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Ocean deoxygenation: Everyone's problem

Causes, impacts, consequences and solutions

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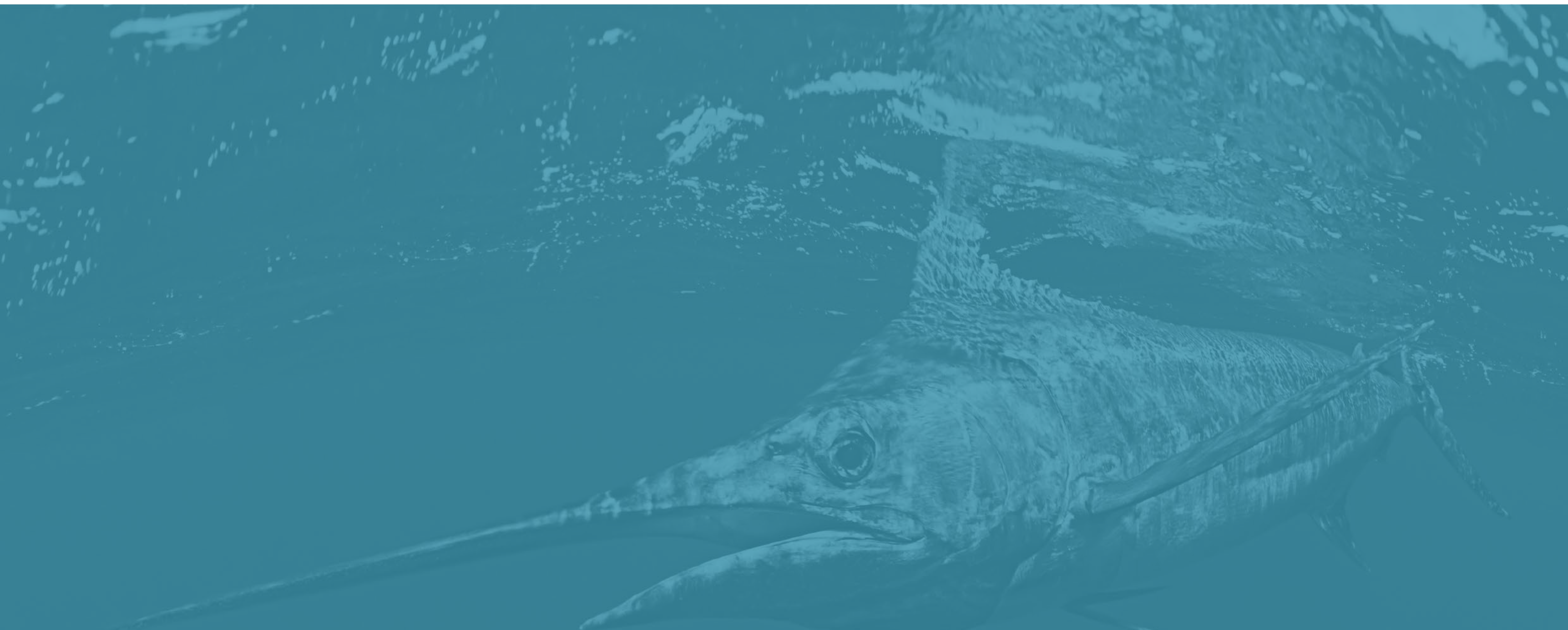

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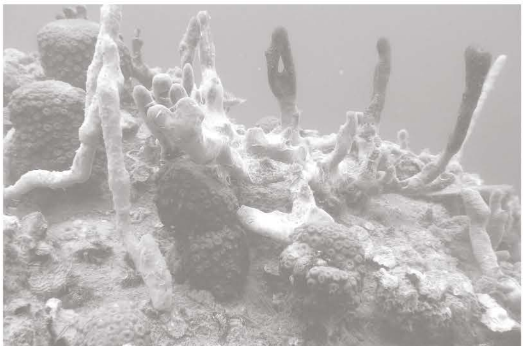


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Ocean deoxygenation: Impacts on ecosystem services and people

9

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Summary

- Effects of ocean deoxygenation on people remain understudied and inherently challenging to assess. Few studies address the topic and those that do generally include more readily quantified economic losses associated with ocean deoxygenation, exclude non-use and existence value as well as cultural services, and focus on relatively small, bounded systems in capitalized regions. Despite the lack of extensive research on the topic, current knowledge based in both the natural and social sciences, as well as the humanities, can offer useful insights into what can be expected from continued ocean deoxygenation in terms of generalized impact pathways.
- People receive benefits from ocean ecosystem services in the form of well-being (assets, health, good social relations, security, agency). Ecosystem services are translated to human well-being via social mediation, such that differences in levels of power and vulnerability determine how different social groups will experience hazards created by continued ocean deoxygenation. Despite not knowing the precise mechanisms of ocean deoxygenation-driven biophysical change, established social mechanisms suggest that ocean deoxygenation will exacerbate existing social inequities.
- Reductions in dissolved oxygen (DO) are generally expected to disrupt ecosystem functioning and degrade habitats, placing new challenges and costs on existing systems for ocean resource use. Coral reefs, wetlands and marshes, and fish and crustaceans are relatively more susceptible to negative effects of ocean deoxygenation. People reliant on these systems and animals may experience relatively more negative impacts. In the near-term, some hypoxia-tolerant species, particularly gastropods, may see benefits from reduced DO levels due to altered food webs, and potential increases in ecosystem services should be considered in adaptation strategies.
- People in low latitudes, coastal urban and rural populations, poor households in developing countries, and marginalized groups (such as women, children, and indigenous populations) are most vulnerable to the impacts of ocean deoxygenation. Communities where these characteristics overlap are uniquely vulnerable, notably coastal communities in low income developing countries (LIDCs).
- Improved understanding of nuanced impact pathways of ocean deoxygenation to human well-being outcomes will be of critical importance for effective planning in response to ocean deoxygenation going forward. Analyses of ecosystem services should consider the entire range of ecosystem service types, even where not quantifiable, in order to provide the information needed for proper planning, including how different groups of people will be impacted, based on their vulnerability to hazards caused by low DO levels. Transdisciplinary approaches to assess systems holistically present promising means for gaining policy-relevant knowledge of complex social-ecological system dynamics.
- Policies and actions aimed at adapting to and mitigating for ocean deoxygenation should focus on reducing the vulnerability of groups and individuals by addressing ultimate and proximate causes of high sensitivity and exposure to low DO hazards, and building adaptive capacity. Attention should be paid to the central role that social institutions play in mediating access to ecosystem services and the inherent inequities in the ways humans experience natural hazards.

