing in low levels of hypoxia (< 25% of the year). Black arrows on the otolith photos show the tracks of a laser that was used to sample the otoliths for the chemical analyses. Red arrows on (B) indicate wintertime minima.

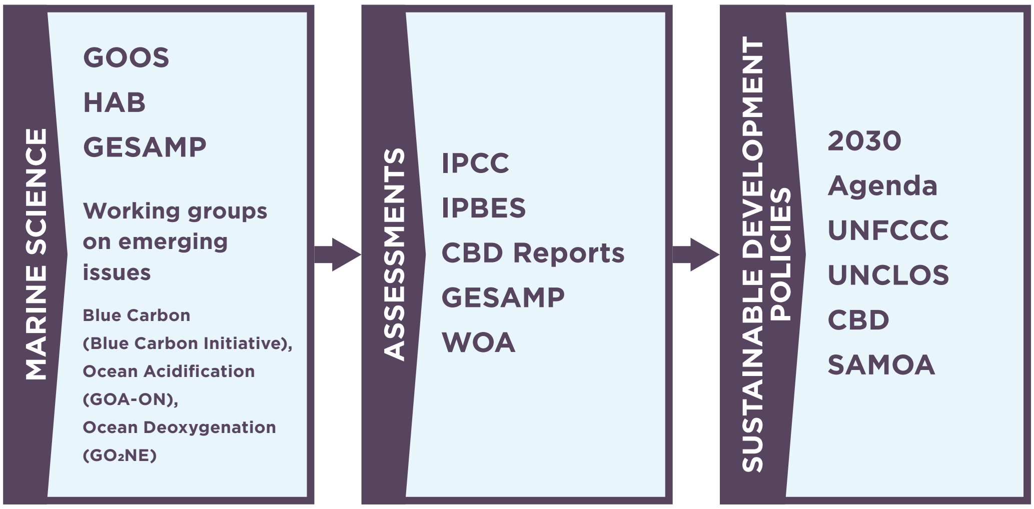


Figure 11.13 From Science to Policy. Examples of the different stages and instruments involved in the marine science-policy interface, starting from marine science, to assessments, to sustainable development policies. Acronyms and abbreviations not defined elsewhere: IPCC = Intergovernmental Panel on Climate Change; IPBES = Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services; CBD =Convention on Biological Diversity; UNCLOS = United Nations Convention on the Law of the Sea; SAMOA = SIDS [Small Island Developing States] Accelerated Modalities of Action pathway.

critical to identifying a wide range of ocean problems and their solutions from the accumulation of plastic in the ocean (e.g. GESAMP WG 40 - Group of Experts on the Scientific Aspects of Marine Environmental Protection Working Group focusing on sources, fate and effects of plastics and micro-plastics in the marine environment) to the implementation of harmful algae blooms warning systems (IOC-UNESCO, 2017).

The science-policy interface is especially important as climate and ocean change increasingly affect ocean health and marine resources. In response to this need, UN organizations and NGOs coordinate interdisciplinary scientific working groups and programmes, focusing on emerging issues, important to ocean and human health, including ocean acidification (Global Ocean Acidification Observing Network (GOA-ON)), coastal Blue Carbon ecosystems (the Blue Carbon Initiative), and Harmful Algae Blooms (IOC HAB Programme). The information and findings compiled and obtained by these working groups contribute directly to global assessments, including the Intergovernmental Panel for Climate Change and the World Ocean Assessment, which in turn are the basis for global sustainable development policies, such as the 2030 Agenda for Sustainable Development (UN General Assembly, 2015) and the UNFCCC (UN General Assembly, 1994) (Figure 11.13)

In 2016 the IOC-UNESCO established the 'Global Ocean Oxygen Network' (GO_2NE) expert group as the first international body with a primary focus on the causes and impacts of decreasing oxygen levels on the ocean, including its coastal waters (IOC/EC-XLIX/2 Annex 6, IOC EC-XLIX, Dec. 4.1 (III)). The charge of GO_2NE includes the science of physical, chemical and biological processes, marine and human life, and the ecological goods and services the ocean provides. GO_2NE aims to provide needed scientific input, facilitate communication among different stakeholders, and help support decision makers to take measures required to stem increasing deoxygenation at local, regional and global scales. This global effort is expanding to include focused working groups, such as the regional group the Western Pacific Ocean Oxygen Network (WESTPAC O_2NE), and to work on important topics collaboratively with other international scientific working groups (e.g. the International Ocean Carbon Coordination Project working group VOICE - Variability in the Oxycline and Its Impacts on the Ecosystem, and the Scientific Committee on Oceanic Research (SCOR) working group 155 focusing on Eastern Boundary Upwelling Systems (EBUS): diversity, coupled dynamics and sensitivity to climate change). These groups are indispensable in the identification of specific steps to slow and reverse deoxygenation and its effects, which vary among locations depending on the cause of the problem, and co-occurring stressors.

