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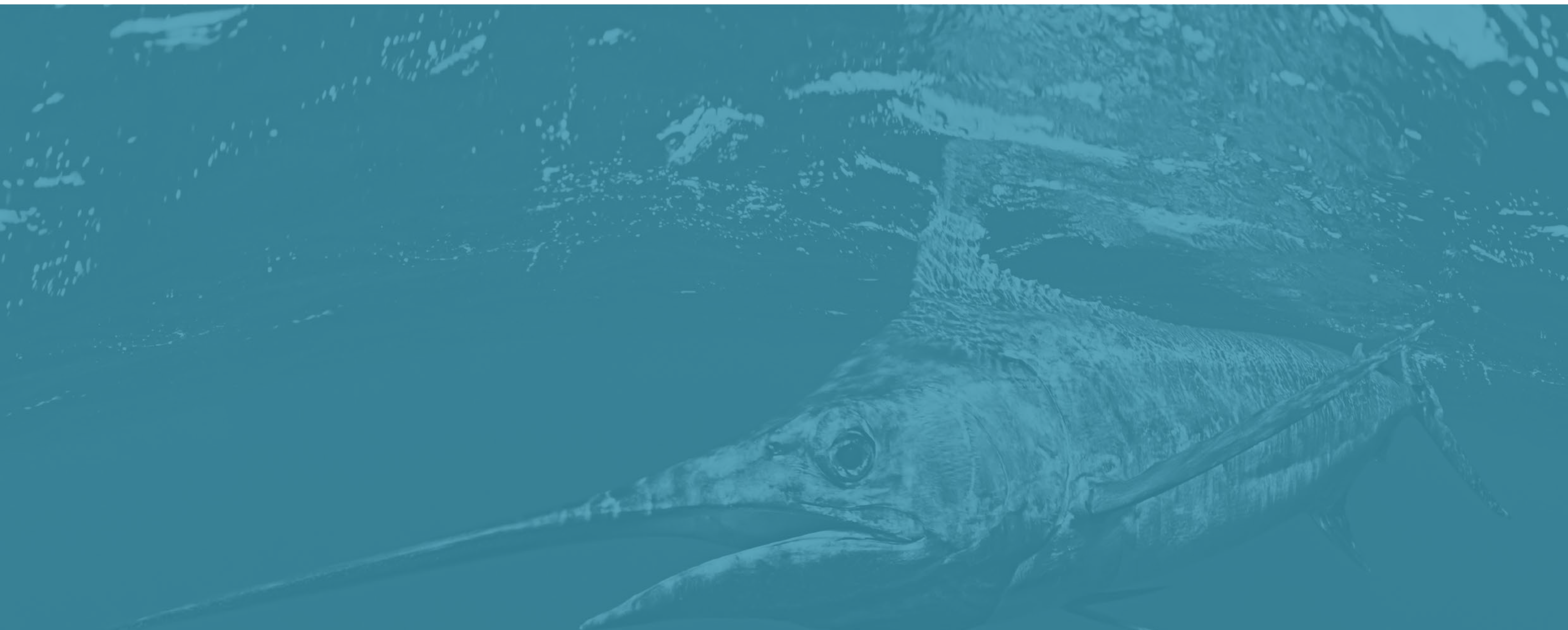
Ocean deoxygenation: Everyone's problem

Causes, impacts, consequences and solutions

Edited by D. Laffoley and J.M. Baxter



3.2 Ocean deoxygenation from eutrophication (human nutrient inputs)

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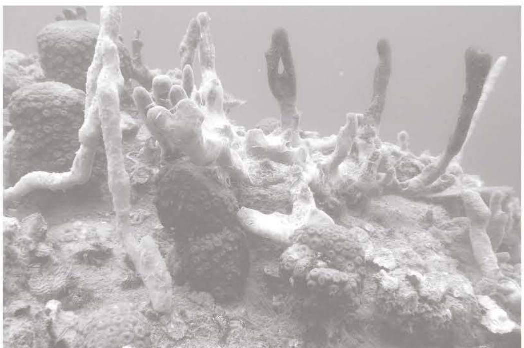

IUCN GLOBAL MARINE AND POLAR PROGRAMME

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3.2 Ocean deoxygenation from eutrophication (human nutrient inputs)

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SECTION 3.2

Summary

- Coastal deoxygenation is driven by excess human inputs of nitrogen and phosphorus that increase the production of carbon and its accumulation in the ecosystem.
- Respiration of the excess carbon by bacteria results in oxygen deficient waters in stratified systems.
- Deoxygenation reduces suitable habitats for many bottom-associated marine organisms and disrupts biogeochemical cycles.
- Climate-driven increases in water temperature and increases in watershed precipitation will likely aggravate estuarine and coastal ocean deoxygenation.
- Mitigation measures require social and political will but can be effective.

Eutrophication-driven low oxygen	Potential consequences
Post-industrial expansion in the 1850s, human alterations to watersheds, and increasing use of artificial fertilizers in the 1950s to present have increased the amount of reactive nitrogen (Nr-N) in the ecosphere by three-fold.	• Enhanced phytoplankton production in estuaries and coastal waters and accumulation of organic matter in the lower water column and sea bed. • Excessive algal biomass, which may be noxious or harmful (toxin-production). • Excess carbon reaches the lower water column and sea bed in the form of senescent algal cells, zooplankton faecal pellets, or aggregates.
Physical features of the water column confine the geographic extent of oxygen deficiency in coastal waters; increased nutrients support enriched phytoplankton.	• Haline or thermal stratification, or both, dictate the presence of a pycnocline (strong density difference in the water column) across which dissolved oxygen diffusion is hindered. • Increased water residence time enhances the probability of oxygen depletion occurring in a coastal area. • There is an optimal depth at which oxygen deficiency may develop; shallower waters are usually well-mixed and deeper waters do not receive as much fluxed carbon. • Physical barriers such as sills at depth, and advection of offshore waters affect the level of deoxygenation, positively or negatively.
Eutrophication-driven deoxygenation affects living resources and coastal ecosystems.	• Low oxygen decreases suitable habitats for many bottom-dwelling marine organisms. • Organisms that can swim away do, but the remaining immobile and burrowing fauna will eventually perish in low oxygen conditions for extended periods. • Low oxygen water masses alter migrations, reduce food resources for resident fauna during and after low oxygen events, and affect growth and reproduction.
Reduction of nutrient loads will require social and political will and a reversal of human consumptive habits.	• Improvements in nutrient management have lessened the negative effects of deoxygenation in multiple areas. • Reduction in excess nitrogen requires less use of fossil fuels, implementation of best management practices for agriculture, improved wastewater treatment, and changes in food habits. • Anticipated climate changes with warmer waters and increased precipitation will likely aggravate deoxygenation.

3.2.1 Introduction

Human activities alter landscapes and air and water quality in the process of providing food, fuel and fibre to a burgeoning human population. Reactive forms of nitrogen (Nr-N) generated by fossil fuel burning (post 1850s) and industrial production of fertilizers (post 1950s), as opposed to inert N_2 gas generated naturally through lightning and biological nitrogen fixation, enter the environment three times more now than historically (Galloway et al., 2008, 2014; Gruber & Galloway, 2008; Reed & Harrison, 2016; Seitzinger et al., 2010). Mining for phosphorus, since the middle of the 17th century, for use primarily as fertilizer, has resulted in an approximate tripling of the quantities stored in terrestrial and aquatic ecosystems, with a similar three-fold increase in the flux to the coastal ocean (Bennett et al., 2001). These life-supporting, but in excess, nutrients find their way to estuarine and coastal waters where they support high and often massive production of phytoplankton cascading at times to deoxygenation of the receiving waters. The process of excessive production of carbon, in this case phytoplankton, is known as eutrophication, and usually results from high nutrients loads into aquatic ecosystems. Symptoms of eutrophication in aquatic ecosystems are noxious, and often toxic, harmful algal blooms and the reduction of dissolved oxygen concentrations, i.e. deoxygenation.

