Working Paper

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Increase in Oxygen Depletion in the Marine Environment

Drivers and Recommendations

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Working Paper

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Purpose and scope

The working paper examines published papers and available global data to understand the location, extent, and duration of coastal dead zone (hypoxic areas) formation. It also looks at the trends in dead zone development and the conditions driving their formation. Documenting dead zones helps us to understand the scale of the problem and encourages governments and other stakeholders to develop strategies to combat their formation.

Summary

An assessment of coastal dead zones was undertaken based on a review of 841 published papers. Almost 1000 hypoxic or eutrophic "hot spots" were identified, nearly double the number reported in a review from 2008 (Diaz and Rosenberg in 2008). It is not possible to tell how much of this increase might be attributable to increased reporting; however, the upward trend broadly correlates with growing human populations, coastal development, increased fertilizer use and a warming global ocean.

There are several well-known drivers of eutrophication that can lead to dead zone formation, but often it is not possible to determine the cause of a hypoxia event. This is due to the complexity of oxygen dynamics in coastal waters, the cumulative effects of multiple stressors (which makes it difficult to determine root causes) and the general lack of in situ data. The main drivers of dead zone formation in coastal areas include:

- runoff of excess fertilizers used in agriculture
- the disposal of untreated or poorly treated sewage and contaminated stormwater into waterways
- drainage of manure from livestock into waterways
- discharge of effluent and nutrients from aquaculture installations
- soil washed into waterways as a result of deforestation and land use change
- dams and water regulation infrastructure that reduce sediment transport and change nutrient ratios
- changing wind patterns (as a result of climate change) which can impact the timing, location, and duration of coastal upwelling that pushes high nutrient, low oxygen water towards the coast.
- the role of coastal topography has been shown to be an important factor, with enclosed coastal areas where water circulation is reduced, being particularly vulnerable.

These drivers are exacerbated by global climate change, since warmer ocean waters result in a decline in dissolved oxygen concentrations in the upper part of the water column (Schmidtko et al 2017). Changes in precipitation, runoff and evaporation, also due to global climate change, can influence oxygen levels in estuaries and coastal waters (Whitehead et al., 2009). In spite of these complexities, there are examples of interventions that have resulted in improvements in the oxygen levels and health of impacted ecosystems.

Recommendations

Recommendations derived from this report fall into three broad categories: monitoring; addressing excess nutrient input; and other direct interventions.

Monitoring

- Develop consistent methodology to detect algal blooms and hypoxia in order to understand the conditions that lead to eutrophication, and the timing, duration, and impacts of hypoxic events.
- High quality, comparable, long-term environmental and HAB data are essential to assess and manage the increasing risks from HABs.
- Water quality monitoring in river catchments supporting agriculture and/or that receive sewage and wastewater discharges should be established by national authorities.
- Early detection of harmful algal blooms and hypoxia are essential both to understand their development and mitigate impacts.

Addressing excess nutrient input (Figure 1)

- Address dead zones created by excess nutrient loads from agriculture (Figure 1) by encouraging farmers to reduce or replace artificial nitrogen fertilizer, and wisely use manure on croplands within impacted river catchments.
- Encourage farmers to develop and maintain buffer zones between fertilised areas and water courses. These vegetated strips of land trap excess nutrients. Plantings can include food producing perennial plants.
- Ensure some cover crop all year around – there should be no bare soil during the off season. Off season cover crops use excess nutrients, limit erosion, bind carbon, supress weeds, and can fertilise the soil for next (harvest) crop (e.g., nitrogen fixing legumes).
- Countries should set priorities (including best practice advisories for farmers) for the control of fertilizer use and for control of sewage and wastewater discharge into river catchments based upon the vulnerability of the receiving coastal environment to eutrophication and hypoxia.
- In relation to climate change impacts, some crop varieties (that require high nutrient input or produce excess nutrients and organic matter) may need to be replaced by more sustainable crops (ones that do not need additional fertilizer) in the catchments of vulnerable coastal environments to avoid the creation of new dead zones.
- Ensure plant biodiversity along all water courses to utilise nutrients.
- Maintain the natural meandering flow of drainage systems to slow down water movement increasing the utilisation of nutrients.
- Consideration needs to be given to designing dams to limit trapping of sediment so as to maintain the movement of silica (necessary for a stable nutrient ration).

Other direct interventions

- Interventions including mechanical harvesting of algae (especially toxic algae), ultrasonic treatment and the development of safe algicide.
- Biological treatment such as stimulating grazing zooplankton, macroalgae, oyster cultivation, options need to be further explored.

Additional actions related to reducing nutrient loads in coastal ecosystems are illustrated in Figure 1.

Figure 1. Ten actions that could contribute to reducing nutrient pollution, the principal driver of the formation of anthropogenic dead zones.

1

Introduction

To better understand the occurrence of dead zones in coastal waters, UNEP and GRID-Arendal have conducted a global assessment of coastal estuarine systems based on a database compiled by the World Resources Institute (WRI) in collaboration with the Virginia Institute of Marine Science (VIMS). The database includes 762 coastal areas impacted by eutrophication and/or hypoxia and may be found here: https://www.wri.org/data/eutrophication-hypoxia-map-data-set

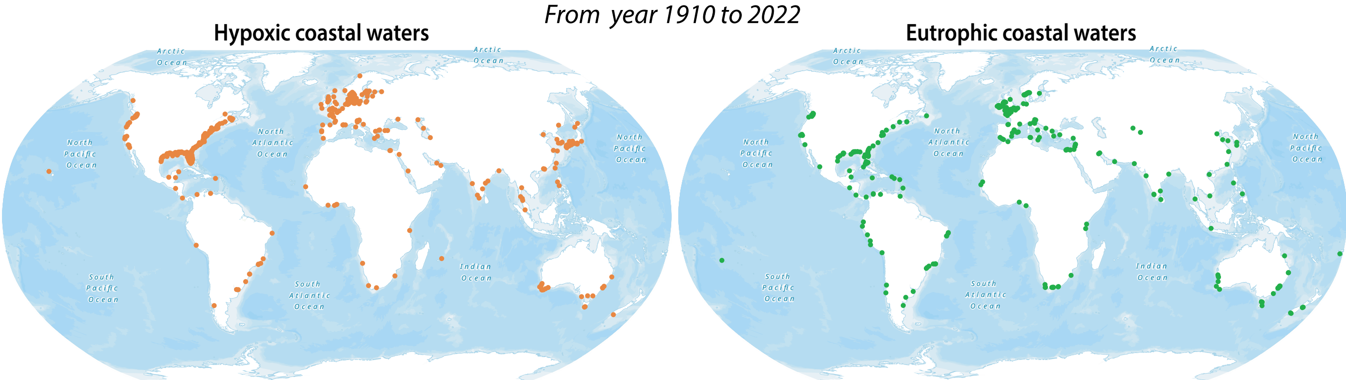
The review presented here adds a further 79 case studies to the WRI/VIMS database. We find that there are (as of 2022) 958 hypoxic or eutrophic "hot spots" around the world's coastline (Figure. 2) and that the number of impacted sites reported in 2022 is nearly double that from 2008 (a review carried out by Diaz and Rosenberg in 2008 documented 400 known coastal dead zone locations). Although the magnitude of the increase may be partly the result of increased reporting, dead zones are increasing. The upward trend in the number of impacted sites correlates with growing human populations, loss of coastal habitats and biodiversity, global climate change and a corresponding increase in the use of fertilizer. The trend for an increase in dead zones is a threat to biodiversity, amenity, and human health.

As the study was based on a literature review there is a strong geographic bias towards Europe and North America

where the bulk of research has been carried out. A problem with our literature review is that we found each case study used different methods and took their own approach to study the effects of eutrophication and hypoxia. Hence the results are not comparable at any detailed level which makes it impossible to correlate "events" with other known physical and biological parameters. However, the dataset does allow some broad trends and associations to be made as are outlined below.

958 hypoxic or eutrophic "hot spots" around the world's coastline

From year 1910 to 2022



Source: Diaz, Selman and Chique, 2011; GRIDA 2022

Figure 2. Map based on the analysis of 958 case studies for coastal waterways in which hypoxic and/or eutrophic conditions have been measured (current up to 2022; GRID-Arendal, 2022; see GRID-Arendal Story Map https://storymaps.arcgis.com/stories/fbba8234192240bda71d1577498d7e0e).

In addition to documenting dead zones, the study also identified 55 locations where steps taken by government have resulted in improvements in water quality and dissolved oxygen levels (Figure 3). A significant number of the improvements reported (64%) were due to improved management and treatment of municipal wastewater.

In general, surface waters contain high concentrations of dissolved oxygen because of photosynthesis and atmospheric exchange. However, in recent decades there has been a dramatic increase in the occurrence of oxygen depleted dead zones in coastal waters, principally located in areas where rivers discharge excessive nutrient loads from the land into the ocean (e.g., Pitcher et al., 2021). The excess nutrients cause the rapid growth of marine plants, animals, and bacteria (a process known as eutrophication). When the organisms die, their decomposition consumes oxygen. When oxygen levels fall, the waters can become hypoxic[1] and are referred to as dead zones (Figure 4).

Estuaries and coastal waters are considered hypoxic when dissolved oxygen concentrations are less than 2–3 mg per litre of water (Figure 5). In contrast, well oxygenated surface waters generally have dissolved oxygen concentrations greater than 6 mg per litre of water (e.g., Figure 6).

At very low oxygen concentrations there are negative effects on biota and ecosystem processes (Diaz and Rosenberg, 1995; Figure 5). The extent and duration of dead zones can vary markedly. They can occur in small bays and inlets, as well as large, restricted seas, such as the Baltic Sea where the dead zone can cover an area greater than 60 000 km^2 (Conley et al., 2011). They can also be short lived seasonal events (e.g., Gulf of Mexico) or permanent features (such as the Baltic Sea). The relationship between eutrophication and the severity and extent of a dead zone is influenced by the amount of runoff, the degree of water column stratification, levels of primary productivity, microbial activity, and respiration rates (Altieri and Gedan, 2015).

1. Hypoxic means depleted of oxygen; anoxic refers to a total absence of oxygen. Anoxic sediments typically have the smell of rotten eggs because the bacteria use sulphide to process organic matter instead of oxygen.

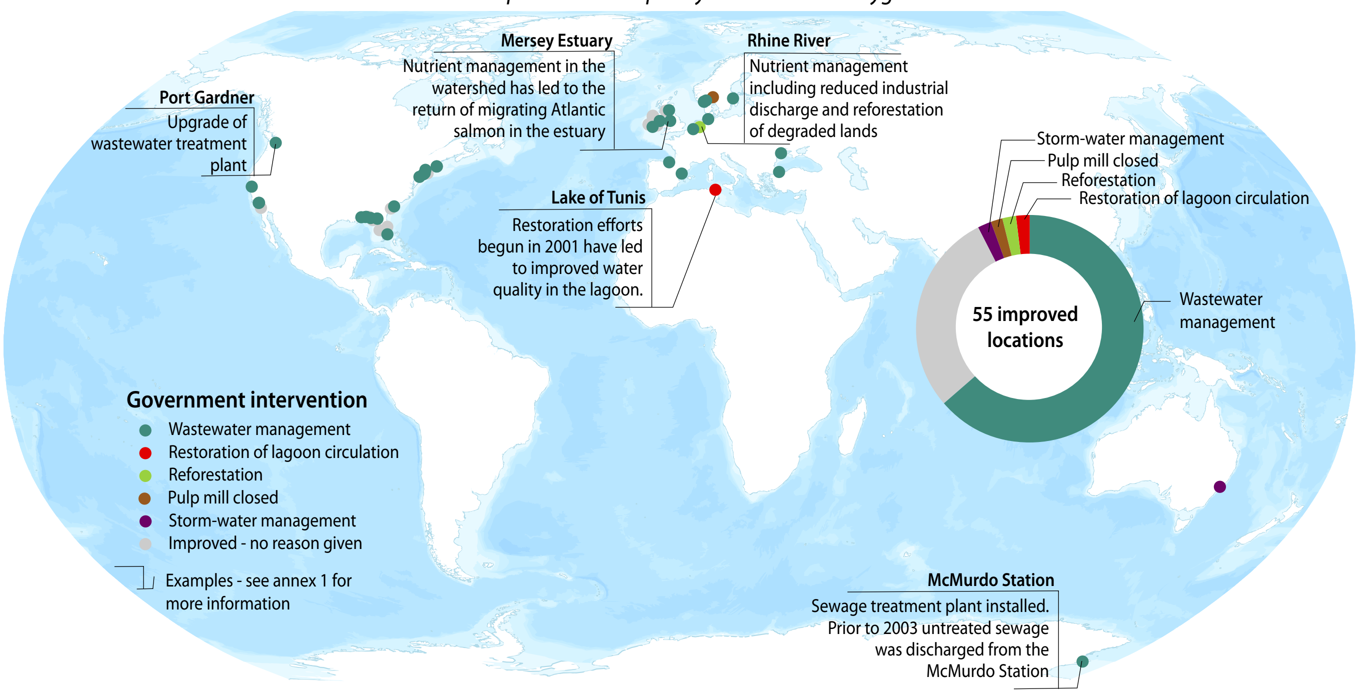


Figure 3. Fifty-five locations identified in the review where steps taken by government have resulted in improvements in water quality and dissolved oxygen levels.