Social and biophysical trends related to effects of low oxygen conditions	Potential consequences
Dissolved oxygen levels are lowest at low latitudes, eastern coastal margins, and coastal waters subject to eutrophication.	• Groups near to and reliant on these areas will be most at risk to resulting hazards. • Less proximal groups may also see risk due to biophysical teleconnections and socio-economic interconnectivity.
Persistence of low O_2 zones varies over space and time.	• Some ecosystem services may see positive impacts in the short-term, but the trend is toward habitat degradation and reduced ecosystem services. • In the near-term, negative impacts may be lessened where localized low O_2 can be avoided by use of higher O_2 areas nearby.
Groups vary in their vulnerability to natural hazards.	• Groups with more exposure and sensitivity to hazards and less adaptive capacity will be more negatively impacted by reduced ecosystem services and less able to benefit from any enhanced ecosystem services. • The groups more exposed to hazards of environmental change are more dependent on local environmental quality and less able to mobilize resources to adapt. These same groups are typically those discriminated against or marginalized in societies, on the grounds of class, race and gender identities. • More vulnerable groups will be more negatively affected despite uncertainty in biophysical impacts. • Women, children, groups with restricted mobility, and those living in poverty are most vulnerable to low O_2 impacts. • Low O_2 impacts will further exacerbate existing social inequities.
Marine organisms and ecosystem subtypes are differentially impacted by low O_2.	• People reliant on ecosystem services from coral reefs, wetlands and marshes, fish, or crustaceans may see relatively greater hazards from low O2. • People who benefit from ecosystem services supplied by mangroves, gastropods, or bivalves may experience relatively less hazard, and possibly see enhanced services in the near-term.
Impacts of low O_2 may be enhanced by other stressors, such as ocean warming, acidification, and pollution.	• Impacts may be worse on people exposed to areas experiencing several stressors and people reliant on ecosystem subtypes sensitive to several stressors (e.g. coral reefs). • Impacts on people are more challenging to predict due to uncertainty around synergistic or combined impacts.
Ecosystem services and categories (provisioning, cultural, supporting, and regulating) differ in how they are affected by low O_2 and mediated by social factors.	• Ecosystem service categories more reliant on animals for service provision (cultural, provisioning, and supporting) are likely to be more negatively affected by low O_2, thus will have relatively more impact on people. • Ecosystem service categories more reliant on access to certain places for provision (cultural, provisioning, and supporting) are more susceptible to social mediation of well-being outcomes, thus will have relatively less equitable impact on groups. • Regulating services are generally less susceptible to low O_2 and social mediation, thus will likely have relatively less impact, distributed more equitably.
Ecological interactions can lead to complex and less immediately apparent impacts of low O_2.	• Communities and economic sectors may see complex changes to resources as altered predator-prey and food web dynamics will likely lead to impacts on species not directly affected by low O_2. • Some groups may benefit from species that may see near-term benefits due to predator release or habitat shifts of prey.
Social and ecological positive feedbacks can exacerbate impacts of low O_2.	• Continued urbanization and movement toward coasts both contribute to ocean deoxygenation hazards via eutrophication and increase exposure of people to impacts, while reduced ecosystem services in rural coastal regions may propel further movement to urban areas in search of greater economic opportunity. • Low O_2-induced cyanobacteria blooms have a direct negative impact on human health when blooms are toxic and lead to further reduced O_2 causing run away from equilibrium.

9.1 Introduction

Knowledge of how ocean deoxygenation affects human communities is only just beginning to accumulate and less is known about specific impacts of deoxygenation on economies and societies than about the impacts of other facets of global environmental change, such as sea-level rise, ocean warming or even ocean acidification (e.g. Allison & Bassett, 2015). Assessing effects of environmental change on humans is challenging in that it requires understanding both the biophysical and social mechanisms of change; each represent gaps in knowledge in relation to decreasing levels of dissolved oxygen in the ocean (Cooley, 2012; Rabotyagov et al., 2014). Attention paid to climate change effects in the ocean already lags behind that paid to land-based impacts (Allison & Bassett, 2015) and ocean deoxygenation has only recently received substantial attention (Altieri et al., 2017). How reduced oxygen interacts with other biogeochemical stressors (e.g. pollution and ocean acidification) to affect marine systems is not well-understood (Cooley, 2012) and that lack of understanding will amplify uncertainty of potential impacts on human economic and social systems. There is, thus, a gap in knowledge around how ocean deoxygenation affects the benefits that ocean ecosystems provide for people (ecosystem services) and the ultimate impacts on human well-being.