The post-industrial revolution increase in the use of fossil fuels, beginning in the 1860s, rose gradually over the next 100 years consistent with population growth

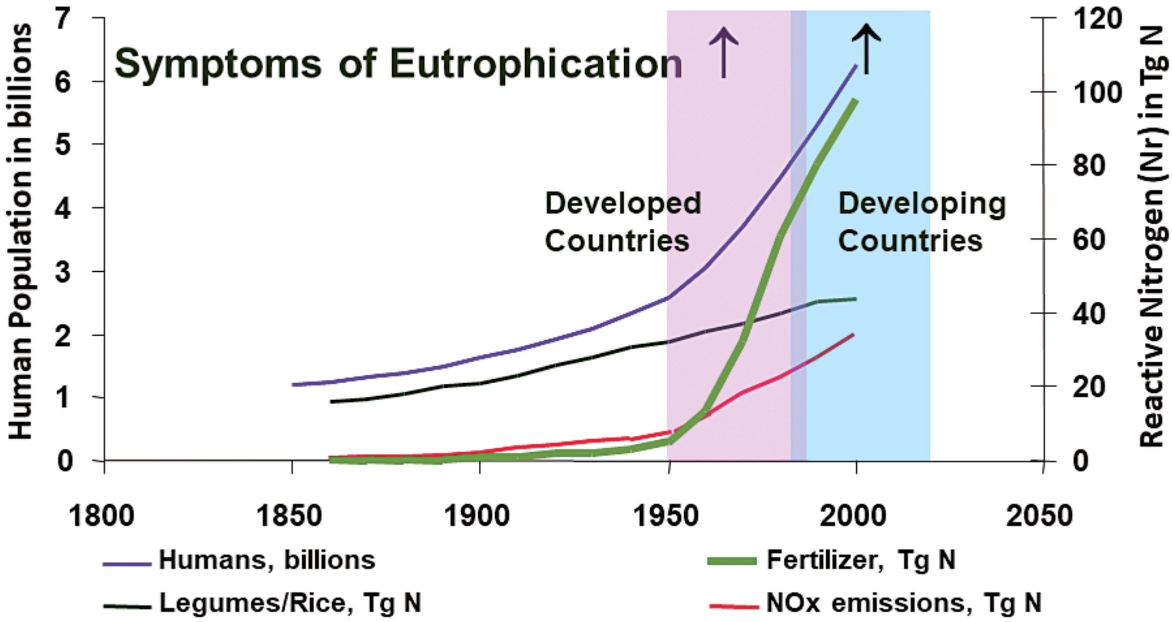

Figure 3.2.1 Period in which the symptoms of eutrophication and hypoxia/anoxia began in developed countries and how the onset of symptoms has shifted in more recent years to developing countries (Rabalais et al. (2014), modified from Galloway and Cowling (2002) and Boesch (2002)).

up to the 1950s (Galloway et al., 2014) (Figure 3.2.1). From then to the 1980s, Nr-N increased linearly by 2.5-fold as fossil fuel use continued to rise with population growth but also as Haber-Boesch production of fertilizer increased along with its increasingly inefficient use in agriculture. Nr-N production has stabilized since the 1980s to ~2010 from off-setting activities, such as reduced NOx emissions coupled with increased fertilizer use for corn production to support ethanol production and animal production. Along with numerous greenhouse gases that contribute to climate change, nitrous oxides (NOx) from the burning of fossil fuels are emitted to the atmosphere and return to the landscape in wet and dry deposition. Planting of legumes, such as alfalfa and soybeans, which naturally fix N_2 in root nodules, also increased gradually since the 1860s, as fodder for animals and rotation with other crops, and contribute to excess Nr-N. However, these crops are also fertilized at times. Nitrogen in fertilizers and animal manure is easily turned into gaseous ammonium and returns from the atmosphere to the watershed via precipitation as another reactive N form. As more and more people need food, agricultural expansion continues, and agribusiness and high fertilizer use become part of a global change in landscapes. Other large-scale landscape changes marginalize the ability of natural ecosystems to convert Nr to inert N_2 gas. These include deforestation, loss of wetlands, drainage of croplands via ditches and subsurface tile drains, impervious surfaces, and changes in hydrology, such as leveeing of rivers that would otherwise allow for natural removal of nitrogen within a flood plain.

The symptoms of eutrophication, including harmful algal blooms and oxygen-deficient bottom-waters, began to occur in parallel with increasing nitrogen loads from the 1950s to 1980s in heavily industrialized watersheds and where artificial fertilizer use steadily increased. These shifts and relationships are consistent in sediment biological and geochemical palaeo-indicators (see Chapter 5). The cohesive temporal patterns of eutrophication and oxygen deficiency are clearer where the number of proxies is higher (Gooday et al., 2009). In regions around the globe where the increase in riverine nutrients was not observed prior to the 1980s (e.g. the lower Changjiang at Datong station; Li & Daler, 2004), nitrate-N rose dramatically up to 2000, when records stopped. Small areas of low oxygen bottom-water (< 1000 km^2) were mapped off the Changjiang in the East China Sea in 1988 and 1998. Since then, the presence of large areas of bottom-water oxygen depletion (> 10,000 km^2) was first documented in 1999 and again in three additional years through to 2013 (compiled by Zhu et al., 2017) The various areas of bottom-water low oxygen surveyed in the East China Sea did not have similar station grids, nor were the defined levels of "low" dissolved oxygen concentrations the same. Regardless, the timing of increasing river nitrogen levels and occurrence of low oxygen conditions followed the time pattern suggested in Figure 3.2.1 for "developing" nations.

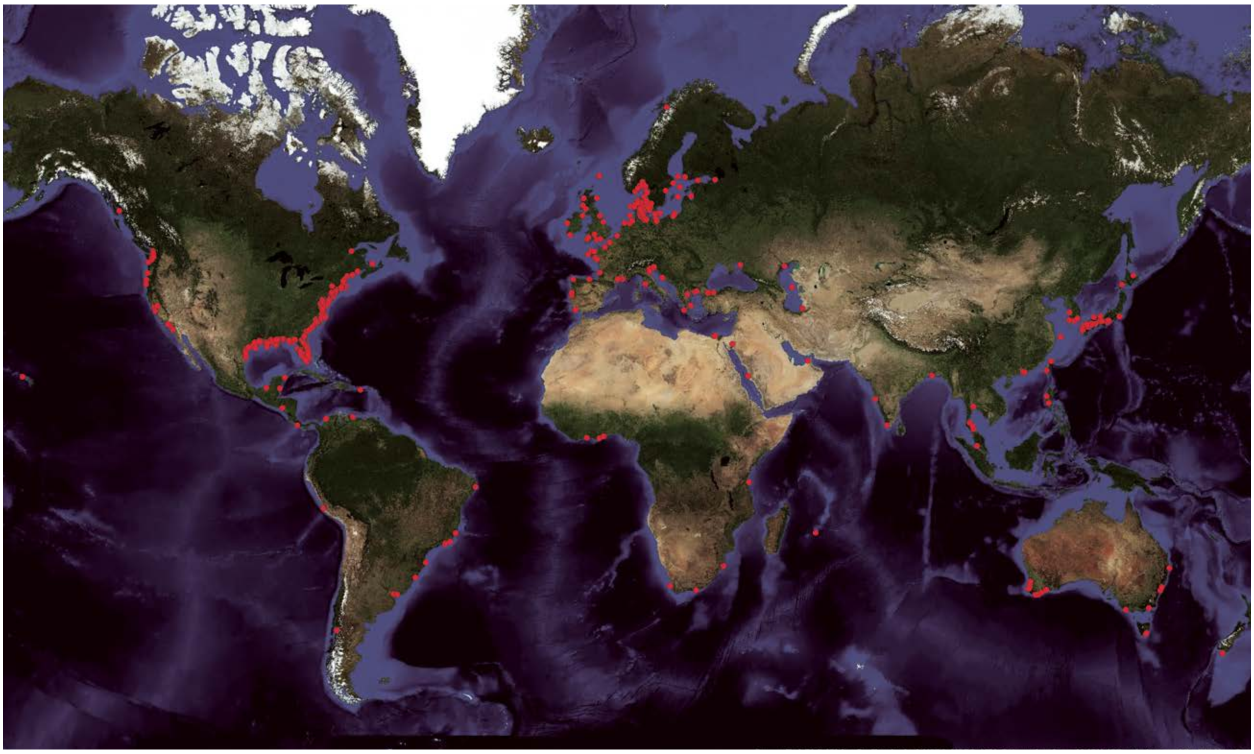

Figure 3.2.2 Distribution of human-caused areas of coastal deoxygenation. A dot represents the first time an area was identified in the scientific literature (as compiled by Diaz and Rosenberg (2008) with some updates). The size of the dot does not correspond to the area or volume of deoxygenated waters. Plotted with data from the World Resources Institute in 2016 (http://www.wri.org/resource/interactive-map-eutrophication-hypoxia; accessed November 2017).