Human activities that can lead to the development of coastal dead zones

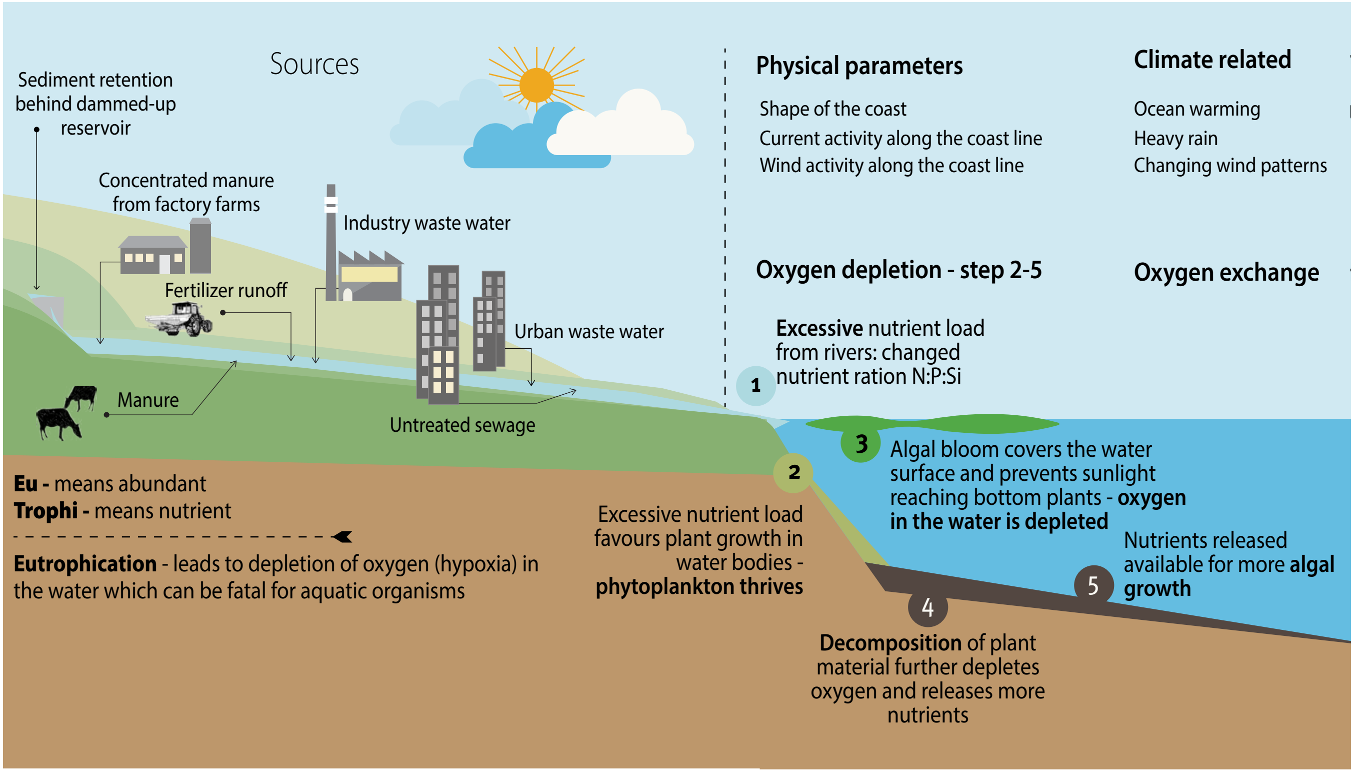
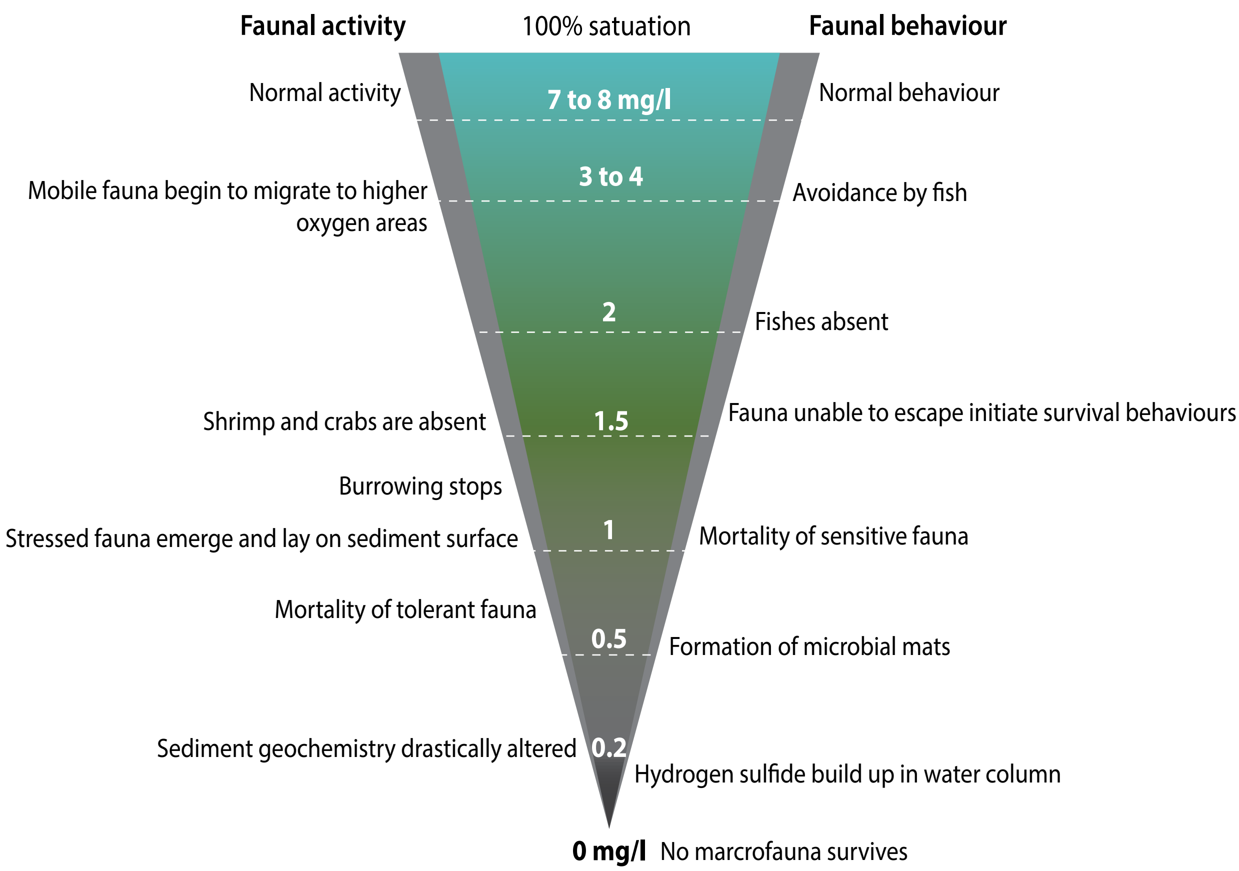


Figure 4. Making of a dead zone.

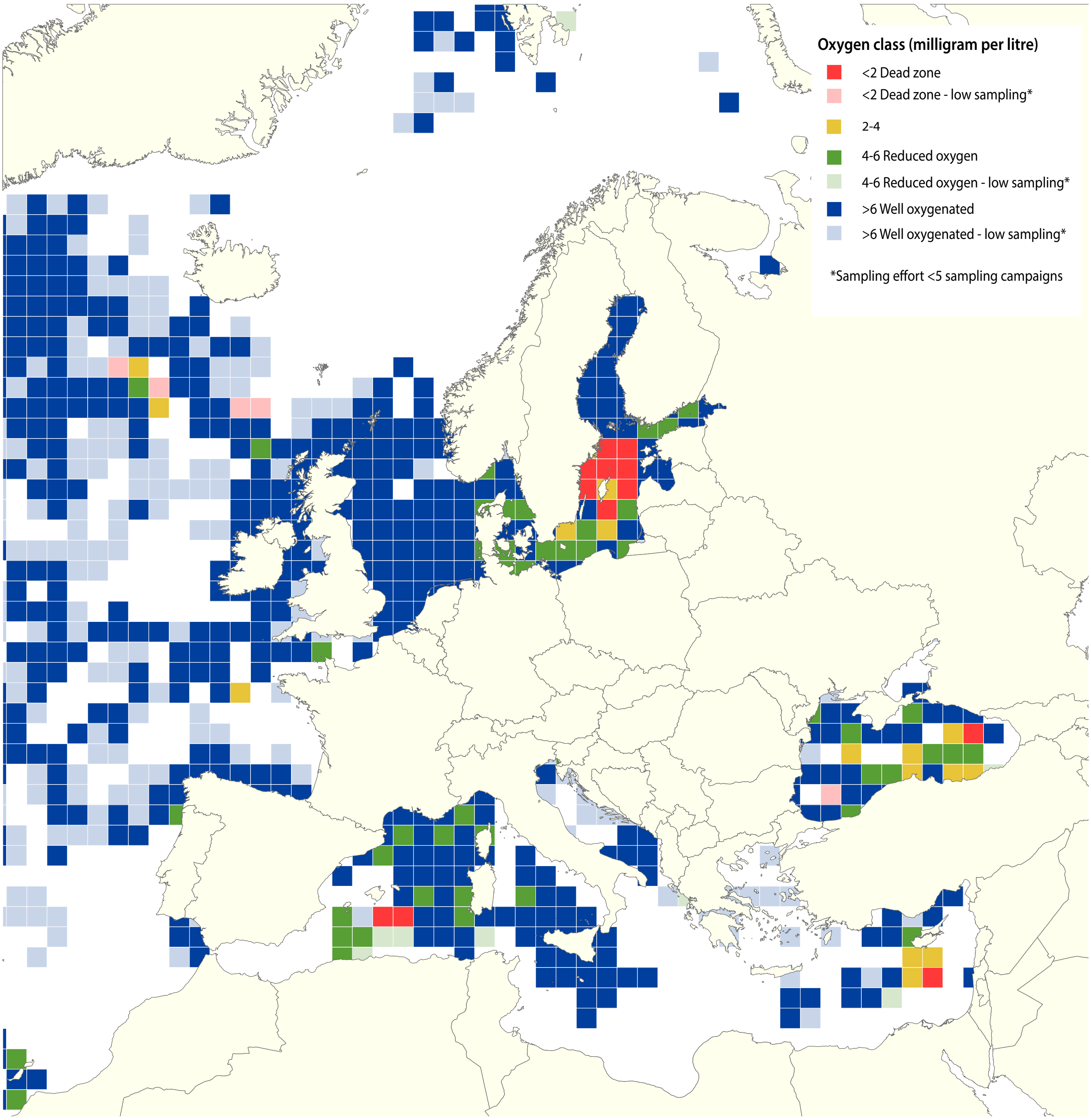
Cone of faunal response to decreasing oxygen concentration in estuarine and coastal environments



Source: Diaz and Rosenberg, 1995

Figure 5. Cone of faunal response to decreasing oxygen concentration in estuarine and coastal environments (Diaz and Rosenberg, 1995).

Average oxygen concentrations in European coastal and marine waters 2009-2019



Source: European Environment Agency, 2022

Figure 6. Average oxygen concentrations in European coastal and marine surface waters 2009–2019. Red areas indicate hypoxic conditions while dark blue areas are well-oxygenated regions (source European Environment Agency, 2022).

2

Drivers of eutrophication in coastal waters

Direct drivers of nutrient pollution in the coast zone include increased fertilizer runoff and increased organic matter input from the expansion of agriculture and aquaculture, municipal wastewater, land use change and freshwater discharge (e.g., river flow regulation). Indirect drivers include population growth and changing hydroclimatic conditions. The exacerbating effects of global climate change are considered in Section 4.

2.1 Fertilizer

The increased use of fertilizers in agriculture has contributed to the increase in coastal dead zones over the last decades (Diaz and Rosenberg, 2008; Altieri and Gedan, 2015). At the beginning of the 20th Century, it became possible to produce cheap industrial fertilizer and its use skyrocketed. Widespread uptake coupled with poor management have resulted in large amounts of excess fertiliser entering waterways and eventually coastal waters. By the mid-2000s the global nitrogen export from rivers has been estimated to be about 60 million tonnes/year, a twofold increase compared to the 1860s (Howarth, 2008). Overall, it has been shown that more than 50% of anthropogenic nitrogen is lost to the environment, with losses varying as a function of climate, crop type, and fertilizer application rates (Lassaletta et al., 2014).