While human impacts of ocean deoxygenation have not been substantially studied, research in the humanities and social sciences has been furthering our understanding of the impacts of environmental change on people since the rapid rise of the new inter-disciplines of environmental sociology, and, more recently, the environmental humanities (e.g. Castree, 2014; Catton & Dunlap, 1978; Cropper & Oates, 1992). Researchers in these fields have analysed socially differentiated impacts, feasibility and outcomes of a range of adaptation options, and the complex nature of support for and challenges to ongoing technical and political responses (Allison & Bassett, 2015). These insights into the character and mechanisms of environmentally-driven social change are largely absent from most "human dimensions" research in major earth (and ocean) system science programmes; such research is typically limited to endeavours to quantify aspects of societal impact — potential vulnerabilities to physical and biochemical changes, monetary value of threatened ecosystem services, and costs and benefits of various options for adaptation and mitigation action (Castree et al., 2014). Asymmetrical use of available knowledge has led to gaps in our understanding of experienced and expected societal impacts of environmental change (including ocean deoxygenation) and ultimately impedes proper planning and policy development (Breitburg et al., 2018). By failing to engage meaningfully with social enquiry, environmental science had failed to account for the role of power relations and social difference in shaping who most impacts the environment and who is most impacted by environmental change. This is now being addressed by rise of environmental justice as a field of environmental studies as well as activism (Bullard, 2018).

Knowledge derived from qualitative and quantitative methods used in the natural sciences, social sciences, and humanities is here employed together with the ecosystem services for human well-being framework (MEA, 2005a), from ecological economics, and the Pressure and Release (PAR) Model (Blaikie et al., 1994), from political ecology, to evaluate the potential impacts of ocean deoxygenation on human societies. Ecosystem services comprise the range of benefits the natural environment provides to humans, which are translated into human well-being via social systems (MEA, 2005). Loss or reduction of a given ecosystem service may constitute a natural hazard or lead to increased impact of natural hazards. The Pressure and Release Model provides insights into how natural hazards (e.g. as a result of ocean deoxygenation) combined with human vulnerability (as a result of social factors) lead to the impacts experienced by communities (Blaikie et al., 1994; Wisner et al., 2004).

Using the combined ecosystem services and PAR framework, supplemented by qualitative insights from case-study research in the environmental social sciences and humanities, we can maximize usability of current knowledge in addressing a topic with few studies explicitly linking the chain of impacts from natural to social changes, as in the case of ocean deoxygenation to human well-being changes. Studies that have addressed this chain of impacts have generally performed partial assessments that analyse economic effects of ocean deoxygenation on industrial and recreational fisheries in developed countries (see Chapter 10), with only a few studies assessing ecosystem services and human well-being impacts more holistically (see Section 9.5). However, use of 'transitive logic' and the ecosystem services and PAR frameworks, allows for construction of generalized impact pathways. In other words, by applying the mathematical concept of 'transitivity,' if A = B and B = C, then A = C, we can effectively maximize application of current knowledge by connecting bodies of knowledge that describe individual steps of the process from ocean deoxygenation to human outcomes. As such, if we know (A) how ocean deoxygenation affects an ecosystem subtype, species, or biophysical process (in one or more general or specific ways), (B) the effects of those biophysical changes on ecosystem service provision, and (C) social mechanisms by which those changes in ecosystem service availability affect human well-being, we can assert generalized expectations for how reduced levels of dissolved oxygen may affect people in such circumstances. A selection of example impact pathways is described in Section 9.6.

In this chapter, we provide an overview of ocean ecosystem services (Section 9.2), introduce both the ecosystem services and PAR frameworks (Section 9.3), and describe generalized trends and variability in observed and expected ecosystem service and human well-being outcomes from ocean deoxygenation (Section 9.4). We present six case studies in which ocean deoxygenation has been tied to ecosystem service changes (Section 9.5) and summarize several generalized pathways through which ocean deoxygenation may impact people (Section 9.6). Lastly, we discuss the potential implications of continued ocean deoxygenation and necessary considerations for appropriately addressing impacts in a social, economic, cultural, and political context (Section 9.7).

Table 9.1 Marine ecosystem services identified in a range of publications and organized by the Millennium Ecosystem Assessment categories (Agardy et al., 2011; Barbier, 2017; Barbier et al., 2011; Cooley, 2012; MEA, 2005a; Orth et al., 2006; Palumbi et al., 2009). Cooley (2012) identified services thought to be susceptible to ocean deoxygenation (✓), susceptible to combined biogeochemical impacts of ocean deoxygenation, pollution, and ocean acidification (✓*), and tolerant of ocean deoxygenation (-). Some services identified in other publications were not included (NI) in Cooley's (2012) assessment.

Regulating		Cultural	
Pollution & waste control	✓	Ceremonial & spiritual use	✓*
Flood & storm protection	✓	Aesthetic	✓*
Regulation		Science & education	✓*
• Air quality	-	Tourism & recreation	✓*
• Climate	-	Therapeutic use	NI
• Hydrologic cycle	-	Traditional use	NI
Human disease control	-	Bequest to future generations	NI
Erosion control	-		
Provisioning		**Supporting**	
Food		Biodiversity	✓*
• Fish	✓*	Nutrient cycling & fertility	✓*
• Invertebrates	✓*	*Biological regulation*	
• Plants	-	• Predator-prey relationships	✓*
• Mammals, birds	✓	• Keystone predators	✓*
Medicine & genetic resources	✓	*Habitat provision*	
Ornamental resources	✓*	• Nursery	✓
• Coral	✓*	• Breeding	✓
• Aquarium fish	NI	• Feeding	NI
• Shells	NI	Primary production	-
Building materials		Sediment formation & retention	?
• Fibre	?		
• Wood	✓		
• Lime, coral	-		
Fuel & energy			
• Timber	✓		
• Oil and gas	-		
• Wind, wave, thermal, tidal	NI		
Transport, trade & tourism	-		