The number of human-caused coastal ocean areas of deoxygenation has risen significantly since the 1960s (Diaz & Rosenberg, 2008) (Figure 3.2.2) with an approximate doubling of the number of areas every decade since the 1960s through 2007. Multiple coastal areas in the Baltic Sea were identified more recently from hydrographic data records (Conley et al., 2011). The number of deoxygenated waters in coastal areas is considered to be about 500 (Breitburg et al., 2018; Diaz & Rosenberg, 2008) but reflects different methodologies and approaches to "counting," grouping or not grouping closely related areas, quality of data, and institutional capacities to conduct the necessary research. For example, Altieri et al. (2017) compiled data on deoxygenation from tropical regions, where the number of low oxygen areas per capita of coastline was much lower than in temperate regions where institutional research capacity is much greater. Furthermore, they concluded that coral reefs are associated with half of the known coastal tropical deoxygenated waters with over 10% of all coral reefs at elevated risk for deoxygenation based on local and global risk factors. There are, however, areas that are no longer oxygen deficient due to management scenarios to reduce excess nutrients (see 3.2.7).

3.2.2. Process of coastal deoxygenation

The physical, chemical and biological processes that lead to deoxygenation differ in magnitude and importance by water body, but there is one basic response (Figure 3.2.3). Deoxygenation occurs when the amount of dissolved oxygen in the water column is decreased by the process of respiration at a faster rate than resupply. Resupply could be through air-sea exchange, photosynthetic production of oxygen, advection of oxygenated waters, or by diffusion of dissolved oxygen across a density barrier. The density barrier, or pycnocline, forms horizontally between two water masses that differ in temperature, salinity or both. The density difference prevents the diffusion of oxygen from a higher concentration layer to a lower concentration layer. In some areas, upwelled waters provide nutrients for the stimulation of primary production, especially Eastern Boundary layers, or bring oxygen-deficient waters from depth onto the continental shelf. These are not features of the Gulf of Mexico shelf adjacent to the Mississippi River, which forms the basis of the Figure 3.2.4.

The carbon source that fuels the respiratory reduction of oxygen most often originates from settled phytoplankton

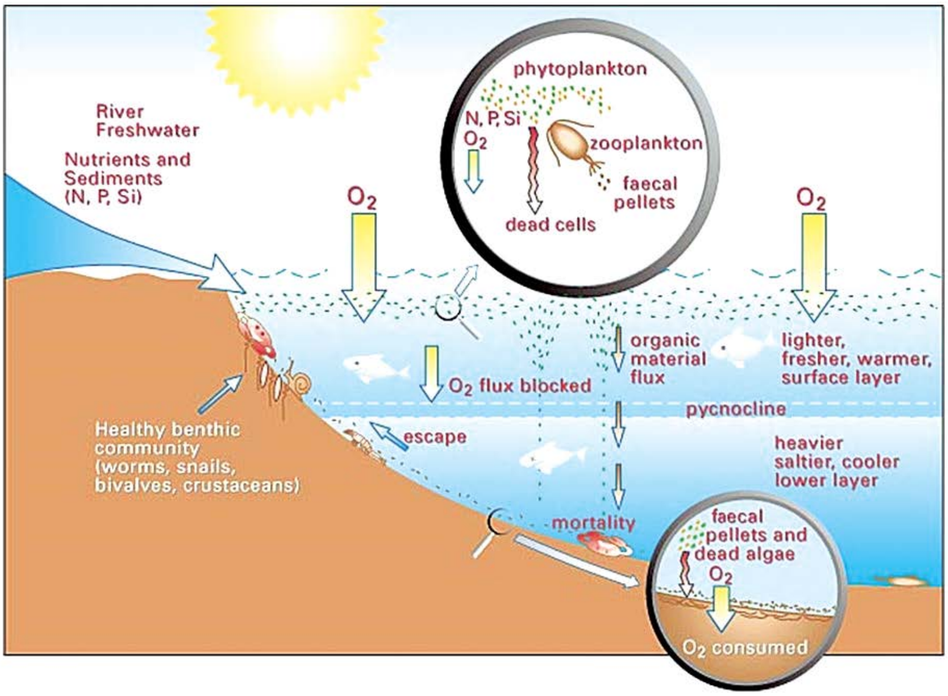

Figure 3.2.3 Biological, chemical and physical processes of eutrophication-driven coastal deoxygenation (modified from Downing et al., 1999).

production in the form of senescent phytoplankton cells, zooplankton faecal pellets, or marine aggregates. The organic matter sinks below the pycnocline to the lower water column or to the sea bed. Aerobic bacteria that utilize the carbon source consume oxygen in the process and deplete the dissolved oxygen in the water column below a strong density gradient. The byproduct, carbon dioxide, is generated and accumulates in the lower water column, leading to acidification.

The responses of marine organisms range from mortality to shifts in behavioural and reproductive ecology. Organisms that are motile will try to emigrate from the area; others living within the sediments move closer to

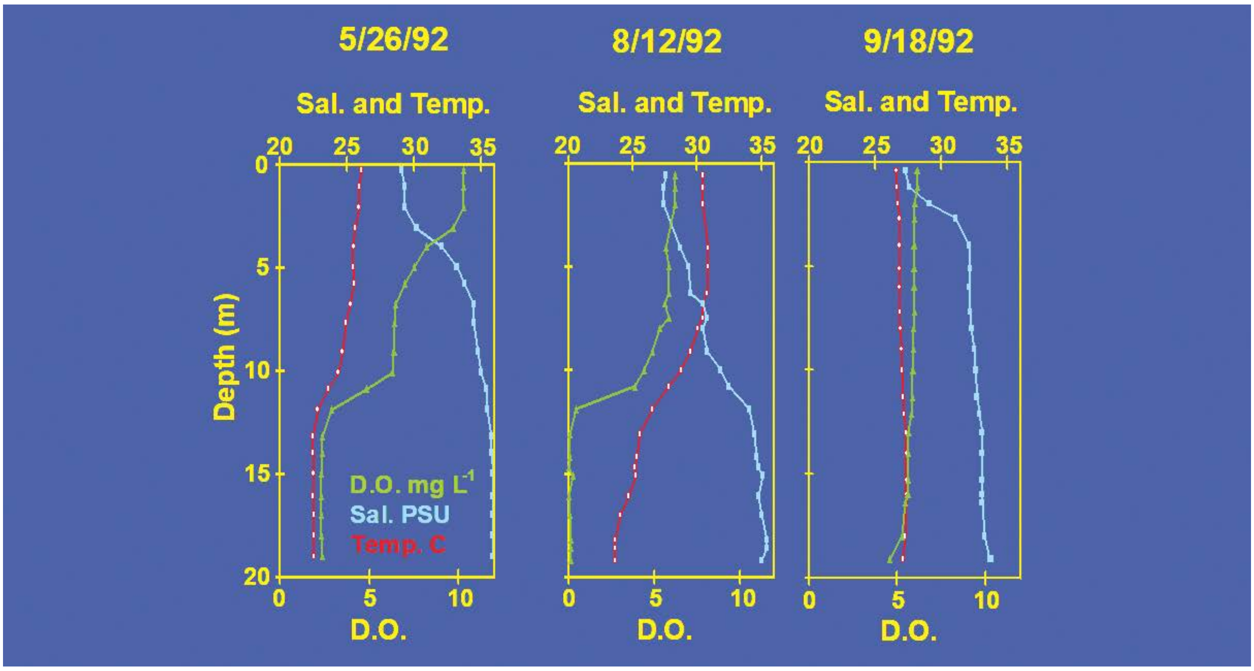

Figure 3.2.4 Development of thermal and haline stratification in spring and summer and mostly destratified water column in autumn, northern Gulf of Mexico continental shelf west of the Mississippi River. Source: N.N. Rabalais.