2.2 Sewage

Growth in human population is commonly associated with an increased intensity and/or frequency of coastal eutrophication and formation of dead zones. People are attracted to live in coastal settings and consequently inputs from sewage treatment plants, household septic systems and urban run-off increase with the growth in the number and population of coastal settlements (Tuholske et al., 2021). Globally, sewage and wastewater are estimated to contribute an amount of nitrogen that is equal to about 40% of the amount from agriculture (Tuholske et al., 2021).

Increasing coastal population density and intensive agriculture drive coastal eutrophication

China accounts for about 32% of the world's consumption of nitrogen fertilizers (Wang et al., 2021), and about 44% of the Chinese population lives along the coastline. As a result of fertiliser runoff and sewage pollution, over 20% of the coastal waters in China are classified as "affected by eutrophication" (MEE, 2020). Recently Wang et al. (2021) described two phases of growth in the occurrence of eutrophication in Chinese coastal estuaries, with one phase of slow development from the 1970s to 1990s and a fast development phase after 2000.

It is often difficult to determine which nutrient source is most responsible for the onset of eutrophication, as most regions are susceptible to outflows of combinations of sewage and wastewater, industrial discharges, farm effluent (including aquaculture) and fertilizer washed into rivers and streams from farmland. However, Strokal et al. (2016) used modelled data to determine that between 20 and 78% of dissolved N and P in Chinese rivers comes from livestock manure point sources. In other studies, the isotopic signature of carbon and nitrogen are being used to help identify nutrient sources. Ke et al. (2020), for example, found that sewage from urban rivers was the major pollution source in Jiaozhou Bay, northern China.

A study by Li et al. (2019) used the Marina 1.0 model (a downscaled version of Global NEWS focused on China; Strokal et al., 2016) to look at solutions to limit the export of nutrients from Chinese rivers. They calculated (using a back casting method) that halting coastal eutrophication by 2050 would require a reduction of between 50 and 90% of total N and P export from the Hai, Huai and Huang Rivers. Using various scenarios for nutrient reduction they determined that the target could be met by improvements in manure recycling and a reduction in fertilizer use (essentially substituting manure for manufactured fertilizer).

Figure 7. Algal blooms, Baltic Sea, satellite image (from European Space Agency).

Impact of sewage pollution on oxygen levels in coastal waters

In the coastal zone of the Baltic Sea approximately 35% of all coastal ecosystems experienced hypoxia between 1955 and 2009 (Conley et al., 2011), with the overall frequency of hypoxia increasing (see Figure 7 example of wide spread algal bloom). A significant proportion of the excess nutrient load is attributed to sewage outflow. The hypoxic conditions reduced after sewage treatment was upgraded in the inner Stockholm Archipelago (Norkko et al., 2012), but the problem persists.

In South Africa, the state of municipal wastewater and sewage treatment management has deteriorated in recent decades (due to lack of capacity, poor revenue collection and dwindling investment; Winter and Carden, 2022) leading to increasing coastal eutrophication. Adams et al. (2020) note that half of the country's estuaries are now affected by nutrient pollution resulting in hypoxia, fish kills and loss of ecosystem services.

2.3 Livestock

Manure from livestock can contribute to hypoxia if it is allowed to wash into rivers and streams. Effluent from intensive/industrial pig farms has been reported to have the greatest concentrations of suspended materials, nitrates, and phosphates (Cesoniene et al., 2019) but manure from any livestock can cause problems.

The advent of industrial farming practices has had unintended consequences. Traditional farms that integrated livestock with crops allowed for the livestock to be fed by local crops, and livestock manure to be applied directly to nearby cropland. Nowadays, a farming area may just focus on livestock production and instead of utilising locally produced feed, import a large proportion of the animal feed. The manure, when it is applied on nearby crop fields, is often in excess to needs (Byrnes et al., 2020). The result is that large nitrogen and phosphorus surpluses often occur in regions with high livestock density (Svanbäck et al., 2019) with excessive nutrient loads in runoff entering the coastal zone and driving eutrophication.

A study on livestock waste management in Wisconsin USA calculated that every kilogram of excess phosphorus runoff from livestock waste resulted in economic losses of US$74.5 (related to the impact of algal blooms on property values and recreational activity). The authors (Sampat et al., 2021) demonstrate that the economic impact of nutrient runoff in the area is a strong incentive for the development of a nutrient management and valorisation market (converting the waste into value added products).

2.4 Deforestation and land clearing

It is common in environmental assessments to find that nutrients are significantly enriched in streams draining deforested watersheds (Likens and Bormann, 1974, Figure 8).

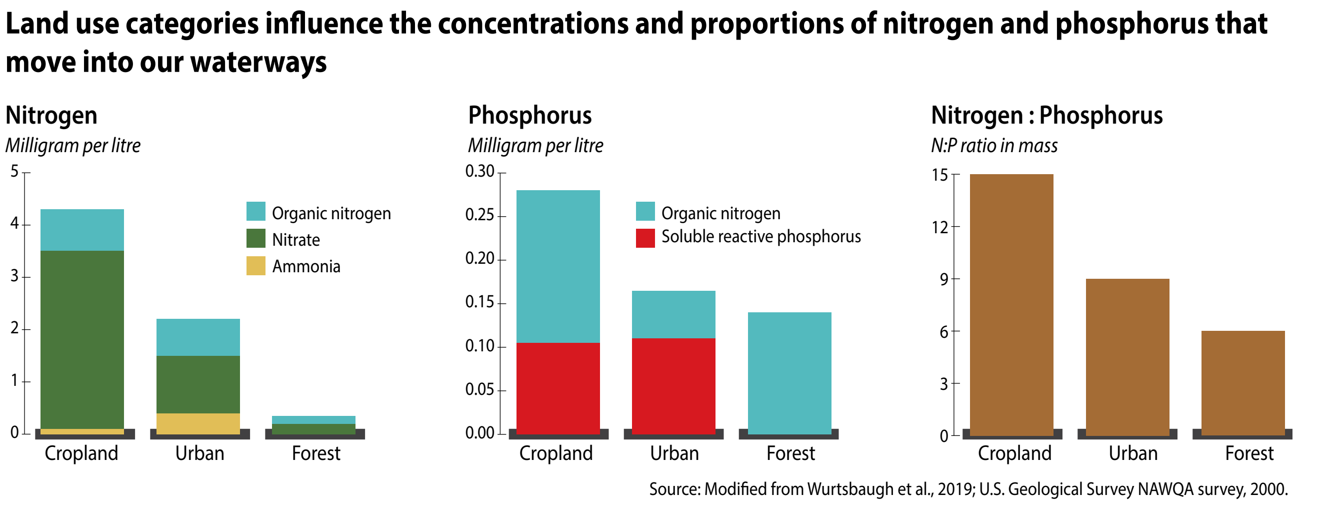


Figure 8. Comparison of flow-weighted mean nutrient concentrations in rivers draining cropland (n=104), urban (n=38) and forest (n=36) *from USGS NAWQA survey 2000.

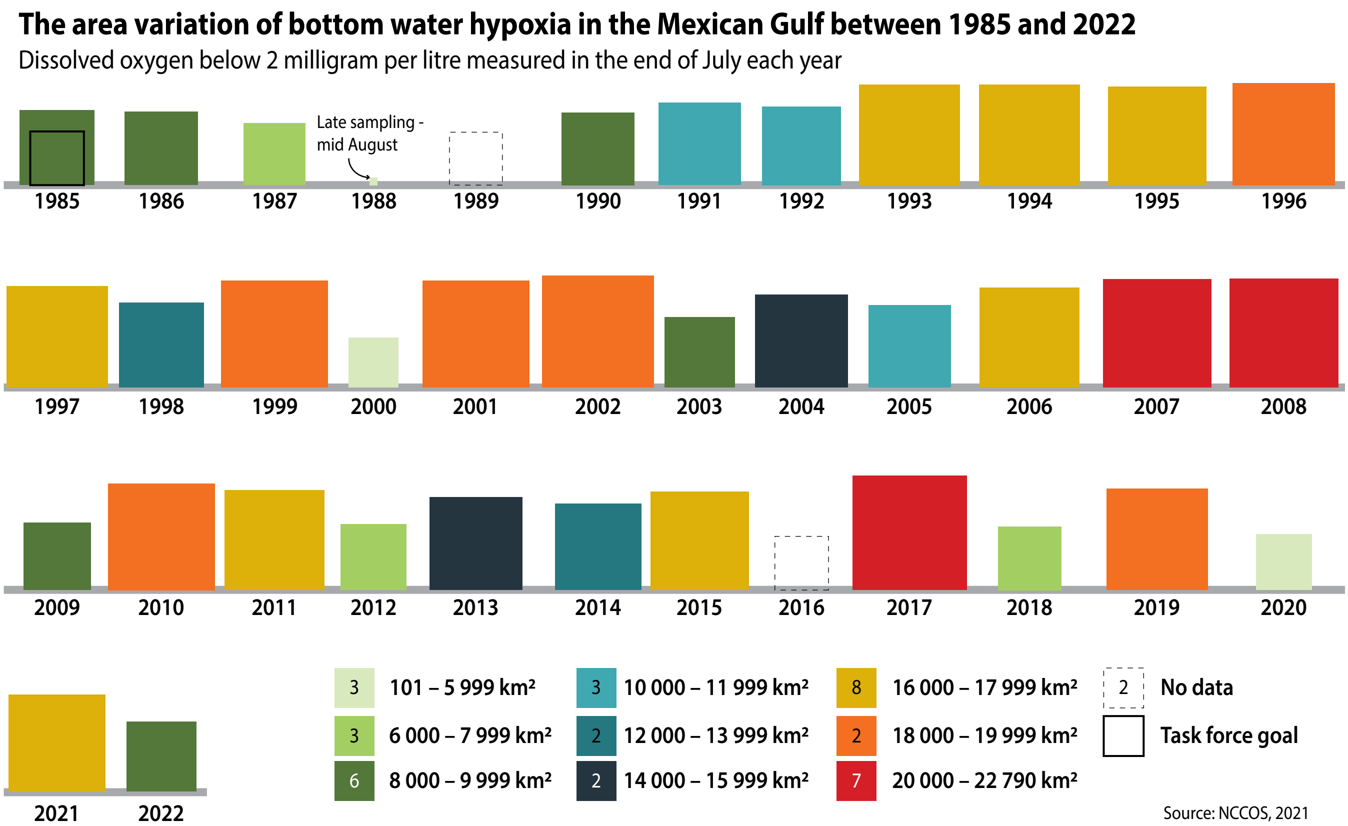


Figure 9. Size of the hypoxic area in the Gulf of Mexico (green bars) measured during the ship surveys which began in 1985. The black line in the bottom panel represents the target goal established by the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force. The 5-year average size of the hypoxic area is shown by the black dashed line (NCCOS, 2021).

This is the case for example in the Mississippi River catchment, which has been substantially modified by human activities and whose increased nutrient load has created the world's second largest (after the Baltic Sea) dead zone of over 16 000 km^2 in the Gulf of Mexico (Rabalais et al., 2002; NOAA, 2021; Figure 8). Deforestation and land clearing for agriculture contributed to removal of of the Mississippi basin's natural capacity to withhold nutrients from runoff.

Sargassum blooms

The floating brown macroalgae Sargassum spp. has become a recurring problem on tropical beaches on both sides of the Atlantic. There have been a number of hypotheses put forward to explain the dramatic increase in the volume of Sargassum (Louime et al., 2017) with nutrient discharge from the Amazon River identified as one of the major drivers (other possible contributing factors include ocean warming, changes in ocean currents and nutrients associated with increased dust from the Sahara; Wang et al., 2019).

A recent study by Lapointe et al (2021) demonstrated a 111% increase in N:P ratio in the tissue of Sargassum spp. since the 1980s. They found the highest increase in N was related to N-rich terrestrial runoff, especially adjacent to river mouths. Although a direct correlation between periods of high nitrogen river discharge and sargassum volume is not apparent, the authors concluded that the Amazon River plume has likely supported sargassum growth especially in 2015, 2017 and 2018. Lapointe et al (2021) suggest that periods of high nitrogen flux are related to Amazon deforestation (increased 25% since 2010) and flooding, combined with increased fertilizer use (up 67% since 2010)..

Drifting sargassum can wash up on beaches and accumulate in near shore areas. This can result in thick deposits of decaying material on the shore and produce what are termed sargassum brown tides in the shallow water. Van Tussenbroek et al. (2017) found that the decay of particulate organic matter released into the near shore environment from beach cast seaweed can produce anoxic and hypoxic conditions. They found that the combination of decreased light from floating mats, increased temperature below the mats, and the released organic matter resulted in the death of seagrass and coral species along the Mexican Caribbean coastline. They also found that the release of nutrients from the decaying sargassum can promote eutrophication.