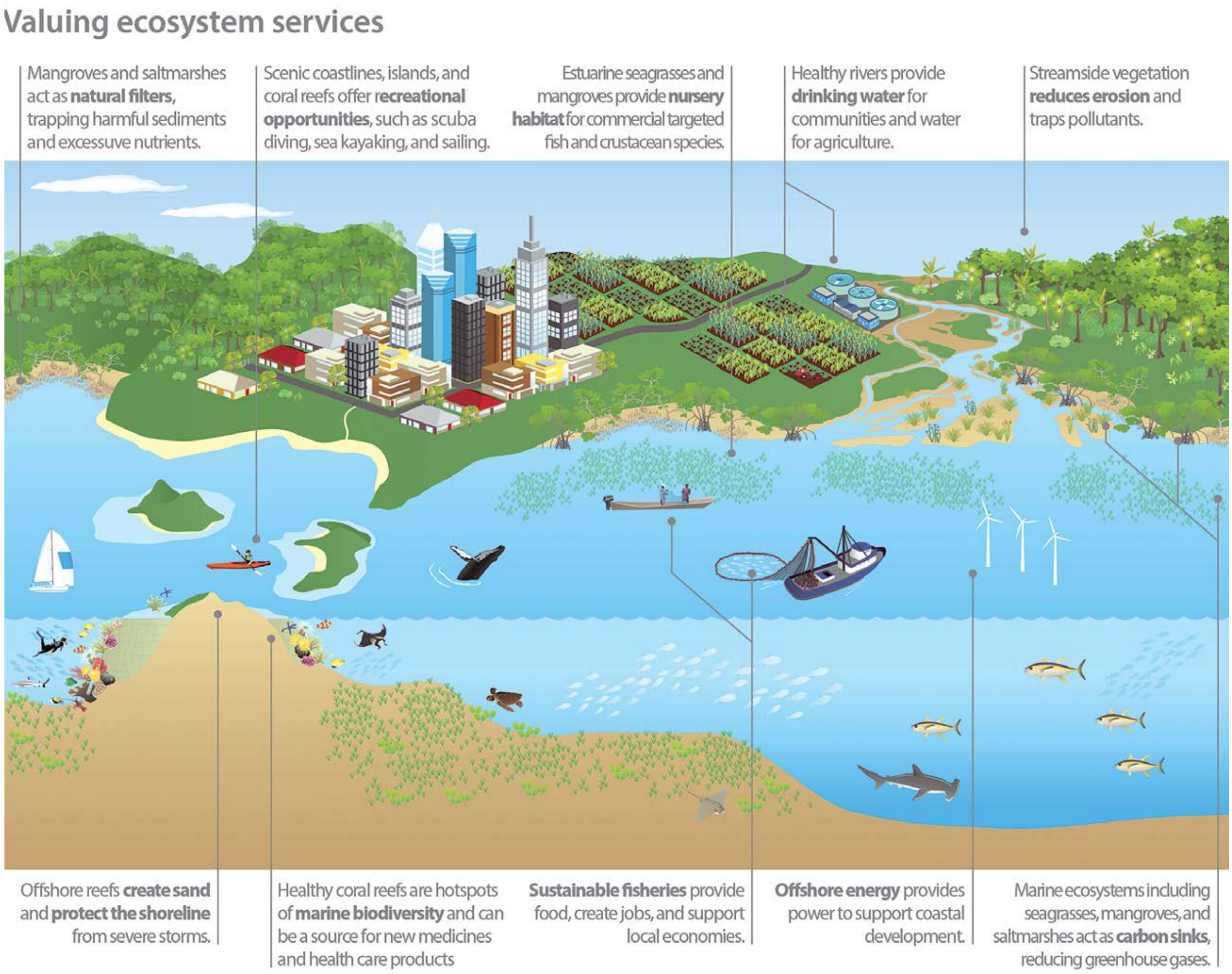

Figure 9.1 Ocean ecosystem services. Rreproduced with permission from Agardy et al. (2011). Illustrator Tracey Saxby, Integration & Application Network, University of Maryland Center for Environmental Science.

9.2 Marine ecosystem services

Ecosystem services are the benefits humans derive from the use of an ecosystem (MEA, 2003). Benefits conferred from ecosystem services reach beyond monetary gains and include all services provided by the natural system that may not be easily seen or quantified yet are critically important to the continued existence of people and societies. Ecosystem services (Figure 9.1, Table 9.1) are typically grouped into four broad categories, defined by the Millennium Ecosystem Assessment (MEA, 2003):

i) *Provisioning services*, include material benefits derived from the use of an ecosystem's resources, for example, provisioning of food through fishing, gathering, and farming, production of energy via tidal energy technologies and offshore drilling, or generation of income through livelihood activities like transport, trade, and tourism.

ii) *Cultural services* are "non-material benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences." These services include the cultural, therapeutic, historical, or religious values people derive from the ecosystem and contribute to their sense of place, quality of life and overall mental, emotional and spiritual health.

iii) *Regulating services* are those that play a role in regulation of large-scale biophysical processes such as climate and air quality. In the ocean, they include pollution and waste control, storm and flood protection, regulation of air quality, climate, and hydrologic cycling, human disease control, and erosion control.

iv) *Supporting services* are those that enable ecosystem function and continued contribution

Table 9.2 Summary of the relative magnitude of ecosystem services provided by different coastal system subtypes. Double asterisks (**) denote ecosystem subtypes that are negatively affected by all three biogeochemical stressors addressed by Cooley (2012): ocean deoxygenation, ocean acidification, and pollution. Adapted from MEA (2005a), Table 19.2.