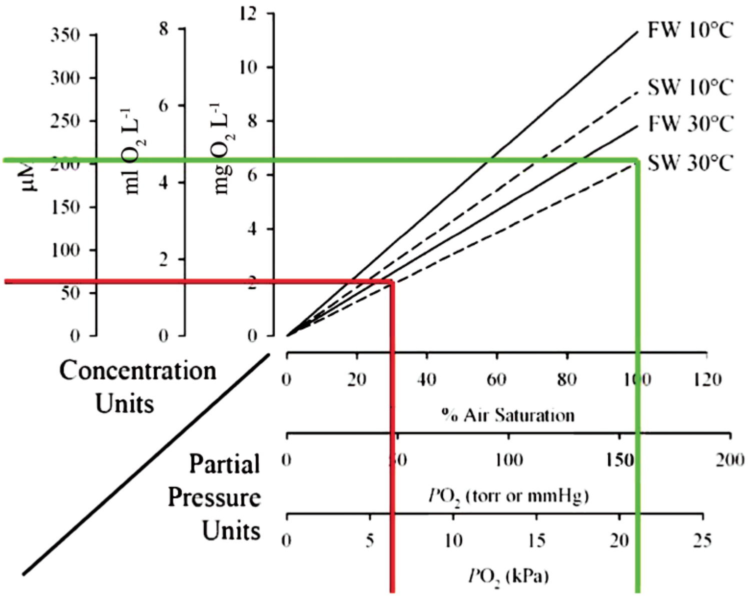

Figure 3.2.5 Nomogram for dissolved oxygen in fresh water (FW) and sea water (SW) at 10 °C and 30 °C (Rabalais et al. (2010), modified from Diaz and Breitburg (2009)). Concentration units are on the Y-axis, and partial pressure units are on the X-axis. Red line is the common definition of "hypoxia" at 2 mg O_2 L^{-1} dissolved oxygen, or approximately 30% saturation. Green line is 100% saturation in sea water (salinity of 35) at 30 °C.

the sediment-water interface but will eventually die if the dissolved oxygen concentration remains low for long enough. Migration is altered, suitable habitat is reduced, and fish and shellfish landings may be reduced.

3.2.3 Dissolved oxygen levels

There is no agreed definition of what concentration or saturation level equates to deoxygenation. It is the process of loss of dissolved oxygen in a water body over time, in this case through eutrophication-induced oxygen deficiency (Cloern, 2001; Diaz & Rosenberg, 2008; Rabalais et al., 2010). The ability to document change over time is difficult due to a lack of suitable long-term data (Gilbert et al., 2010). Yet, Gilbert et al. (2010) found considerable evidence of decreasing levels in dissolved oxygen concentrations for many areas of the coastal ocean and the open ocean, with the rate of decline an order of magnitude greater in the coastal ocean (within 30 km of the coast) versus the open ocean (> 100 km from the coast).

The solubility of oxygen in coastal waters is determined by a combination of salinity and temperature. Dissolved oxygen saturation decreases with increasing salinity at similar temperatures, and decreases with increasing temperature at similar salinities (Figure 3.2.5). Warming oceans and coastal waters with climate change are expected.

"Hypoxia" is a commonly used term for waters with less than 2 mg O_2 L^{-1} of dissolved oxygen (equivalent to 1.4 ml L^{-1}, 63 µM, or approximately 30% oxygen saturation). This is the dissolved oxygen concentration where demonstrable behaviour by marine life, such as escape of bottom-dwelling fish and mobile invertebrates out of the area (Figure 3.2.6) or mortality of sedentary crabs, molluscs and worms, occurs. Others, including regulatory agencies, identify a range of physiological or behavioural changes along a continuum of oxygen concentrations (Vaquer-Sunyer & Duarte, 2008).

Figure 3.2.6 Brittlestars and gastropods, normally hidden in cryptic spaces on a coral reef, attempting to flee low-oxygen conditions during a hypoxia event that affected coral reefs on the Caribbean coast of Panama in 2017. Hypoxia resulted in the mass mortality of brittlestars, gastropods, and other motile invertebrates. © Dr Maggie D. Johnson.

Figure 3.2.7 Wilson Inlet, Australia © dpa picture alliance / Alamy stock photo.

3.2.4 Geography

The main features of a coastal area that becomes deoxygenated are: (1) high biological production from over-enrichment by high nitrogen and phosphorus loads; (2) a stratified water column from salinity, temperature or both, mostly in water depths < 100 m; and (3) long water residence time. Longer water residence time allows for development of phytoplankton blooms, containment of fluxed organic matter and the development of stratification.

3.2.4.1 Estuaries

Estuaries vary in physiography, but those most conducive to the formation of hypoxia are characterized by longer water residence times that allow for accumulation of carbon and respiratory depletion of oxygen. Stratification is also a key factor for the development and maintenance of deoxygenation, e.g. Chesapeake Bay, USA (Kemp et al., 2005) and Wilson Inlet, Australia (Brearley, 2005) (Figure 3.2.7).

Deoxygenation is mostly periodic (annually in summer) or, to a lesser extent, episodic (tidal influence) (Rabalais et al., 1994). Seiching of the deoxygenated waters of central Chesapeake Bay from winds forces the water mass into shallow coastal waters for temporary exposure to deoxygenated water (Breitburg, 1992) (Figure 3.2.8). Similar wind-driven deoxygenated water mass movements occur in Mobile Bay, USA (Schroeder & Wiseman, 1988). Data from two oxygen meters deployed 1 m above the bottom in 20 m water depth within the large area of deoxygenated waters 77 km apart on the Louisiana shelf adjacent to the Mississippi River illustrated: (1) a continuous bottom-water dissolved oxygen concentration at the more western station that was severely oxygen-deficient and often anoxic from mid-June to mid-August, and (2) nearer the Mississippi River delta (Figure 3.2.9), a diurnal signal of values often less than 0.1 mg L^{-1}or as high as 3-4 mg L^{-1} (Rabalais et al., 1994). In the case of the former, a temporary increase in dissolved oxygen concentration was caused by advection of deeper more oxygenated water into the deoxygenated water mass (Rabalais et al., 1994).

Stratification, thermally-controlled in the case of Jinhae Bay, South Korea where freshwater input is insignificant (Lee et al., 2017), defines the period of initial deoxygenation, the period of maximal deoxygenation and the increase in bottom dissolved oxygen as it breaks down. Salinity-driven stratification is also involved in many cases. Stretching for 75 km, the uppermost reaches of the Pearl River are permanently deoxygenated (He et al., 2014). Whereas the lower reaches of the Pearl River estuary, while severely deoxygenated in summer, may be re-oxygenated from mixing by typhoons (Su et al., 2017). Similar processes disrupt stratification and re-oxygenate the water column in the low oxygen waters of the northern Gulf of Mexico (Rabalais et al., 2007a). In both instances, re-stratification followed by