2.5 Aquaculture

There has been enormous growth in the aquaculture industry over the last 20 years. In 2013, aquaculture production exceeded wild-catch fisheries and the industry has expanded into all parts of the coastal zone including marine waters, brackish waters, freshwater, and land-based (fish grown in tanks) production (Rickard et al., 2022). In the case of marine finfish aquaculture, round pens 120 to 200 m in circumference are anchored to the seabed with floatation devices holding the upper section of nylon net near the surface so that the cage extends from the sea surface to the seabed. Multiple pens can be grouped together and positioned with moorings. In deeper water the floating pen may have a floor also made of nylon net. These systems rely on prevailing tidal and wind-generated currents to bring in oxygenated water and carry away the effluent.

Marine finfish pens release faeces and uneaten food, which settles to the seafloor. Accumulation of organic matter can cause the sediments to become anoxic within a 50-to-100-meter radius of the pen. High levels of sulphides and methane have been measured in sediments around fish farms and have been found to be enriched in heavy metals (Weitzman et al., 2019). Of particular concern to the present study is that fish pens have been shown to impact water quality, affecting dissolved oxygen levels. Leakage of hydrogen sulphide gas from highly polluted sediments into the overlying water column has been observed near finfish pens (Black et al., 1996). In these ways fish-pen aquaculture can be a contributing factor for, if not the main cause of, eutrophication of some coastal and estuarine environments (Wang et al., 2008)..

Given the likely vulnerability of fjords to eutrophication (due to limited flushing), the impacts of fish-farms on the oxygen levels in fjords have received some attention (Molvaer et al., 2007). The research tends to suggest that fish-farms located close to the fjord's sill (at the entrance to the fjord) will lower any negative impacts that aquaculture may have (Skogen et al., 2009). However, the results are site specific, and each fish pen installation needs to be carefully examined to minimise the potential for negative impacts.

2.6 Dams and water management

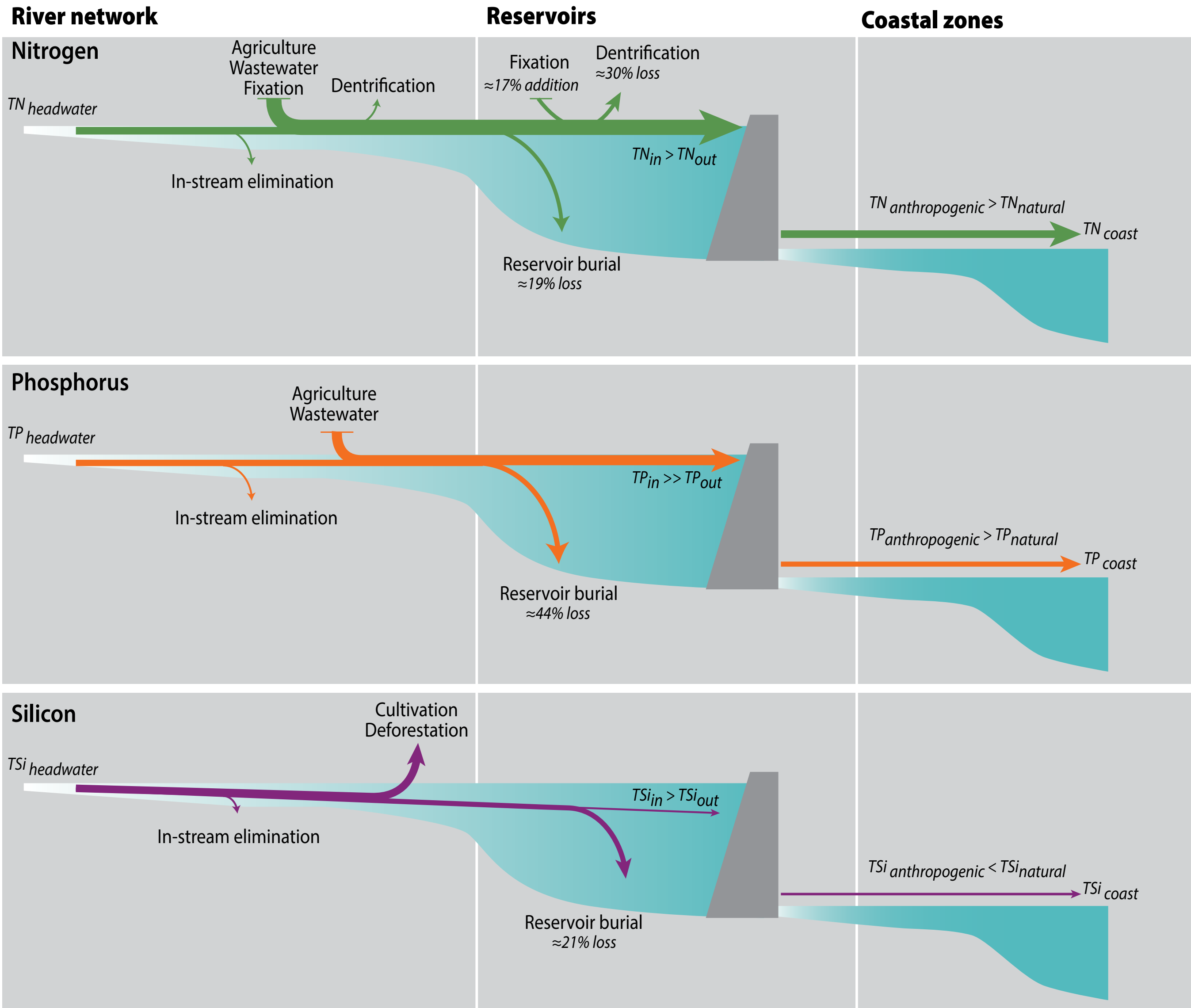
Two-thirds of rivers globally are dammed and are therefore no longer free-flowing (Grill et al., 2019). Nutrients dissolved or suspended as particulate matter in freshwater streams and rivers eventually make their way to coastal and estuarine environments. Building a

dam may remove excess nutrients and thus be beneficial in reducing downstream eutrophication, alternatively it may change the chemical balance of nutrients which can increase coastal eutrophication. The situation in every river catchment must be analysed separately to understand what actions should be taken to address downstream issues with excess nutrients.

Under natural conditions, nutrients such as carbon (C), nitrogen (N), phosphorus (P) and silicon (Si), are transported along the river and to the sea. Building a dam slows the water flow (turbulent, rapidly-flowing rivers absorb oxygen more efficiently than tranquil, slow-flowing rivers) and results in the nutrients being used within the dam reservoir by algae and aquatic plants, transforming dissolved nutrients into particulate matter (sediments). The dam reservoir may itself become eutrophic if the nutrient load is too high (Li et al., 2011). In such situations the dam may be beneficial in relation to down-stream water quality, since the excess nutrients have been turned into sediment that is stored in the dam reservoir (Figure 10). However, the reservoir may also promote chemical transformation of dissolved nutrients, which when released into the marine environment may promote eutrophication (Maavara et al., 2020). This can occur in cases where the ratios of the limiting nutrient received by the marine environment are altered by the upstream reservoir. The ratio of nutrients (mainly nitrogen (N), phosphorus (P) and silicon (Si)) can influence the type of algae present. For example, in many marine environments it is silica, not nitrogen, that limits the growth of diatoms (a type of algae that use silica in their skeletons and can cause toxic algal blooms). So, if the reservoir results in the preferential removal of silicon the result can favour the growth of non-silicious toxic algae downstream (species that are not dependent upon silicon; Howarth and Marino, 2006; see Figure10).

The Impact of dam construction on rivers

Changes in the nitrogen, phosphorus, and reactive silicon from the land to sea



Source: modified from Maanara et al., 2020

Figure 10. Impact of a dam on N, P, and reactive Si from the land to sea (from Maavara et al., 2020).

3

Naturally occurring low oxygen regions of the ocean

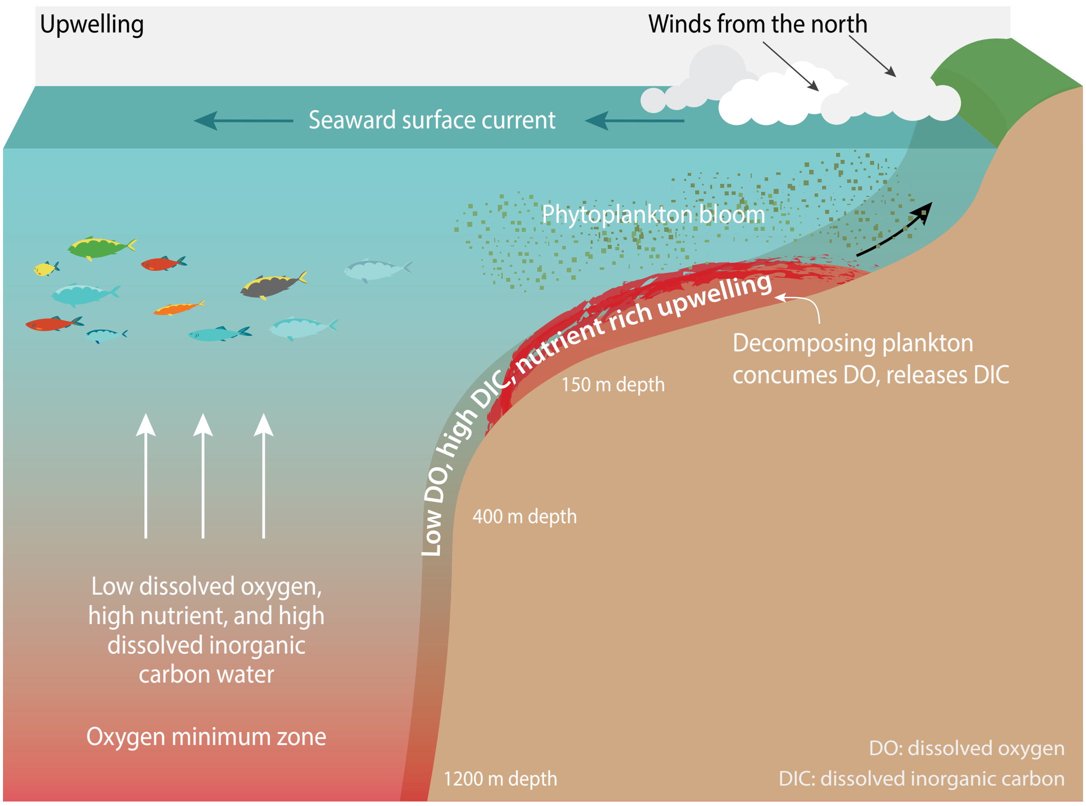
Hypoxia in coastal waters is generally a consequence of human-induced factors, such as nitrogen pollution, but areas of low oxygen are also found to naturally occur in the ocean. These areas, known as oxygen minimum zones (OMZ) occur at mid-water depths (200–1000 m) worldwide but especially along the western coast of continents. The well mixed surface waters of the open ocean have high concentrations of oxygen but with depth oxygen levels decline. This is because very little mixing happens to bring in oxygen, and the decomposition of organic matter that rains down from the surface consumes oxygen faster than it can be replaced. In contrast, oxygen is usually plentiful in the deep ocean. The result is the formation of an oxygen minimum zone (OMZ), sandwiched between the surface ocean and the deep ocean. OMZs comprise up to 10% of the volume of the global ocean and are expanding due the decrease in oxygen solubility and increased stratification as a result of warming water due to global climate change (e.g., Stramma et al 2008; Breitburg et al 2018).

In some areas these cold, oxygen-depleted, but nutrient rich bottom waters are brought to the surface near the coast (a wind-driven process referred to as coastal upwelling[2]). The nutrients in the cold water stimulate the growth of algae providing food for many marine organisms (Figure 11). Such upwelling systems are very productive but under certain conditions excessive concentrations of nutrients can result in the formation of algal blooms leading to dead zones. Examples of upwelling induced dead zones can be found periodically off the west coast of the United States (see box), in the eastern Atlantic, the Bay of Bengal and the Arabian Sea.

Naturally occurring low oxygen zones can also be found in restricted coastal basins which are cut-off from the deeper ocean by shallow sills. There is no supply of oxygen into the deep wate of these basins with the entire water column below

2. Coastal upwelling is caused by a combination of wind driven currents and the rotation of the earth (Coriolis force) which result in water being carried away from shore. Deep, cold water rises (upwelling) to replace this water.