Direct and Indirect Services	** Estuaries and Marshes	Mangroves	Lagoons and Salt Ponds	Intertidal	Kelp	Rock and Shell Reefs	Seagrass	**Coral Reefs
Food	●	●	•	●	•	●	•	●
Fibre, timber, fuel	●	⬤	●					
Medicines, other	•	•	•		●			•
Biodiversity	●	●	●	⬤	●	⬤	●	⬤
Biological regulation	●	⬤	●	•		•		●
Freshwater storage and retention	•		•					
Biochemical	•	•			•			•
Nutrient cycling and fertility	●	●	●	•	•	•		●
Hydrological	•		•					
Atmospheric and climate regulation	●	●	●	•		•	•	●
Human disease control	●	●	●	●		•	•	•
Waste processing	⬤	⬤	●			•	●	•
Flood/storm protection	●	●	•	•	•	●	●	⬤
Erosion control	●	⬤	•				•	•
Cultural and amenity	⬤	•	●	⬤	•	●	●	⬤
Recreational	⬤	•	•	⬤	•			⬤
Aesthetics	●	•	●	●				⬤

of other categories of ecosystem services. In the ocean, they include nutrient cycling and fertility, biological relationship regulation, habitat provision, primary production, biodiversity, and sediment formation and retention.

Ecosystem service assessments frequently express the value of ecosystem services in monetary terms; however, such quantifications should be considered proxies to reflect potential contributions to human well-being, which is ultimately the measure of benefit from ecosystems that most reflects human-centred perspectives on the multiple 'contributions of nature to people' (Díaz et al., 2018). Such quantifications are also inherently imperfect as they cannot incorporate and value in monetary terms every benefit an ecosystem provides. For example, the ocean is estimated to provide US$2.5 trillion annually in benefits to people as a "gross marine product" and have an "asset" base of US$24 trillion (Hoegh-Guldberg et al., 2015). The magnitude of these estimates convey the importance of the ocean to people and still, they are considered to be conservative, as they do not include benefits produced *from*, but not *by* the ocean, such as offshore oil and gas or wind energy, or "intangible" benefits, such as climate regulation, oxygen production, or any cultural services (Hoegh-Guldberg et al., 2015). Non-use and existence values as well as cultural services are challenging to evaluate quantitatively (Cooley, 2012) and, as a result, are generally less-represented in ecosystem service assessments (MEA, 2005a).

All marine ecosystem subtypes provide services, though of varying type and magnitude (Table 9.2). Mangroves, coral reefs, and estuaries and marshes provide the largest relative magnitude of ecosystem services per unit area, followed by lagoons and salt ponds, intertidal zones, rock and shell reefs, seagrass, and kelp (Table 9.2) (MEA, 2005a).

9.3 Implications for human well-being

9.3.1 Deriving human well-being from ocean ecosystem services

Well-being is the ultimate value people derive from ecosystem services and consists of five primary qualities: (1) basic material for a good life, (2) health (mental and physical), (3) good social relations, (4) security, and (5) freedom of choice and action (MEA, 2005b). These components of well-being relate to personal and social functioning, and express what a person values doing or being (Sen, 1999). Importantly, definitions of well-being and its constituent parts are known to vary across communities and cultures (Harthorn & Oaks, 2003; Lupton, 1999; Nelkin, 2003). In particular, health is conventionally considered a physical quality, while many cultures, including many indigenous groups, consider psychological, social and cultural aspects of health as inherently inter-connected with physical health (Arquette et al., 2002; Garrett, 1999; Harris & Harper, 1997; Wolfley, 1998).

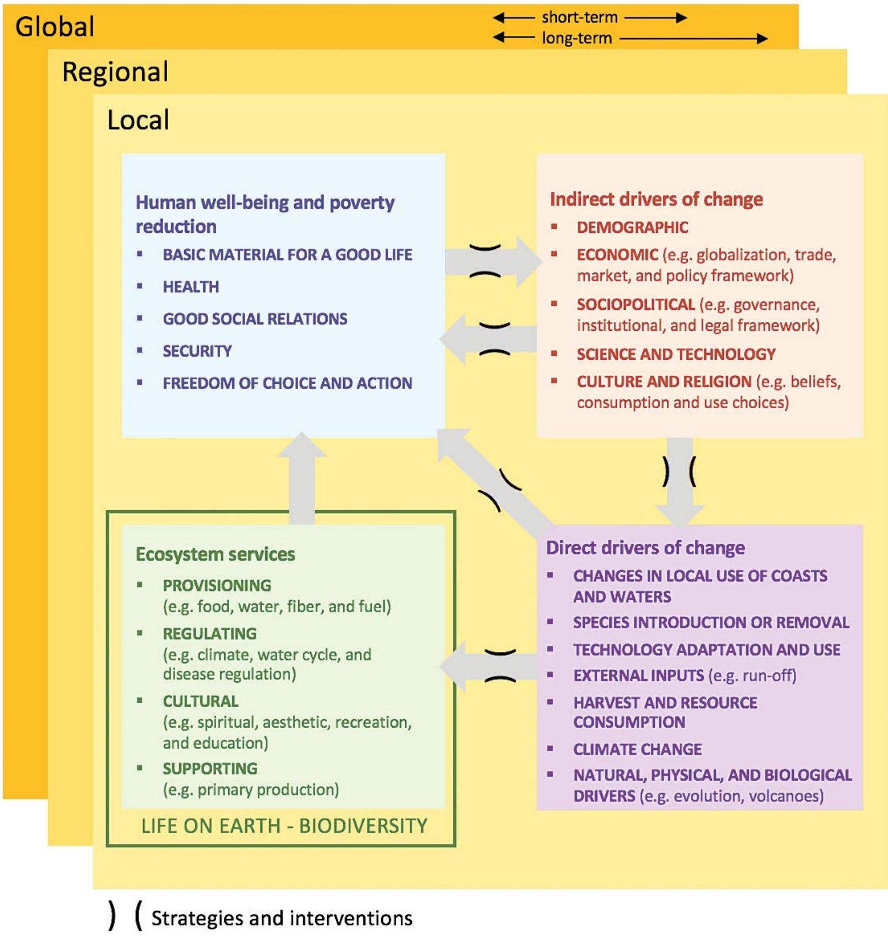

Figure 9.2 The 'macro' Millennium Ecosystem Assessment framework. Adapted from MEA (2005).