Scientific cooperation will be critical to ensure that ocean oxygen levels are sufficient to continue to support vital marine ecosystem services, and to manage ocean resources in a sustainable manner (Agenda 2030, Sustainable Development GOAL 14)

Box 11.1. Further progress in the science of ocean deoxygenation is needed to better predict the patterns and consequences of ocean oxygen decline, and to inform policies and technological solutions to reduce further decline (GO_2NE, 2018). Critical areas include:

- Expanding oxygen observations in the open ocean and coastal waters, including through integration with existing programmes and networks, targeting regions where more data will improve assessment of the current status and patterns of oxygen change.
- Experiments and observations to improve understanding of critical mechanisms that control the patterns and effects of oxygen declines.
- Numerical models with improved ability to predict current effects of low oxygen and other stressors, future changes in oxygen levels, and potential benefits of management options at global, regional and local scales.
- Assessments of effects on human economies and societies, especially where oxygen declines threaten fisheries, aquaculture and livelihoods.
- Development of a data management system, with rigorous quality control and leadership by a globally recognized oceanography data centre that provides open access for use in science and policy.
- Continued improvement of oxygen monitoring equipment, including sensors that accurately measure ultra-low oxygen concentrations and low-cost sensors that will make more extensive monitoring in undersampled coastal waters possible.
- Capacity building in coastal areas of the developing world for observations on core oceanographic parameters, especially oxygen, and on the impact of deoxygenation on fisheries and biodiversity, will have to be given high priority.

(Voluntary Commitment GO_2NE: #OceanAction15767: Enhancing global ocean oxygen science from local seas to the global ocean to preserve ocean health and human well-being). Focused working groups will help to broaden understanding and contribute to the underlying science regarding the influence of nutrient pollution on increasing deoxygenation (SDG 14.1). They support the implementation of sustainable fisheries (SDG 14.7), and aim to improve the knowledge of how reduced oxygen levels are linked to additional stressors, such as harmful algal blooms, ocean acidification and global warming, that combine to reduce marine ecosystem resilience and ecosystem services (SDG 14.3).

11.6 Improving predictions of future patterns and effects

Solutions to ocean deoxygenation, and development of adaptation strategies in its presence, depend on sound and sufficient science. As this report shows, great strides have been made in understanding the causes, consequences and future patterns of ocean oxygen decline. But there are still great challenges in projecting the current information to the large temporal and spatial scales needed to implement sound policies and to improve predictions of future conditions and impacts on human welfare (Breitburg et al., 2018) (Box 11.1.).

Natural and social science advances are also critical to increasing the recognition of ocean deoxygenation as an important consequence of human alterations to our global environment. To date, little direct evaluation of the ecosystem services threatened or already impaired by deoxygenation has occurred. Yet these evaluation exercises could readily be performed. A pluralistic approach to ecosystem services valuation, adopting multiple metrics, will provide a more complete picture of services at risk (Limburg et al., 2002).

11.7 Concluding comments: The way forward

Curtailing ocean oxygen loss due to climate change, restoring oxygen lost as a result of excess nutrient discharges, and minimizing negative effects of deoxygenation now and in the future, require steps that are straightforward in their simplest expression, but difficult, and costly to put into practice. Ultimately, however, the societal cost of inaction is too great to ignore. The path towards improved oxygenation of the earth's ocean and coastal waters requires:

- Reduction of greenhouse gas emissions that cause atmospheric and ocean warming.
- Reduction of nutrient inputs to the ocean that exacerbate oxygen loss in coastal waters.

- Inclusion of climate change effects in developing nutrient reduction strategies.
- Alleviation of anthropogenic stressors (e.g. pollution, overfishing, trawling or mining/drilling disturbance) that threaten resilience and increase vulnerability of marine ecosystems to deoxygenation.
- Adoption and implementation of marine spatial planning and fisheries management strategies that identify deoxygenation vulnerabilities and protect species and habitats.
- Recognition of ocean deoxygenation as one of multiple climate-induced stressors.
- Unification of research, management and policy actions across coasts and the open ocean, across biology, geochemistry, and physics, and the social sciences, across problems of warming, acidification and deoxygenation, and across academic, industry, government and regulatory sectors (IOC, 2018).

Under the Paris Agreement nations declared their intent through nationally determined contributions (NDCs). While 70% of the 161 nations submitting NDCs recognized the importance of the ocean for climate mitigation and most recognized ocean warming, only one made the link to ocean deoxygenation (Gallo et al., 2017), suggesting the need for much stronger communication with international policy makers such as delegates to the UNFCCC. Our hope is that this report represents a step towards greater recognition of ocean deoxygenation as an environmental, societal and economic problem, and contributes to solutions.

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