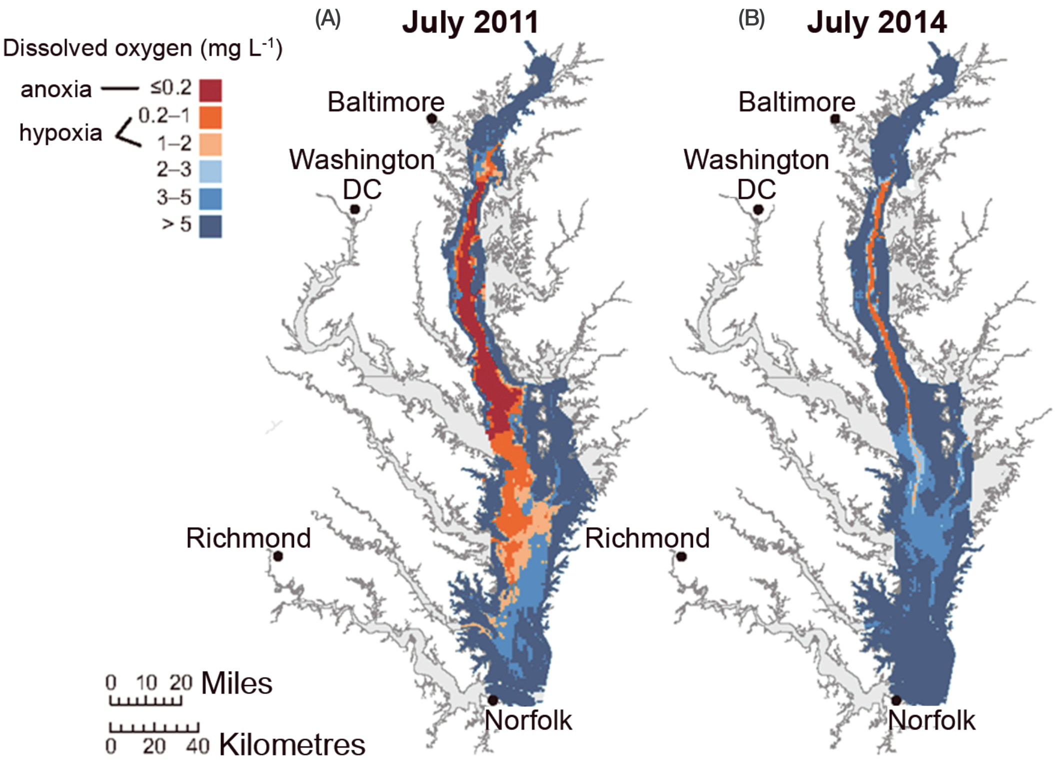

Figure 3.2.8 Distribution of bottom-water dissolved oxygen concentrations in Chesapeake Bay, USA, (A) a near-record high hypoxic volume, and (B) a near-record low hypoxic volume (from Testa et al., 2014).

rapid deoxygenation through respiration of organic matter occurs. The Pearl River estuary organic load is dominated by *in situ* marine phytoplankton biomass (autochthonous) (Su et al., 2017) similar to predominantly marine production in the northern Gulf of Mexico (Nelson et al., 1994; Rabalais et al., 2014; Turner & Rabalais, 1994). The marine source of excess organic matter is a feature of anthropogenic-driven deoxygenation forced by excess nutrient loads from human activities.

3.2.4.2 River-dominated ecosystems

Many river-dominated coastal ecosystems have a large freshwater discharge carrying high nutrient loads (Figure 3.2.10). Thermal warming in the summer strengthens salinity-driven pycnoclines. Examples, not inclusive, are: (1) the northern Gulf of Mexico continental shelf adjacent to the outflow of the Mississippi River (Rabalais et al., 2007a); (2) the northern Adriatic Sea that receives the effluent of the Po River (Justić et al., 1987); (3) Chesapeake Bay where the Susquehanna River provides most of the freshwater inflow (Murphy et al., 2011; Testa et al., 2017); (4) the north-western shelf of the Black Sea with inputs from the Danube, Dneiper and Dneister rivers (Mee et al., 2005, 2006; Zaitsev, 1992); and (5) the oxygen-deficient coastal area in the East China Sea receiving the increasingly nitrogen-laden waters of the Changjiang (Yangtze River) and atmospheric deposition of Nr-N from a heavily populated region (Yan et al., 2010; Zhu et al., 2017). Deoxygenation is a recurring, seasonal feature of these areas, except for the shelf adjacent to the Danube River, which has seen a reversal of deoxygenation. Earlier reports of deoxygenation under the influence of the Changjiang (Chen et al., 2007) have increased in frequency (Zhang et al., 2010; Zhu et al., 2017).

Initial hydrographic data documenting deoxygenation on the Louisiana continental shelf were few in the 1970s, but systematic surveys beginning in 1985 began to document increasingly larger areas of bottom-water oxygen deficiency (Rabalais et al., 2002) and severity (Rabalais et al., 2007a). Deoxygenation developed on this shelf ca. 1950s and accelerated in severity in the 1970s (Rabalais et al., 2007b) consistent with the increase in nitrogen export from the Mississippi River. Palaeo-indicators (fossilized biological or geochemical indicators of environmental change) also indicate that low oxygen values similar to current conditions were not a feature of this shelf prior to the 1900s (Rabalais et al., 2007b, 2014). The palaeo-indicators are not useful for size of area, but the deoxygenated area on the Louisiana shelf is the second largest coastal region caused by human eutrophication in the coastal ocean,

Figure 3.2.9 Mississippi River Delta © Universal Images Group North America LLC / Alamy stock photo.

averaging 14,000 km^2 since 1985 and reaching 23,000 km^2 in 2017.

Much as in the north-western Black Sea, deoxygenation conditions have shifted in the Po River-influenced Adriatic Sea. Justić et al. (1987) documented a decline in the dissolved oxygen content in the northern Adriatic Sea since the early 1900s. Historical reconstruction of assemblages of the hypoxia-tolerant bivalve *Corbicula gibba* in the Gulf of Trieste (north-east corner of the Adriatic Sea) showed periods of high abundance and organic content versus rare occurrence with implications for eutrophication and deoxygenation dating back 500 years (Tomašových et al., 2017). Associated hypoxia-sensitive foraminifera have declined in abundance and low-oxygen tolerant forms increased since the 1900s indicating a more recent development of deoxygenation similar to the record in Justić et al. (1987). Deoxygenation in the upper portion of the Northern Adriatic Sea opposite Rovinj diminished in presence and geographic extent in the period 1972–2012 with reduced influence of the Istrian Coastal Counter Current (Djakovac et al., 2015). The frequency of events in the western area, which is under a direct influence of the Po River discharges, did not change significantly, although the intensity of deoxygenation events recently were lower than during the 1970s through the early 1990s (Djakovac et al., 2015). Thus, different processes of deoxygenation, geographic area, and methods of determining deoxygenation complicates its occurrence in this broad region.

Figure 3.2.10 Mississippi River plume as it enters the northern Gulf of Mexico. Visible is the high suspended sediment load. Not visible are the high loads of nitrogen and phosphorus that enhance phytoplankton production on the adjacent continental shelf. © N.N. Rabalais.

Figure 3.2.11 Seto Inland Sea from the summit of Mt Misen, Japan © DGP_travel / Alamy stock photo.

3.2.4.3 Semi-enclosed seas

The semi-enclosed Baltic Sea is the largest eutrophication-driven area of deoxygenation in the world's coastal ocean, reaching an area of 25,000 to 60,000 km^2 in the period 1969—2008 (Conley et al., 2009). Deoxygenation has been a periodic feature of the Baltic Sea for the last 8000 years (Zillén et al., 2008) and is highly dependent on inflow events from the North Sea (Mohrholz, 2018) and high freshwater inflow leading to salinity stratification. Deoxygenation has been aggravated since the 1960s (Conley et al., 2009) by increased nutrient loads from the watershed (Savchuk et al., 2008). The Baltic Sea is composed of connected basins with different depths, but the general situation is for the formation of hypoxic and mostly anoxic conditions on a permanent basis other than during major inflow events. The water column from about 90 m to 130 m in the Eastern Gotland Basin is hypoxic and below 130 m to 250 m is anoxic (Conley et al., 2009).

The Seto Inland Sea (Figure 3.2.11) of Japan has a long history of harmful algal blooms, deoxygenation, and reversal of symptoms of eutrophication resulting from nutrient management (Honjo, 1993). Many of its sub-basins are deoxygenated in summer. There are some regions, including Osaka Bay, Harima-Nada, Hiuchi-Nada, Hiroshima Bay, Suo-Nada and Beppu Bay, where hypoxia occurs every summer (Kasai, 2014). In some sub-areas, e.g. Hiuchi-Nada, deoxygenation is governed more by hydrographic processes than oxygen consumption (Kasai et al., 2007). There remain areas exposed to higher loads of nutrients, especially near population centres.