For well-being to be achieved a society requires sufficient social, human, natural and manufactured (or economic) capital (MEA, 2003), all of which is derived from or reliant on services provided by the natural world. In contrast, poverty is defined as the "pronounced deprivation of well-being" (MEA, 2003) and occurs when ecosystem services are unavailable or inaccessible. While ecosystem services are essential for deriving well-being, they do not guarantee well-being. Rather, social factors (i.e. societal characteristics, institutions, instruments, organizations, technology, practices and socio-cultural norms) determine whether the well-being potential of ecosystem services is realized and by whom (Fisher et al., 2013); in other words, the process is 'socially mediated'. Critical social factors, that either enable or inhibit one's ability to obtain well-being from ecosystem services, are identified as 'Indirect drivers of change' in the Millennium Ecosystem Assessment's 'macro' framework (Figure 9.2).

Social differentiation is a strong determinant of a group's ability to experience well-being benefits from ecosystem services as access to services is largely dependent on social status and power (Leach et al., 1999). Controlled through endowments (i.e. ownership of assets) and entitlements (i.e. access to the resources or their services), increased availability of ecosystem services will not increase the well-being of those already living in poverty (i.e. without access to sufficient resources), unless their capacity to access the new services is also increased. Thus, ecosystem services are considered beneficial for poverty prevention, but not poverty reduction (Fisher et al., 2013). Groups with less power and capital also tend to be more directly dependent on ecosystem services than groups with the capacity to purchase traded or manufactured goods, or with the capital assets to avoid the consequences of any decreased functioning of regulating and supporting services (Adger & Kelly, 1999; Leach et al., 1999; Sen, 1981).

Numerous mechanisms translate ecosystem services into human well-being, with the most easily (and commonly) quantified being the contribution of

CHAPTER 9

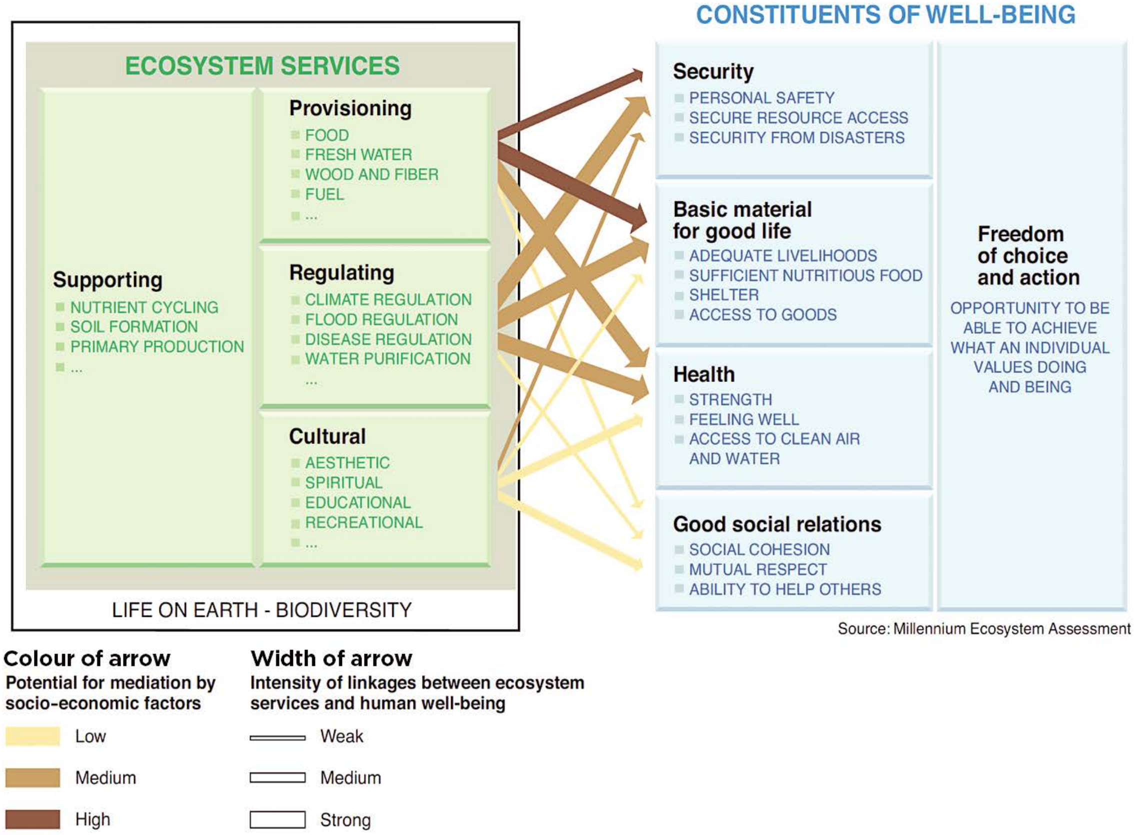

Figure 9.3 The 'micro' Millennium Ecosystem Assessment framework (MEA, 2005).