Impact of upwelling on the development of hypoxic in coastal waters



Source: Modified from Chan et al., 2019

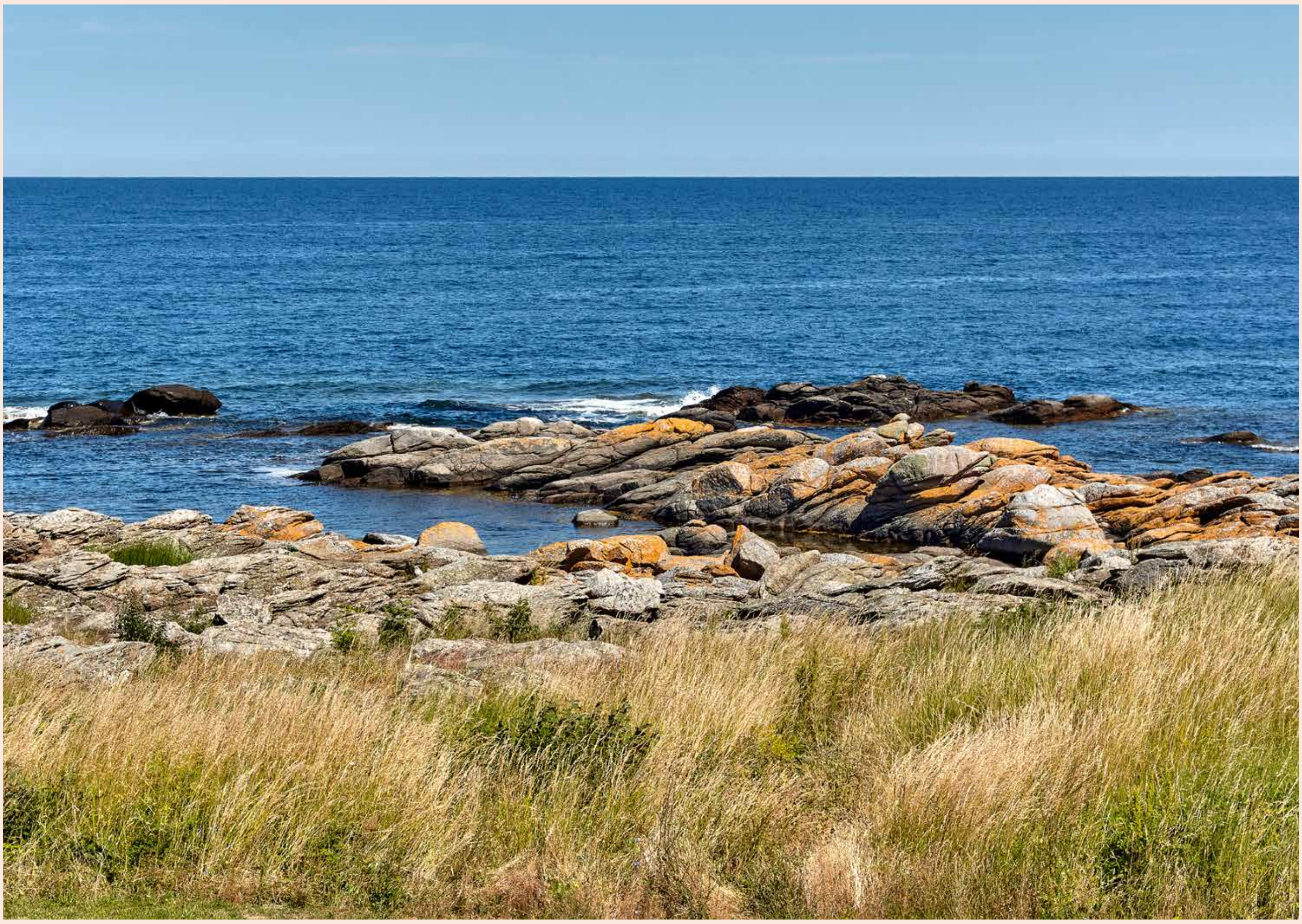
Figure 11. Impact of upwelling on the development of hypoxic in coastal waters (from Chan et al., 2019).

the surface mixed layer consequently starved of oxygen. In some cases, the depletion of oxygen is absolute such as in the isolated deep-water basins of the Black Sea and the Baltic Sea (Pitcher et al., 2021). Storms can bring deep hypoxic water into shallow depths, killing the fauna and releasing hydrogen sulphide gas (the "rotten egg" smell produced as a result of anaerobic sulphate reduction in bottom sediments). Basins that are not well connected with the rest of the world ocean and that tend towards more hypoxic bottom waters include the Arabian Sea, Bay of Bengal, Andaman Sea, Sea of Japan, South China Sea, Celebes Sea and Banda Sea (see Figure 1). Because of the poor circulation, these basins are vulnerable to becoming hypoxic or even anoxic if other factors (e.g. increased input of nutrients; warming temperature) push them towards a situation where oxygen levels are further depleted in their bottom waters (e.g. Naqvi, 2021).

The Baltic Sea

The Baltic Sea is a well-known example of an enclosed sea with oxygen-depleted bottom waters (Figure 12). Since the late 1980s, the Helsinki Commission [HELCOM] has been working to reduce anthropogenic nutrient loads into the Baltic (Backer and Leppanen, 2008). However, the reasons why the Baltic Sea has dead zones is due to multiple causes, among which is the natural geography of the basin, having restricted connections with the Atlantic Ocean, and climate. Prior to any human activities, the Baltic has had several phases of naturally occurring hypoxia during periods of warmer climate in the early Holocene 6000–2000 years ago and again in the Medieval Warm Period 750–1200 years ago. This natural variability is recorded in Baltic Sea sediments as layers of laminated silt and clay (Hille et al., 2006) and is apparently due to reduced circulation and enhanced stratification when surface waters are insufficiently cooled in winter to ventilate the deep basins.

Since the industrial revolution a 10-fold increase of hypoxia in the Baltic Sea has been documented, linked primarily to the increased inputs of nutrients from land and to a return to warmer climate conditions because of anthropogenic global climate change (Carstensen et al., 2014). Hypoxia impacts bottom-living organisms and fish communities in the Baltic Sea as well as biogeochemical cycles of nitrogen, phosphorus, and iron. Efforts to reduce anthropogenic nutrient inputs have resulted in less intense and less frequent events of eutrophication, but hypoxia is still present over an area exceeding 60 000 km^2.



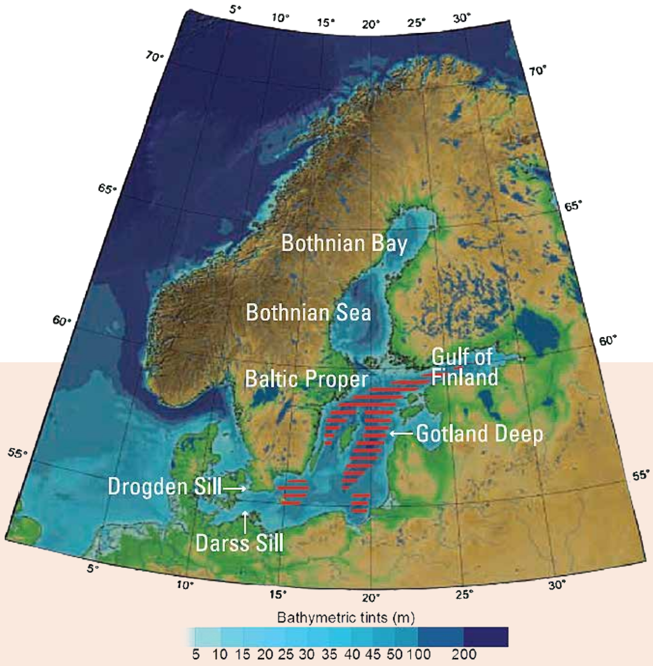
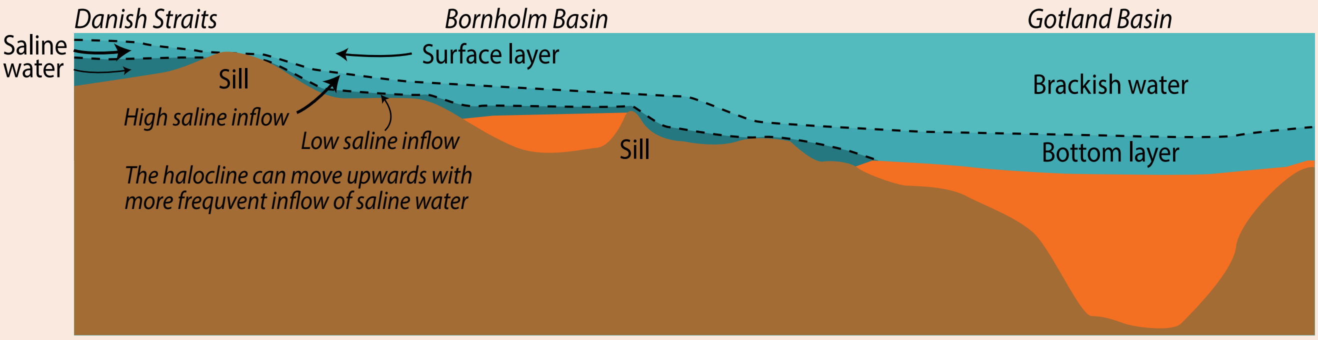
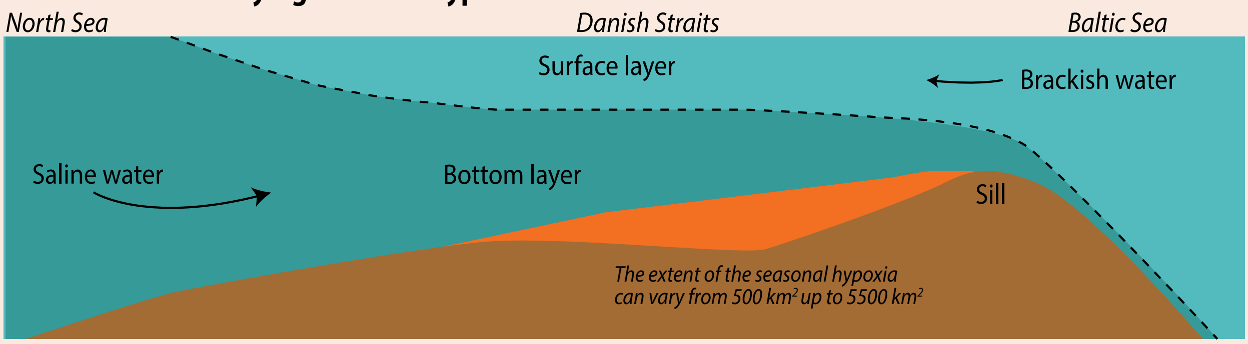


Figure 12. Map of the Baltic Sea identifying its major basins and sills governing the inflow of saltwater. Red shading designates the maximum hypoxic area (from Conley et al., 2009). Left hand panel – Patterns of hypoxia in the Baltic Sea red hatched areas (a) perennial hypoxia in the central Baltic Sea; (b) seasonal hypoxia in the Danish straits; (c) episodic hypoxia in shallow coastal waters such as Limfjorden (from Carstensen and Conley, 2019).