The Bohai Sea is a semi-enclosed shallow coastal ecosystem on the Chinese mainland with a narrow connection to the northern East China Sea. The area receives the effluent of the Huanghe and other rivers in an area of rapidly expanding economic developments and associated increases in population. During the past 20 years, increasing eutrophication has led to a high frequency of red tides in the Bohai Sea (Lin et al., 2008), but deoxygenation was not associated with the algal blooms (Zhai et al., 2012). An investigation of scallop aquaculture failure resulted in the documentation of localized deoxygenation in areas of stronger stratification (Zhai et al., 2012). A more recent study in the Bohai Sea (Zhao et al., 2017) clarified Bohai bathymetry and associated features of stratification; deoxygenation was restricted to bathymetrically depressed areas. This differs from the areas studied by Zhai et al. (2012) that were shallower and near sources of fresh water.

3.2.4.4 Fjords and deep waters

Fjords such as Saanich Inlet, British Columbia (Figure 3.2.12), are naturally susceptible to deoxygenation because water residence time is long, sills may prevent exchange with oceanic waters, and thermal stratification

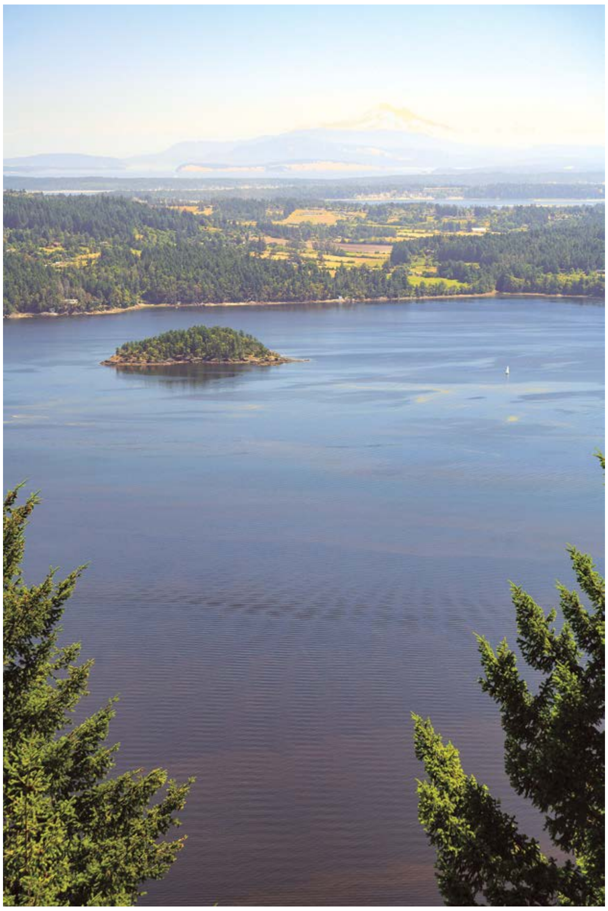

Figure 3.2.12 Saanich Inlet looking towards Mt Baker, Washington State. © Danita Delimont / Alamy stock photo.

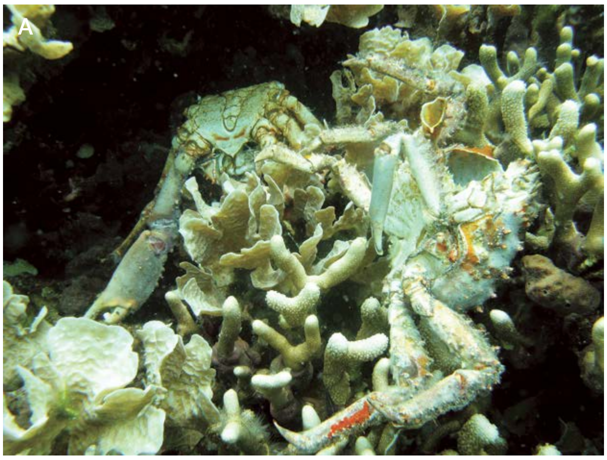

Figure 3.2.13 Extremely low oxygen levels (< 0.5 mg L^{-1}) near the bottom of a coral reef in Bahia Almirante, Panama killed (A) corals and crabs and (B) affected sponges where low oxygen conditions killed the bottom half of the sponges (Altieri et al., 2017). © Andrew Altieri.

may establish in warmer months (Matabos et al., 2012; Richards, 1965; Tunnicliffe, 1981). Fjords, however, may also be subject to excess nutrients and carbon from human sources, inducing hypoxia, for example Hood Canal in Puget Sound and Puget Sound proper (Brandenberger et al., 2011; Matabos et al., 2012; Parker-Stetter & Horne, 2008) and Himmerfjärden, Sweden (Bonaglia et al., 2014; Savage et al., 2002). The Himmerfjärden, on the other hand, has a long history of deoxygenation. Water sources to the fjord come from land run-off, outflow from Lake Mälaren from the north-west, and discharge from a sewage treatment plant (Bonaglia et al., 2014). The upper part of the estuary experiences regular summer deoxygenation, while the lower part is occasionally oxygen-deficient.

Many areas of Puget Sound experience regular mixing through tidal exchange processes that may reduce the effects of anthropogenic DIN loading, but some are less well mixed and are therefore vulnerable to eutrophication and deoxygenation (Puget Sound Institute, 2012-2015). There is some evidence that DO levels were generally higher in the mid-20th century than they are today (Puget Sound Science Review, 2016) with the latter correlated with increased anthropogenic activity. This conclusion was based on a comparison of historical water quality data to contemporary data (through 2009) (Puget Sound Institute, 2012-2015). The deep waters in the Lower St. Lawrence estuary are presently deoxygenated over a 1,300 km^2 area owing to a decreasing proportion of oxygen-rich Labrador Current Water in the water mass entering the Gulf of St. Lawrence (Claret et al., 2018; Gilbert et al., 2005). Additionally, the organic carbon content and the accumulation rates of dinoflagellate cysts and benthic foraminifera have increased from the 1960s to 2000, and a shift in the stable carbon isotope signature of the organic carbon suggests enhanced accumulation of marine organic carbon (Thibodeau et al., 2006).

3.2.4.5 Tropical seas

Deoxygenation events in tropical seas are few compared to higher latitudes but are also less studied or reported (Altieri et al., 2017). Deoxygenation recorded in tropical regions often reflects mostly untreated sewage inputs and agricultural runoff (areas identified in Diaz & Rosenberg, 2008). Seasonal deoxygenation has been observed in the past decade in the Chetumal Bay between northern Belize and eastern Mexico and has affected the health of coral reefs in the area (Herrera et al., 2004). Several estuaries in tropical Brazil are without sufficient oxygen because of untreated sewage from large population centres and pose health hazards (Kozlowsky-Suzuki & Bozelli, 2002; Marques et al., 2004; Somerfield et al., 2003; Valentin et al., 1999). Similar areas exist around the globe (République de Côte d'Ivoire, Ukwe et al., 2006; Manila Bay, Philippines, Jacinto et al., 2011; Sotto et al., 2014).

In the Morrocoy National Park, Caribbean coast of Venezuela, changing climate patterns and nutrient