provisioning services (such as fisheries) to material wellbeing (in the form of income, assets or wealth). Social factors that mediate the relationship between ecosystem services and human wellbeing are also better developed for provisioning services (MEA, 2005a, b). Fisher et al. (2013) note that regulating and supporting services such as the role of coastal and shelf sea and oceanic ecosystems in nutrient cycles, the carbon cycle and oxygen production, derive from ecosystem components and processes that cannot be easily owned or readily controlled and that people cannot be excluded from using, such as the climate system and oceanic circulation. The contribution of these services is driven by complex biogeochemical cycles and large-scale (planetary to mesoscale) forces and their accessibility is not dependent on entitlements. Therefore, the services and their drivers of change can only be effectively governed by high-level actors at a global or transnational scale, through institutions such as the UN Convention on the Law of the Sea, the Paris Agreement of the UN Framework Convention on Climate Change, and the Montreal Protocol on Substances that Deplete the Ozone Layer, and so on. Conversely, in the case of provisioning and cultural services, access can be regulated and denied at national and sub-national scales, through a variety of socio-political controls. The magnitude and strength of social mediation linkages between ecosystem services categories and components of well-being are represented in the Millennium Ecosystem Assessment's 'micro' framework (Figure 9.3).

9.3.2 Human risk from loss / reduction of ecosystem services

Social factors also play a role in how people experience impacts from natural hazards, such as an absence or reduction of ecosystem services. As illustrated by the Pressure and Release (PAR) model, risk is calculated based on the intensity and frequency of natural hazards and a groups' level of vulnerability to the hazards (Figure 9.4) (Blaikie et al., 1994). Thus, the risk social groups (households, communities, fishing fleets, nations, etc.) are exposed to due to ocean deoxygenation will depend on the degree of hazard experienced (exposure), the degree to which that social group depends upon or benefits from the affected ecosystem services (sensitivity), and their capacity to adapt to the reduction or loss of services (adaptive capacity; Adger, 2006). Vulnerability is a structural and durable social condition established through a 'progression of vulnerability' driven by failures in social systems that

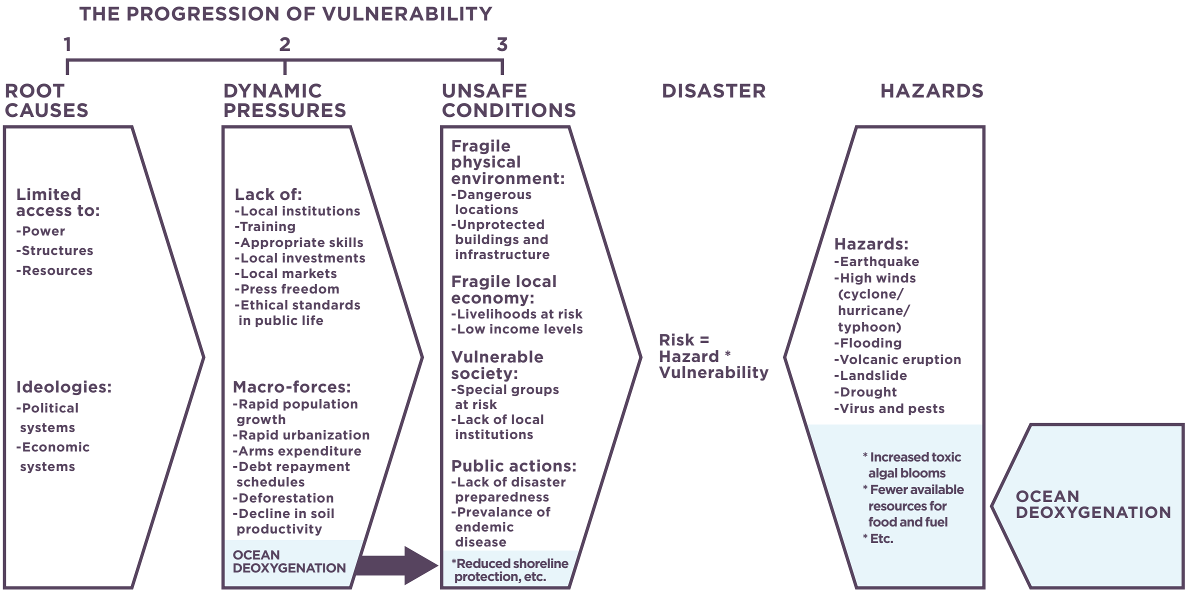

Figure 9.4 Pressure and Release (PAR) model modified to include examples of hazards posed by ocean deoxygenation (shaded in blue). Adapted from Wisner et al. (2004).

ultimately result in 'unsafe conditions' leaving people susceptible to natural hazards (Figure 9.4) (Blaikie et al., 1994). This susceptibility is what connects hazardous events to differential levels of risk with impacts that can be disastrous.

Ocean deoxygenation does not itself constitute a hazard, in that reduced ocean oxygen levels do not pose a direct threat to humans, but it contributes to the evolution of risk in two ways (Figure 9.4). First, ocean deoxygenation can drive development of slow-onset hazards via reduction in supporting and provisioning services, such as loss of an important fish stock due to degradation of critical habitat; and second, ocean deoxygenation can contribute to increased human vulnerability to hazards via reduction in regulating ecosystem or cultural services, such as reduced protection from storms due to degraded reefs resulting from coral mortality under low oxygen conditions or reduced adaptive capacity due to loss of community connection to an impacted ecosystem. Thus, as an anthropogenically-catalysed aspect of global environmental change, ocean deoxygenation contributes to human risk by both increasing incidence and magnitude of some hazards and increasing vulnerability of some groups of people.