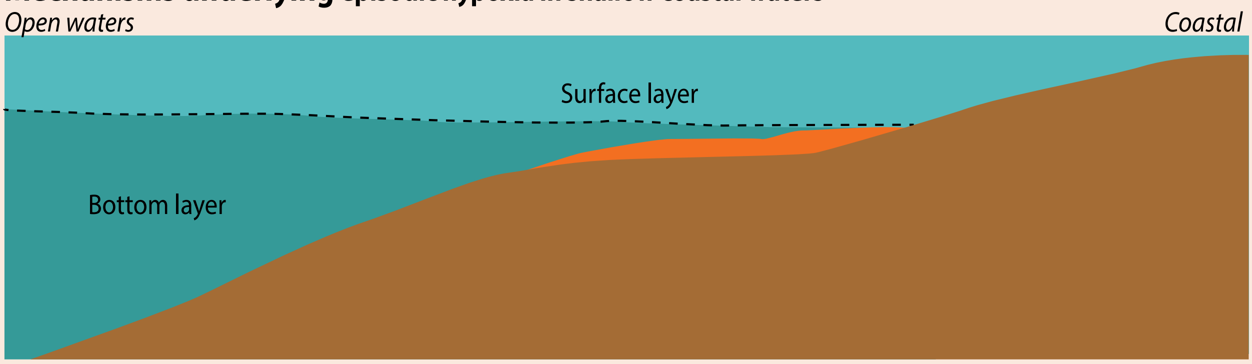
Mechanisms underlying perennial hypoxia in the open central Baltic Sea



Mechanisms underlying seasonal hypoxia in the Danish straits



Mechanisms underlying episodic hypoxia in shallow coastal waters



- - - Halocline — The potential for hypoxia exists when oxygen consumption exceeds the supply of oxygen

Source: Modified from Carstensen and Conley, 2019

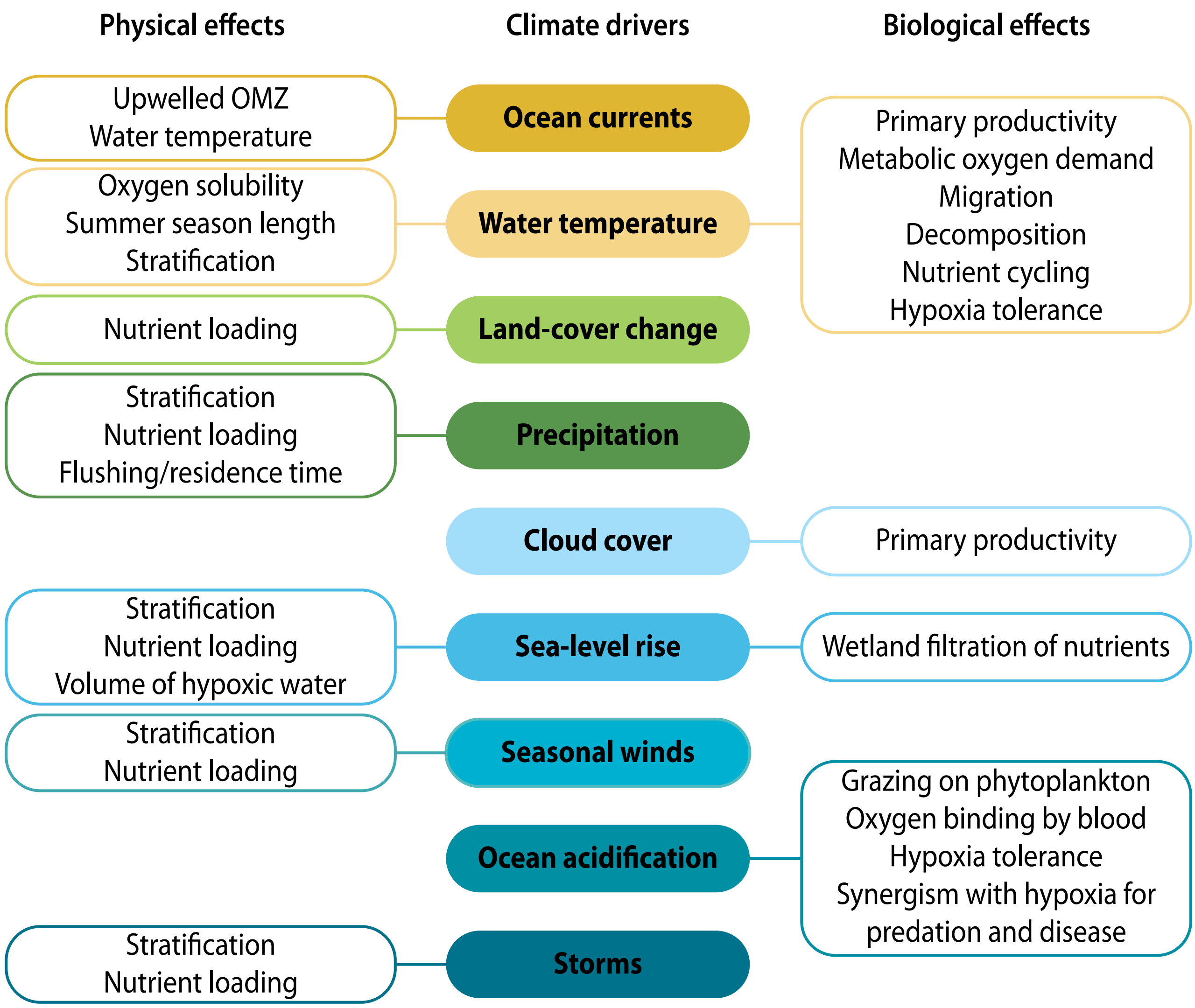
4

Climate change and dead zones

Climate change is warming the world's oceans. The amount of oxygen that can be dissolved in seawater depends on temperature – warm water cannot absorb as much oxygen as cool water (Altieri and Gedan, 2015). Observations indicate that the amount of oxygen in the open ocean decreased by as much as 3.3% in some locations (IPCC, 2022) and ocean models predict a further 1 to 7% decline by 2100 (Stramma and Schmidtko, 2019). This reduction in oxygen, coupled with increased stratification, changing circulation patterns, changes in rainfall and storm activity, and the increase in anthropogenic nutrients has resulted in spatially complex patterns of dissolved oxygen in the global ocean (Robinson, 2019, Figure 13).

Dissolved oxygen concentration and saturation levels in ocean waters are dependent upon water temperature.

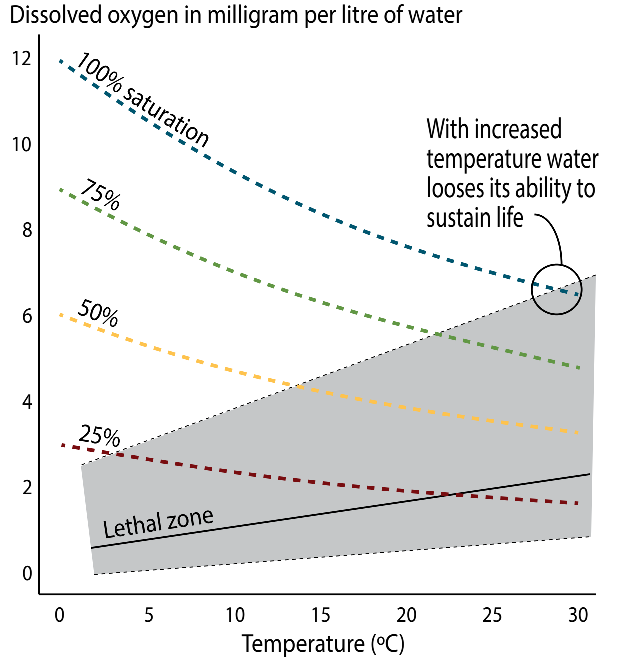
The climate drivers and their associated physical and biological effects



Source: Altieri and Gedan, 2015

Figure 13. The climate driven physical and biological responses that contribute to hypoxia (from Altieri and Gedan, 2015).

The relationship between dissolved oxygen saturation and lethal dissolved oxygen as a function of temperature



Source: Altieri and Gedan, 2015

Cold water can absorb more dissolved oxygen than warm water (Figure 14). For this reason, there is concern about the potential impact of global climate change on the expansion of existing dead zones and the creation of new ones. In their review paper, Altieri and Gedan (2015) found that 94% of dead zones are in regions that are expected to experience at least a 2 °C temperature increase by the end of the century. There is large spatial variation in the projected extent of ocean warming, with the polar seas warming the most and tropical seas less so. There is also large variability in projected warming in some areas. For example, the UK shelf seas may experience between 1.5 °C and 4 °C of warming by 2100 (Jenkins et al., 2009).

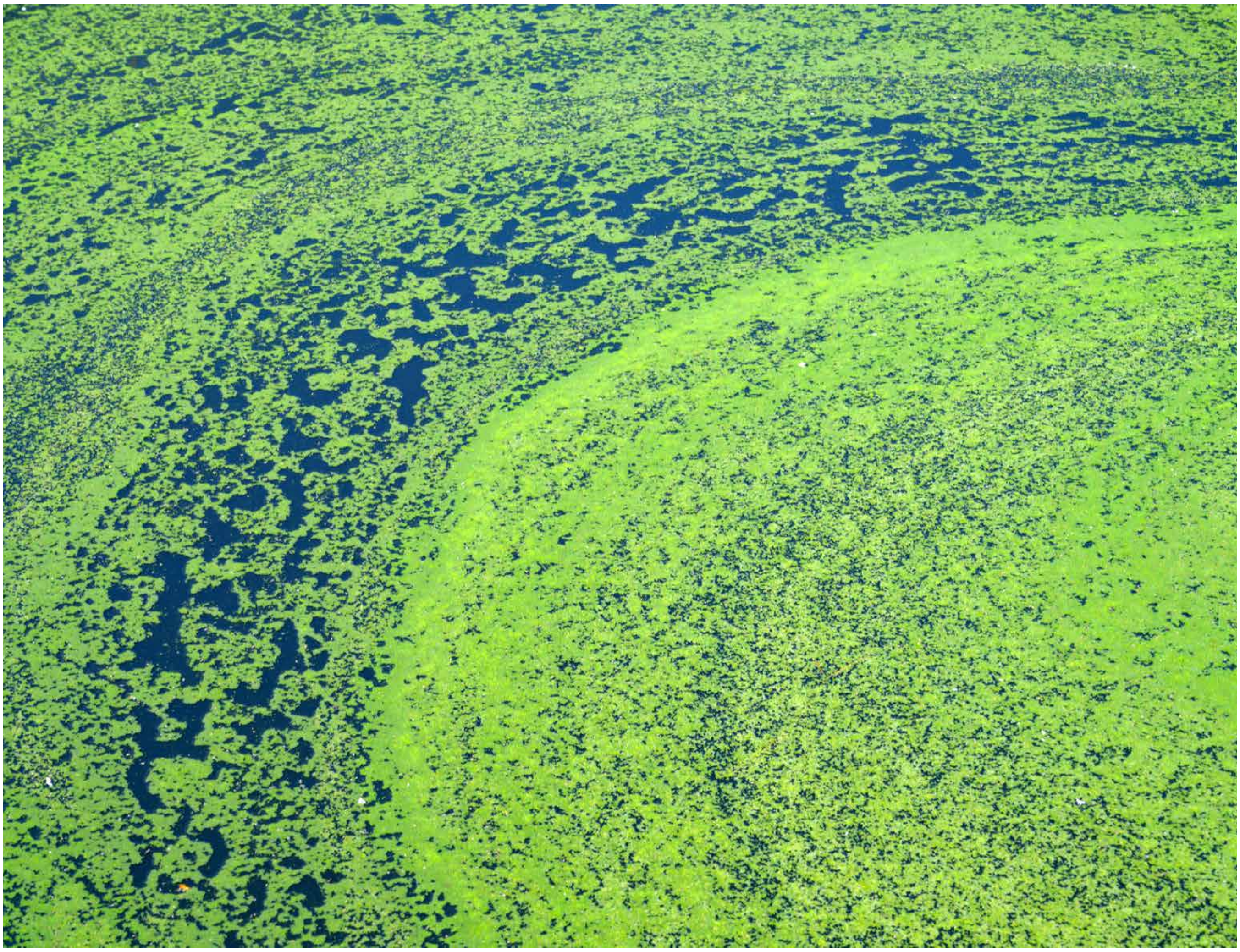
Figure 14. The relationship between dissolved oxygen saturation and lethal dissolved oxygen as a function of temperature (from Altieri and Gedan, 2015). The shaded area captures 90% of observations for dissolved oxygen concentration lethal to biota and the solid black line is the 50% quartile for all organisms. The graph illustrates how increasing temperature results in a corresponding decrease in dissolved oxygen and an increase in lethal conditions for biota.

It is important to recognise that changes in the occurrence of extreme events, rather than the average background environmental conditions, can cause major disruptions to marine ecosystems. In an environment that has not previously experienced hypoxia, the first-ever hypoxic event need not last for very long to have severe impacts. Brauko et al. (2020) detected a regional sea surface heatwave lasting for 9 days during the austral summer of 2020 in the Bay of Santa Catarina Island (Brazil). During this period, seawater temperatures reached 29.8 °C. The authors reported that the event caused a decrease in microbenthic, and phytoplankton community richness and anoxia was detected in the bay for the first time.

The circulation of fjord basins is tightly connected with coastal water masses via tidal circulation and coastal wind conditions. Consequently, future climate changes in the North Atlantic wind regime will likely propagate into the fjords. A continued decrease in the density of coastal water masses at fjord sill depths may increase the probability of long stagnation periods with implications of ongoing deoxygenation of fjord basin waters.

Seasonal dead zones off the west coast of the USA

Seasonal hypoxia was first observed on the Oregon shelf in 2002 (Grantham et al., 2004) and has continued to form most years since (Chan et al., 2008). Explanations for the low oxygen water mass include reductions in winds that normally mix and oxygenate shelf waters, lowered oxygen levels in source waters and intensification of upwelling, which has brought low oxygen waters onto the shelf with increasing frequency (Pitcher et al., 2021). A recent NOAA research cruise confirmed the expansion of the low oxygen zone off the coast of Oregon and Washington (NOAA 2021a). They also noted an earlier seasonal start, with hypoxic conditions evident in April whereas in previous years they didn’t appear until late June/July. The winds that drive upwelling, bringing the nutrient rich water to the coast were abnormally strong in 2021. The observed hypoxic events cannot be attributed exclusively to climate change, but it is possibly a contributing factor (Pitcher et al., 2021).