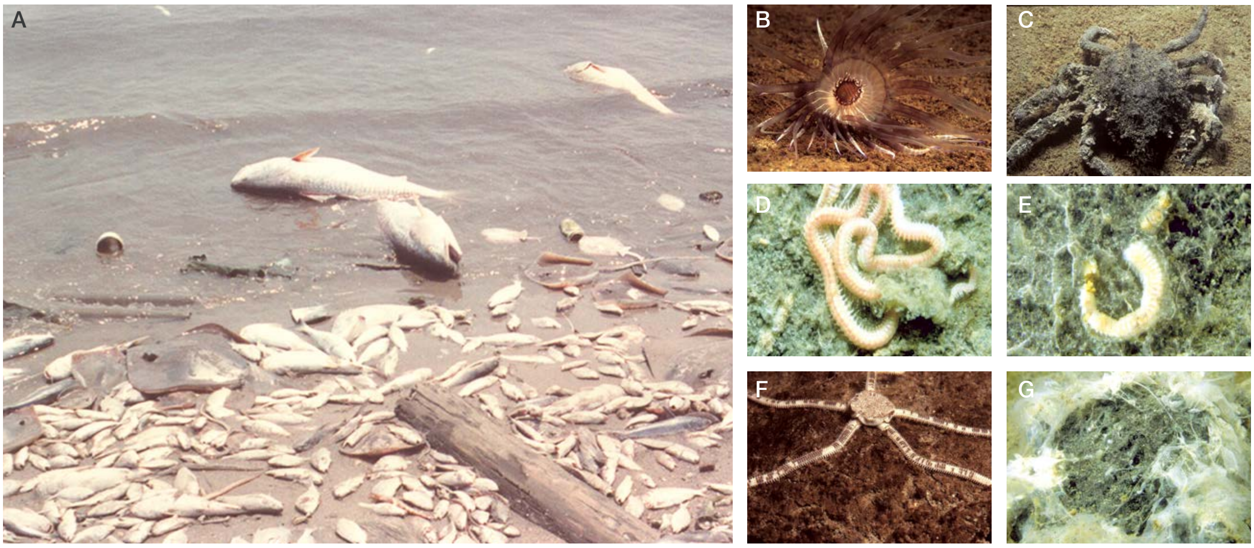

Figure 3.2.14 (A) Fish kill Grande Isle, LA, USA; (B) stressed cerianthid anemone; (C) dead spider crab; (D) stressed polychaete worm; (E) dead polychaete worm; (F) stressed brittlestar, otherwise usually burrowed; (G) anoxic sediments and sulphur oxidizing bacteria. © (A) Kery M. St. Pé; (B), (C), (E), (F), (G) Franklin Viola; (D) Donald E. Harper Jr.

overload has led to algal blooms. Eutrophication led to deoxygenation and contributed to the decline in coral cover, which has fallen from 43% to 5% (Isaza et al., 2006). A massive coral-mortality event caused by deoxygenation affected corals and other reef-associated organisms in Bahiá Almirante in the Bocas del Toro region of Panama (Altieri et al., 2017) (Figure 3.2.13). In a well-oxygenated area only 3 ± 2% of corals were bleached, whereas 76 ± 11% of the corals were bleached in the severely deoxygenated area. The likelihood of coral reefs being exposed to deoxygenation in the future is high given the trends in resource use by developing countries, many in the tropics, which are copying those of the developed world (Figure 3.2.1).

3.2.5 Ecosystem consequences

Deoxygenation affects coastal ecosystems through a decrease in suitable habitats for many bottom-dwelling marine organisms (many examples in Rabalais & Turner, 2001), and, when severely low in dissolved oxygen, disrupts natural biogeochemical processes, leading in some cases to the generation of greenhouse gases.

The negative effects of coastal deoxygenation include loss of suitable essential habitat for many bottom-dwelling fish and benthic fauna, habitat compression for pelagic fish, direct mortality, increased predation, decreased food resources, altered trophic energy transfer, altered bioenergetics (physiological, development, growth, and reproductive abnormalities), and altered migration (Baird et al., 2004; Eby & Crowder, 2002; Levin et al., 2009; Rabalais & Turner, 2001; Wu, 2002; Wu et al., 2003) (Figure 3.2.14). There are systematic exclusions of pelagic fish from low oxygen areas depending on their metabolic status and sensitivity to decreasing dissolved oxygen concentration.

Sedentary benthic organisms will try to escape, but are seldom capable of moving very far, and infauna will start to die off as the oxygen continues to decline (Rabalais et al., 2001a). Some benthic infauna are more tolerant to extremely low oxygen and will survive, but in low abundances and low biomass (Rabalais et al., 2001b). Sediment samples are seldom axenic in coastal waters, because some infaunal invertebrates have adaptations to low oxygen, and hydrogen sulphide exposure. The food availability for returning mobile species to previously defaunated sediments is negligible. Loss of biodiversity, abundance and biomass and shifts in benthic community composition are often the harbingers of eutrophication and deoxygenation in many coastal systems (Karlson et al., 2002), and likewise benthic communities are indicators of recovery (Karlsson et al., 2010). Many physiological responses result in altered behaviour or negative impacts (Vaquer-Sonnier & Duarte, 2008), such as reduced growth, loss of reproductive capacity, mortality, and loss of secondary production, including fisheries.

The nitrogen and phosphorus compounds delivered by rivers and streams are of multiple forms and different quantities. During increases in nitrogen and phosphorus from human activities, the ratios of nitrogen-to-phosphorus-to-silica shift and alter the composition of phytoplankton communities, the food webs they support, and can shift trophic interactions (Turner et al., 1998). Silica is important for the growth of diatoms that are a primary phytoplankton at the base of aquatic food webs. The increased nutrient loads causing deoxygenation may also result in more noxious or harmful phytoplankton blooms, and shift trophic interactions (Davidson et al., 2014; Turner et al., 1998).

The respiration of increased organic matter gives rise to increased pCO_2 levels and lower pH in the bottom waters. The bottom water pH decreases, as dissolved oxygen decreases, and may be aggravated further due to the interaction between open ocean source water acidification and coastal waters (Cai et al., 2011). Lowered pH in coastal waters, in conjunction with weakening sea water buffering capacity and sea water saturation state with respect to aragonite (Cai et al., 2011), remains a serious concern for living resources, especially with regard to shellfish production.

3.2.6 Climate change

Rising air temperatures, as a consequence of human-caused increases in greenhouse gases, is directly correlated with warming ocean waters and deoxygenation in oceanic waters, owing to lower solubility of dissolved oxygen in warmer waters (Breitburg et al., 2018; Keeling et al., 2010). Similar declines in water solubility in warmer waters and other physical factors also apply to coastal areas along with other climate changes that may aggravate symptoms of eutrophication and subsequent deoxygenation in coastal waters (Altieri & Gedan, 2014; Meier et al., 2013; Rabalais et al., 2010, 2014) (Figure 3.2.15). Warming alone will also strengthen the pycnocline and diminish diffusion of surface water dissolved oxygen. Warming waters may change circulation patterns so that advection of deeper oxygen-poor waters move on to continental shelves (Chan et al., 2008; Grantham et al., 2004) or force more wind mixing and reoxygenation (Rabalais et al., 2007a).

Increased precipitation with higher air temperature will result in more water, sediments and nutrients reaching the coastal zone where they are likely to enhance eutrophication through nutrient-enhanced primary production, increased stratification, or both (Baron et al., 2013; Cloern, 2001; Rabalais, 2004; Sinha et al., 2017). Sinha et al. (2017) predicted that eutrophication will worsen in the north-eastern United States and in its mid-west ‘Corn Belt,’ along with areas of India, China and south-eastern Asia. There will be, of course, other geographic areas with less precipitation. Excessive reactive nitrogen entering watersheds can be expected to rise with accelerating human population levels, continued reliance on fossil fuels, expanded agriculture and animal husbandry, and increasingly higher application of fertilizers (Reed & Harrison, 2016; Seitzinger et al., 2010) (Figure 3.2.1).

3.2.7 Management of human-caused deoxygenation

The forms of nitrogen and phosphorus, their loads, and their ratios in nutrient-laden waters reaching the coast affect phytoplankton productivity. If a nutrient is limiting to the growth of phytoplankton, increased loads will support increased phytoplankton growth. Most marine waters are considered nitrogen-limited for growth of phytoplankton, and fresh waters are considered to be phosphorus limited. There are multiple examples, however, of this not being the case (Paerl, 2009; Ren et al., 2009; Turner & Rabalais, 2013). For example, Turner and Rabalais (2013) performed a series of nutrient limitation bioassays over a range of distances from the Mississippi and Atchafalaya rivers, and measured light conditions, salinity and water depth for a 30-year period in the area of deoxygenation on the Louisiana shelf. They found that the number of N-limited bioassays was five times greater than the P-limited bioassays. NP synergism occurred where salinity was > 20 and represented 59% of all samples that were not light-limited. The interaction of N and P co-limitation was frequently synergistically additive. The dissolved inorganic nitrogen:phosphate ratio and various concentrations of DIN and inorganic phosphate (Pi) did not offer reliable chemical boundaries describing likely areas of exclusive N or P limitation in these bioassays. Because of these more recent studies, dual control of nitrogen and phosphorus is recommended for eutrophied coastal waters experiencing deoxygenation (EPA Science Advisory Board, 2008; Paerl et al., 2004, 2016).