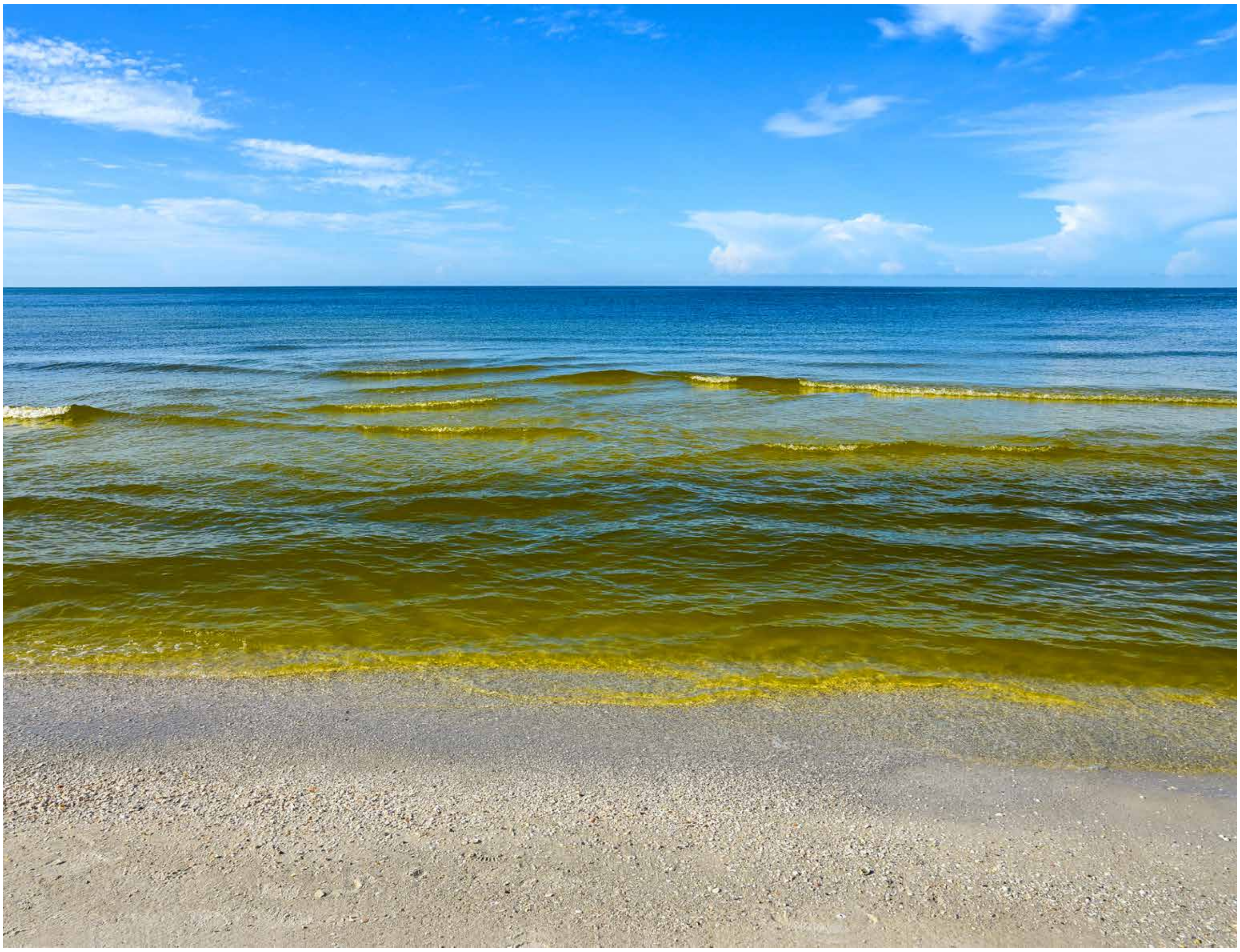
5

Connection between coastal zone type and the potential for hypoxia

5.1 Coastal geomorphology and other factors influencing the development of dead zones

Different types of coastal environment are more or less vulnerable to eutrophication based upon their physical setting, the hydro-dynamic regime, and biological processes.

Lagoons and wave-dominated estuaries generally have a higher risk of eutrophication than well mixed bays and estuaries (Figure 15). They typically have slow flushing rates due to their geomorphology, with a narrow tidal inlet connected to a back-barrier basin resulting in restricted water flow (Harris and Heap, 2003). Such basins are natural sediment traps that also retain water that becomes over-heated in summer months, factors that can drive so-called negative estuarine circulation and plankton blooms when nutrients are available. Negative estuarine circulation occurs when evaporation of the lagoon or estuary basin waters creates warm, high-salinity (salty) water that is so dense that it sinks to the bottom of the estuary/lagoon and flows out to sea, with less salty marine water flowing in on the surface. A key point here is that the warm (25–30 °C), high-salinity (salty) water is also unable to contain much dissolved oxygen (Figure 14). This means the bottom water in such locations has low dissolved oxygen which can be further reduced by excess loads of organic matter consuming oxygen as it decomposes on the seabed.



Fjords, with their deep, stratified waters can be compared with lagoons or wave-dominated estuaries where poor circulation is concerned. Their basin waters can be naturally hypoxic in certain cases, particularly where there is a large/long fjord with a deep basin located behind a shallow sill. In such cases the exchange of water between the fjord basin and adjacent sea is relatively slow and the system is much more susceptible to turning eutrophic with only small increases in anthropogenic nutrient inflow (Pitcher et al., 2021).

In general terms, highly turbid, well-mixed bays and estuaries are less vulnerable to eutrophication than low-energy bays and estuaries with clear waters but poor circulation (Painting et al., 2007; Plew et al., 2020). Turbidity exerts a strong control over primary production – the more turbid the water (coloured by suspended mud) the less light can penetrate and so the less phytoplankton are able to live there. In San Antonio Bay, Patagonia, Argentina, Martinetto et al. (2010) found that tidal flushing, associated with the Bay's nine-meter spring tidal range, prevents anoxic or hypoxic episodes even during blooms of macroalgae. In tidal estuaries and river deltas the normal estuarine circulation, where fresh river water flows out at the surface and is replaced by salty ocean water at depth, is broken down by the strong tidal mixing. This dilutes the nutrients in river water with marine water from the adjacent sea (which is commonly depleted of nutrients). These factors collectively act to supress eutrophication in tide-dominated systems (Figure 15).

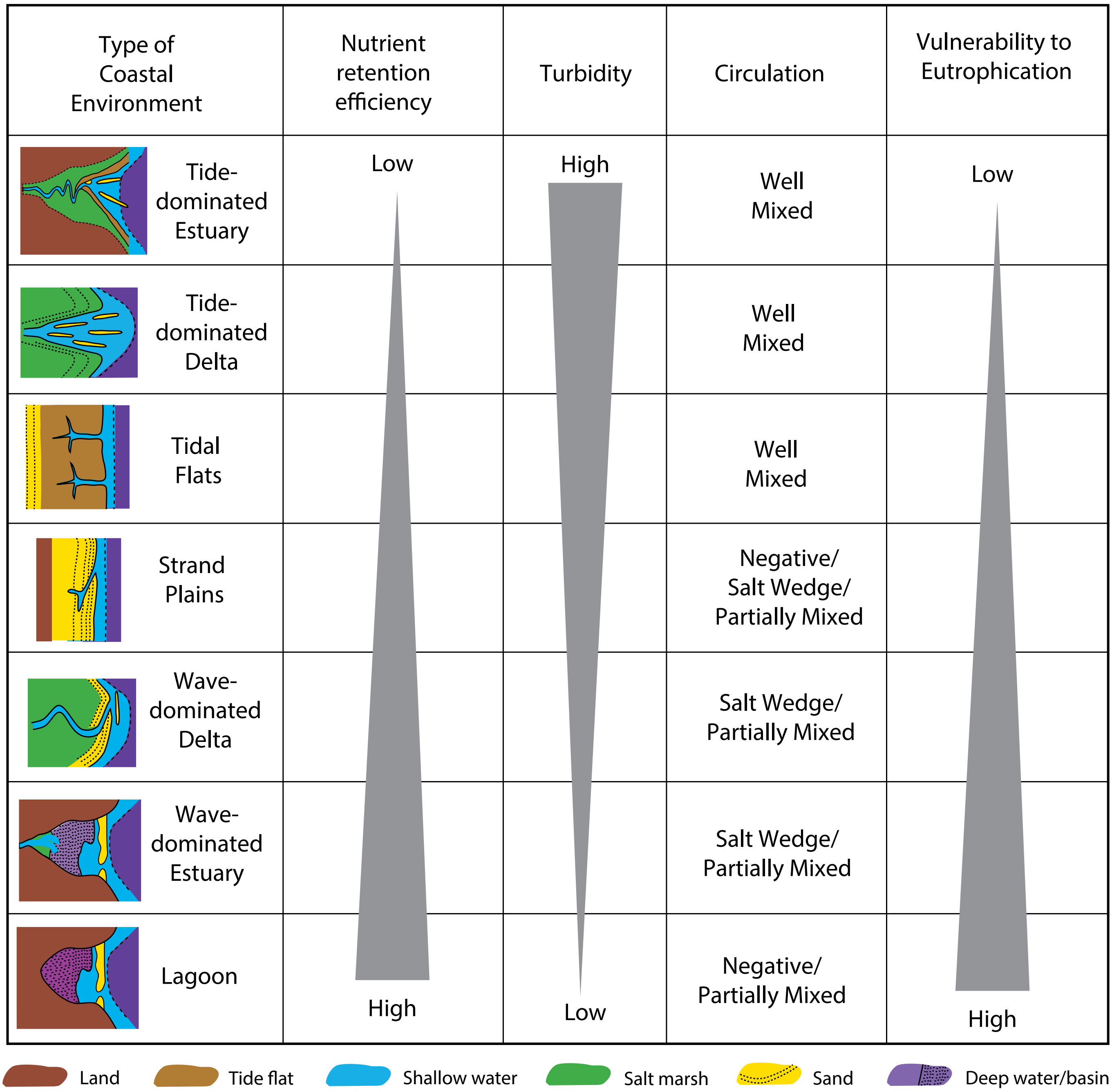


Figure 15. Conceptual model illustrating physical and geomorphic factors that contribute to coastal environments becoming eutrophic (based on literature cited in the text and original drawing by Harris and Heap, 2003). For the purpose of this discussion, fjords will be considered as a type of wave-dominated estuary.

6

Economic consequences of dead zones

The economic impacts of dead zones include impacts on ecosystem services [supporting, provisioning, regulating, and cultural services] and impacts on the commercial sector, namely commercial and recreational fisheries, and tourism (Rabotyagov et al., 2014).

6.1 Impact on fisheries

The economic impact of the dead zone on Gulf of Mexico fisheries was studied by Boehm (2020) who also conducted economic modelling work. In her report she notes that Gulf of Mexico fisheries have the second highest commercial landings in the United States, just behind Alaska. In 2016, Gulf Coast commercial fishing generated at least $17 billion in economic benefits and sustained nearly 200,000 jobs. Gulf Coast recreational fishing together with coastal tourism in 2016 generated an additional $57 billion in economic activity and sustained nearly 500,000 jobs. Modelling by Boehm (2020) indicates that excessive use of fertilizer for agriculture caused between $552 million and $2.4 billion (2018 US dollars) in damage to Gulf fisheries and marine habitat annually from 1980 to 2017. Furthermore, the study estimated that between $98 million and $2.8 billion in damage costs to Gulf fisheries and marine habitat could have been averted every year from 1980 to 2017 through shifts in agricultural practices (Figure 16).

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One of the best-known economic assessments of the impact of dead zones is from the Black Sea (reviewed by Rabotyagov et al., 2014). In particular, the shallow shelf sea adjacent to the mouths of the Danube and Dnieper Rivers. This region was impacted by the growth of a dead zone that began in the early 1970's and was directly attributed to over-use of nitrogen fertilizer on crops in the river catchments. A dead zone of 3,500 km^2 was observed in summer 1973 which increased in area rapidly and reached a peak size of 40,000 km^2 in the late 1980s. The fishery that exploited over 25 species of commercially valuable fish and was worth roughly US$2 billion per year was reduced by 90% (loss in revenue of US$1.8 billion/year). An additional loss occurred in the tourism sector which saw revenue drop by around US$500 million/year.