The ability to develop nutrient management scenarios for nitrogen and phosphorus depends on a knowledge of the sources and amount of nitrogen and phosphorus coming from the watershed. For example, Alexander et al. (2008) used the SPARROW water-quality model that indicated that agricultural sources in the Mississippi River watershed contribute more than 70% of the delivered N and P. Corn and soybean cultivation is the

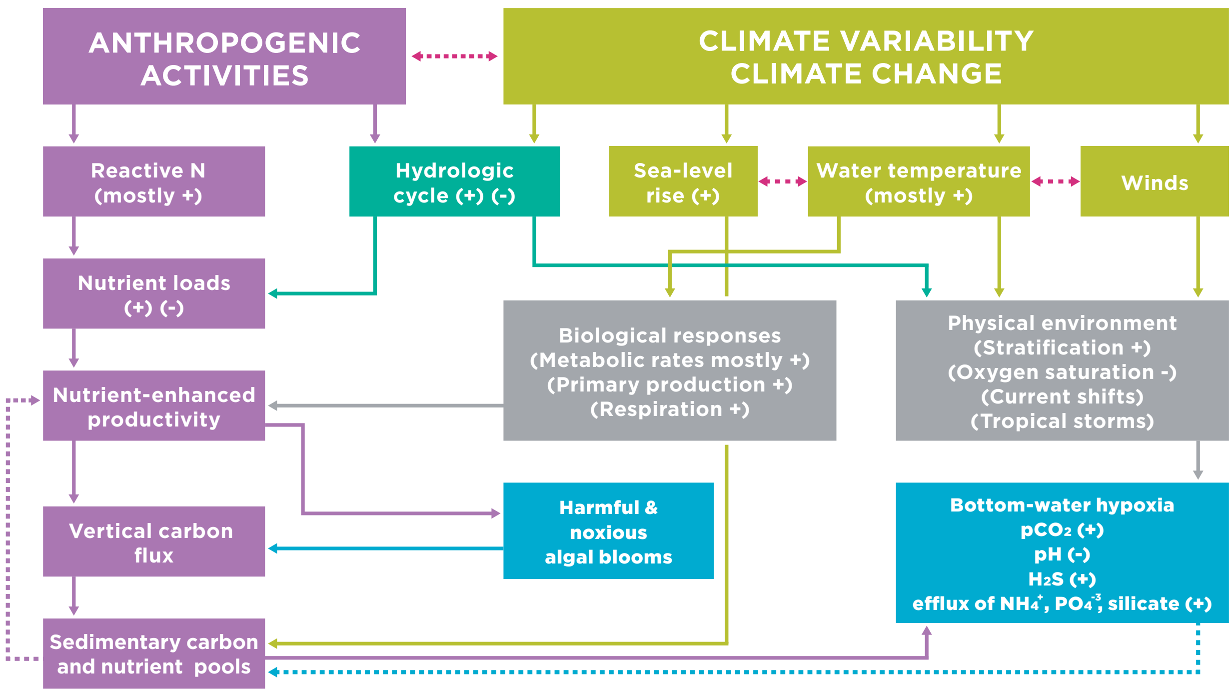

Figure 3.2.15 Conceptual diagram of the impacts of human and climate interactions on nutrient-enhanced productivity, harmful and noxious algal blooms, and hypoxia formation (Rabalais et al. (2014), modified from Rabalais et al. (2010)). Positive (+) interactions designate a worsening of conditions related to algal blooms and hypoxia, and negative (–) interactions designate fewer algal blooms and lessening of hypoxia symptoms. Dashed lines indicate negative feedback processes to nutrient-enhanced production and subsequent hypoxia. The dotted line between "Anthropogenic activities" and "Climate variability/ climate change" indicates that humans largely drive current climate change, but that climate change can certainly affect human activities.

largest contributor of N (52%), followed by atmospheric deposition sources (16%). P originates primarily from animal manure on pasture and rangelands (37%), followed by corn and soybeans (25%), other crops (18%), and urban sources (12%). Other watersheds may have different proportions of sources. For instance, the Chesapeake Bay's watershed generates similar proportions of non-point source runoff (primarily agriculture), wastewater (urban areas), and atmospheric deposition (burning of fossil fuels); management options may differ from those proposed for the Mississippi River basin.

Solutions do exist. These include modification of agricultural practices, construction and restoration of riparian zones and wetlands as buffers between agricultural lands and waterways, control of urban and suburban non-point sources, use of environmental technologies such as tertiary treatment at point sources, and deployment of controls on atmospheric sources (Mitsch et al., 2001). Many smaller efforts are focusing on sustainable agriculture practices, such as longer-rooted plants, perennial crops, crop rotations, growing of multiple crops in alternating areas, and generating biofuels other than corn-based ethanol.

All the above sounds simple. But, there are multiple obstacles preventing success—lack of regulatory authority, competing interests, political and social impediments, multiple jurisdictions, lobbying interests, environmental organizations, non-supportive farm and energy policies, lack of adequate logistical and financial support, and concern for breaking from traditional practices.

Directed mitigation and management of nutrient sources, however, has led to recovery of eutrophication-driven deoxygenation around the globe. Besides the red dots in Figure 3.2.2, there are areas listed in Diaz and Rosenberg (2008) where there are improvements in dissolved oxygen levels due to management of nutrients. The OSPAR Commission (2017) provides an assessment of environmental health for north-west European maritime areas highlighting where progress in reducing eutrophication under the European Water Framework Directive is being made. The OSPAR Commission (2017) reported, overall, fewer problem areas than the previous report for 2001-2005 and attributed the decline in atmospheric and riverine inputs since 1995 for the improvement.

Benthos and sediment studies of the inner Stockholm archipelago in 2008 indicated a shift from defaunated, reduced laminated sediments, indicative of severely low dissolved oxygen concentrations in the 1990s, to reoxygenated sediments and a healthy benthic community dominated by an invasive polychaete following improved water quality (Karlsson et al., 2010). A comprehensive synthesis of benthic community recovery in Danish waters followed significant reduction of nutrients through directed mitigation measures to reduce non-point and point loads of both nitrogen and phosphorus (Riemann et al., 2016). Several other 'success' stories show that management of nutrient loads can remedy coastal eutrophication, and in many cases (not in the Danish waters example), also reverse deoxygenation. In Danish waters (Riemann et al., 2016), increased stratification occurred over the same years as nutrient load reductions, when there were shifts in vegetated benthic ecosystems and water clarity did not improve much.

3.2.8 Conclusions

There is no doubt that nutrient-driven eutrophication in coastal ecosystems that leads to deoxygenation has increased, especially since the 1950s, accelerated in the 1970s to 1980s, and expanded globally since the 1990s. The worsening of deoxygenation follows an increase in human population, expansion of agriculture and animal husbandry including increased fertilizer use, and increased burning of fossil fuels. These trends will continue unless concerted efforts are taken to slow, or drastically reduce, inputs of nitrogen and phosphorus to watersheds from consumptive human activities. This will require a social and political will that is emerging in some societies and countries but not at the level needed globally to stem and reverse the flow of excess nitrogen and phosphorus to coastal waters.

There are many solutions, including consumer-driven shifts in diet that will result in reduced fertilizer use (Howarth et al., 2002). Personal choices towards a less consumptive life style will not only reduce the carbon footprint but also the nitrogen and phosphorus footprints. Eat less or no meat. Strive for a wheat-based carbohydrate and vegetarian diet and avoid products dependent on corn. Use a non-ethanol gasoline. Drive a fuel-efficient or other energy source vehicle. Be mindful of reversing consumptive habits.

Finally, Levin and Breitburg (2015) called for, and rightfully so, the coupling of currently decoupled realms of research, observations and management for open ocean and coastal deoxygenation. The causes are similar, interactions occur between them, biogeochemical shifts in both affect global processes, management options are similar, and both need an integrated education and awareness emphasis. This integration lags behind where ocean acidification knowledge and awareness has been integrated, but can be addressed and improved.

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