Damage costs to Gulf fisheries and marine habitat

Shifts in agricultural practices could avert the damage

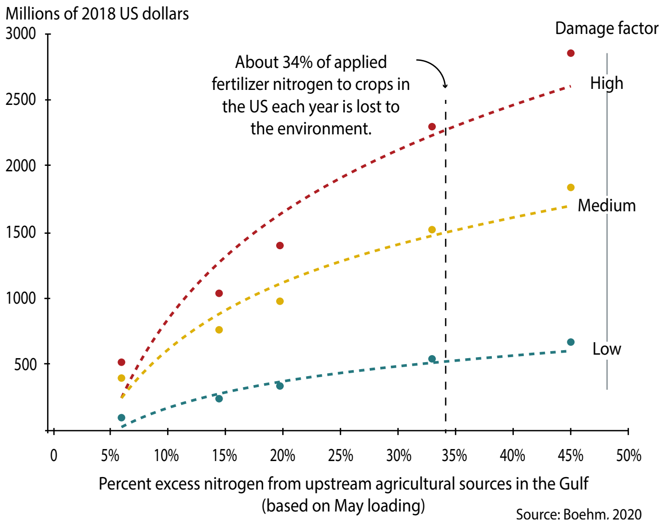

Figure 16. Estimated damage to fisheries and marine habitat ecosystem services caused by the nitrogen pollution that forms the dead zone ranges from $98 million (low damage factor) to $2.8 billion (high damage factor) in 2018 dollars. The damage factors are based on survey results quantify the amount people would be willing to pay to protect certain ecosystem services. For example, using the low damage factor scenario, a 20% reduction in excess nitrogen would reduce damage to fisheries and ecosystems by an estimated $400 million, while under the high damage scenario it would result in a $1.6 billion reduction in damage (from Boehm; 2020).

After the collapse of the Soviet Union in 1989, agricultural production in the region was greatly reduced and fertilizer usage declined rapidly. By 1995 the dead zone had nearly disappeared. However, the benthos that was below the dead zone has not recovered nor has recovery of the once prosperous fisheries been realised (Diaz and Rosenberg, 2008). Introduced species and unsustainable fisheries policies of the surrounding Black Sea countries have contributed to the current situation in which many commercially valuable species have become locally extinct (Ullman et al., 2017).

6.2 Ecosystem services and biodiversity

Commercial fisheries discussed above are considered a provisioning service. The food web built upon the pelagic and benthic ecosystems are supporting services. These sevices include carbon storage, the food and oxygen provided by normal phytoplankton grown, and habitat provided by benthos. The benthic fauna provides regulating service by filtering seawater (molluscs, sponges, corals etc.) to remove particulate organic matter and regulate bacteria in the water column. All of these services are reduced or eliminated altogether when a coastal dead zone develops.

The occurrence of a dead zone in a previously oxygenated environment can have important impacts on biodiversity. Oxygen starvation can devastate benthic communities especially in the case of sessile species as these are unable to relocate to avoid suffocation. This can result in a negative feedback loop, where hypoxia removes filter-feeding bivalves (for example) which, in turn, reduces the environment's capacity to modulate algal blooms. Biodiversity itself plays a critical role in overall ecosystem services.

Impacts of excessive nutrient loads may occur upstream as well as in the marine environment. For example, the journey of nitrogen fertilizer from the corn fields of Iowa to the Gulf of Mexico has many possible endings along the way. Nitrogen fertilizer can cause toxic algae blooms in reservoirs designed for a town water supply located far away from the coast. Stretches of river and wetland ecosystems upstream from the coast can also be impacted.

6.3 Human health

Harmful algal blooms (HABs) are the most recognised impact of nutrient pollution. A 2020 review of human health and marine pollution (Landrigan et al., 2020) documented an increase in severity and frequency and geographical extent of HABs. HABs produce toxins that accumulate in fish and shellfish. Exposure to HABs through ingestion of seafood, skin contact or in the air can cause severe illness in people. This includes neurological impairment, stomach problems, skin irritation and respiratory illness. Animals and birds can also be affected.

Due to increases in nutrient runoff from land, nutrient upwelling, increasing ocean temperature and stratification and changing wind and current patterns harmful algal species are moving into previously unaffected areas. This includes the arctic where hitherto unexposed populations may be impacted by HAB toxins. The health costs of HABs can be high – in the US the annual health costs are estimated to be more than US$20 million (with an additional $18 million damage to fisheries and $7 million impact on recreation and tourism) (U.S. National Office of Harmful Algal Blooms, 2023).

7

Reducing anthropogenic dead zones

It must be acknowledged that the root causes of dead zones are highly complex and interlinked; it is most likely that hypoxia in coastal waters results from the cumulative effects of multiple drivers. In some cases the natural environmental conditions pre-dispose a system to be vulnerable to hypoxia, such as noted above for the Baltic Sea and Black Sea (for example); thus, small anthropogenic changes to the environment can result in major impacts. Climate change impacts (e.g. rising temperature), alone, may drive some vulnerable systems into an hypoxic state (e.g. example of Bay of Santa Catarina Island, Brazil, reported by Brauko et al., 2020). When combined with habitat loss, catchment disturbance, river damming and climate change, the consumption of oxygen related to other impacts (waste water, effluent discharge, agriculture, etc.) can easily tip the balance of a system driving it towards hypoxia. Unless steps are taken to reduce anthropogenic greenhouse gas emissions, reductions in effluent discharge (for example) on their own may not be enough to avoid future hypoxic events. In short, an holistic approach is needed to find the best action(s) to address the formation of dead zones in any given environment.

A good example is Macquarie Harbour, located in Tasmania, Australia. The estuary is host to industrial salmon farming and has suffered from acute hypoxia in recent years. Disturbance in the adjacent river catchments has impacted the turbidity and chemistry of inflowing fresh water. In the austral summer of 2017-18 a major hypoxic event coincided with an outbreak of a fatal fish disease – POMV (pilchard orthomyxovirus) which together resulted in the death 1.35 million farmed salmon and trout. Hypoxic events impact the habitats of other fauna that inhabit the deep basins of Macquarie Harbour, including one endangered demersal fish species, the Maugean skate (CSIRO, 2018).

Oxygen levels in Macquarie Harbour are naturally low due to its geomorphology; a shallow sill separates a deep water basin such that only the upper 15 m of the water column are oxygenated by river inflow (Figure. 17). Episodic intrusion of marine waters over the shallow sill occurs only during extreme weather events, when oxygen levels in the deepest basin waters are replenished. This occurs very irregularly with only 2 significant replenishment events over a 5 year observation period (Hartstein et al., 2019). Effluent from salmon farming exacerbates the situation in Macquarie Harbour which is naturally predisposed towards a hypoxic state. A novel engineering mitigation measure that is currently being trialled is to pump oxygen-rich waters

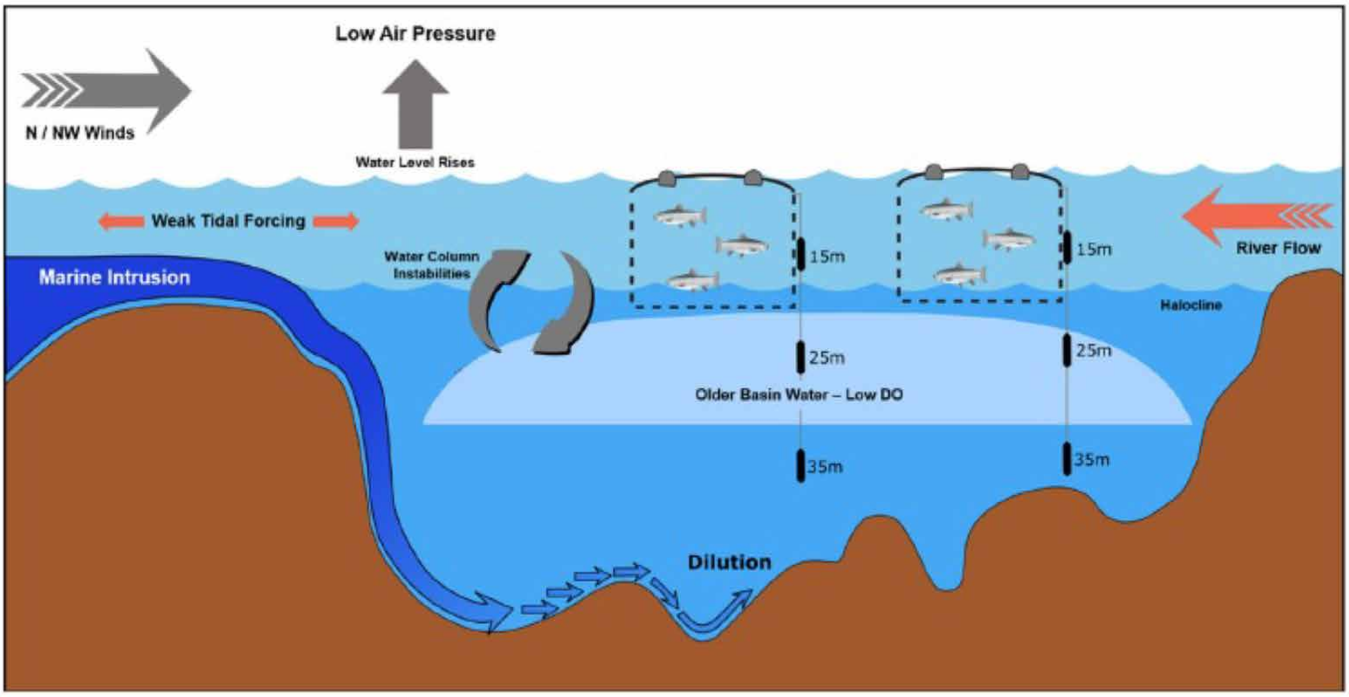

Figure 17. Conceptual model of oxygen content in Macquarie Harbour waters, showing occurrence of a mid-depth oxygen minimum zone (after Hartstein et al., 2019).

into the Macquarie Harbour basin in order to offset the depletion of oxygen that would otherwise occur from the decomposition of aquaculture effluent (Salmon Tasmania, 2023). The so-called "Macquarie Harbour Oxygenation Project" is ongoing as of the time of this writing.

In an early review of proposed engineering interventions in the Baltic Sea, Conley et al. (2009) concluded that "virtually all engineering methods proposed to date for the Baltic Sea's pelagic waters seem unrealistic and/or not viable". A range of engineering solutions have been discussed to accelerate the oxygenation of the hypoxic bottom waters of the Baltic Sea. Suggestions include:

- bubbling or manipulation of the circulation
- biomanipulation of fish species with the goal of reducing summertime chlorophyll concentrations
- chemical precipitation by adding aluminium to remove phosphorus from the water column and enhance its permanent burial in sediments.

The authors further urge for environmental impact assessments to gauge potential effects on biota and the (expected) impact on nutrient bio- geochemical cycles (Conley et al., 2009).

Perhaps one of the most promising mitigation measures is the restoration of benthic habitats that were once present in an impacted estuary or embayment. The removal of filter-feeding benthic communities such as oyster reefs in many coastal areas during the 19th and early 20th centuries led to a reduction in water quality in many cases and probably contributed to the onset of eutrophication. Bricker et al. (2014) suggest that shellfish aquaculture could improve water quality in Chesapeake Bay. If ~40% of the estuary bottom is cultivated for shellfish aquaculture it would promote growth of a now depleted oyster stock, remove eutrophication impacts directly from the estuary through harvest, and consequently remediate hypoxia. In similar studies, Nielsen et al (2016) proposed using mussel farms to remove excess nutrients in a highly eutrophic Danish fjord and Yu and Gan (2021) proposed that oyster aquaculture could reduce hypoxia in China's Pearl River Estuary.

Human interventions to try to improve the oxygenation of dead zones invariably run a risk of unintended consequences, including impacts on biota, changes to interdependent ecological functions and greater than expected energy needs and costs to sustain any intervention. There is a need to consider transboundary aspects when the impacted area is adjacent to multiple jurisdictions. The timing and persistence of a dead zone are other factors that need to be considered. One-off studies can be useful to gain an understanding of the spatial distribution of the dead zones, but they do not provide any insights as to temporal variations in dead zone formation. For example, the timing (year or decade) of when hypoxia or eutrophication first became an issue for a given location and its primary initial cause can only be understood by dedicated, long-term (over several years) research (including modelling) and monitoring programmes. Thus, long-term monitoring is critical to ensure that a location has responded positively to remedial actions and transitioned back from a dead zone to a less impacted environment.

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In Macquarie Harbour, in the state of Tasmania, Australia, 1.35 million farmed salmon and trout died over the 2017-18 summer. That event coincided with higher than usual temperatures and low dissolved oxygen (DO) levels in the harbour and the presence of a fatal fish disease – POMV (pilchard orthomyxovirus).

This assessment of coastal dead zones was undertaken based on a review of 841 published papers. Almost 1000 hypoxic or eutrophic "hot spots" were identified, nearly double the number reported in a review from 2008.

There are several well-known drivers of eutrophication that can lead to dead zone formation, but often it is not possible to determine the cause of an hypoxia event. This is due to the complexity of oxygen dynamics in coastal waters and the general lack of in situ data. The role of coastal topography has been shown to be an important factor in the development of hypoxic conditions, with enclosed coastal areas where water circulation is reduced being particularly vulnerable.

These drivers are exacerbated by a global warming induced decline in dissolved oxygen concentrations in the upper part of the water column (Schmidtko et al., 2017).