9.3.3 Responding to changes

People respond to natural hazards through the different, but related, actions of adaptation and mitigation. Adaptation reflects an adjustment of natural or social systems which moderates harm or exploits opportunities for benefit, while mitigation is a social intervention to lessen the hazard level (Klein et al., 2007). In the context of climate change (one anthropogenic driver of ocean deoxygenation), the word 'mitigation' is narrowly defined as actions to reduce greenhouse gas emissions or to increase carbon capture and storage (IPCC, 2001). In that case, the 'hazard level' is reduced by a reduction in the concentration of greenhouse gases in the atmosphere. In the context of deoxygenation, mitigation may include measures to reduce eutrophication, which can lead to deoxygenation through the bacterial decomposition of ungrazed phytoplankton blooms that result from excess nutrients in the water.

Actions in either category (adaptation or mitigation) can have consequences for the other: social decisions can lead to synergies or trade-offs between the two activities, and resulting impacts on biophysical processes can, in turn, have consequences for one or both (Klein et al., 2007). A group's ability to respond to hazards is limited by their capacity to carry out adaptation and mitigation actions, as these actions have associated costs. Thus, the extent to which societies and their social institutions are capable of taking risk-reducing actions will be determined by the amount of human, natural and manufactured capital they are able to access and mobilize. Similarly, communities that gain ecosystem services not previously available, like a fish species newly inhabiting adjacent waters, may or may not have the adaptive capacity to take advantage of these newly available ecosystem services.

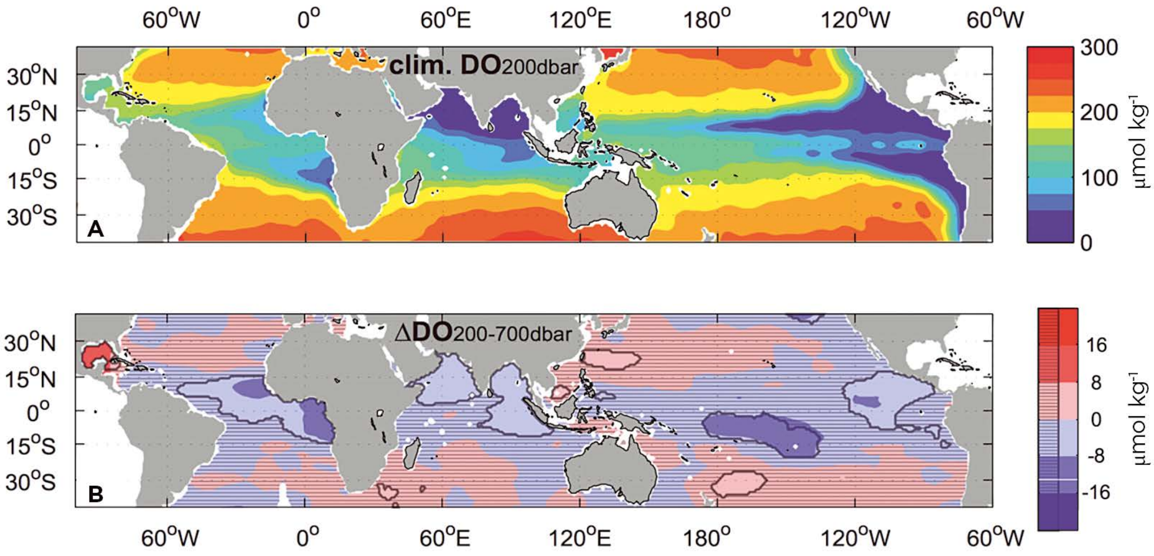

Figure 9.5 (A) Dissolved oxygen levels at 200 dbar at the climatological mean and (B) change in dissolved oxygen levels between 1960-1974 and 1990-2008 (<95% confidence interval in stripes, ≥95% confidence interval without stripes) as averaged from 200 - 700 dbar Adapted from Stramma et al. (2010).

As an example of the role of adaptive capacity, Sumaila et al. (2011) highlight potential monetary costs of climate change adaptation in wild capture and recreational fisheries. As fish distributions change (e.g. populations migrate away from oxygen depleted waters towards more suitable habitat), the functionality of traditional or established fishing grounds are disrupted. Fishers may adapt by travelling further to catch the same amount or even fewer fish, but in the process, accrue greater costs associated with running their boat, and yield smaller profits than under traditional scenarios. If instead, fishers don't have access to vessels capable of travelling further, they may not be able to access the same amount of the resource they could previously. This group has less adaptive capacity and will experience reduced well-being due to loss of income, sustenance, or both. Still instead, a group may choose to take insufficiently sea-worthy vessels out to sea to access the resources and, as a result, experience bodily harm or loss of life (e.g. Blythe et al., 2013), thus seeing a reduction of well-being via direct health costs.

9.4 Trends and variability

Effects of ocean deoxygenation on people, economies, and social systems will vary over time and across geographic regions, social groups, and economic sectors due to differences in levels of hazard and vulnerability. However, several trends and sources of variability can be expected based on current knowledge of the processes linking ocean deoxygenation to human well-being.

9.4.1 Magnitude and geographic variation of ocean deoxygenation

Current dissolved oxygen levels vary widely across the world's ocean (from zero to 300 µmol kg^{-1}) (Figure 9.5A) (Stramma et al., 2010) and current and predicted rates of oxygen loss range from a decrease of approximately 24 µmol kg^{-1} to an increase of the same magnitude in select geographic regions (Figure 9.5B) (Stramma et al., 2010). Relatively warm equatorial ocean waters and eastern ocean coastal margins with productive upwelling systems are less oxygen rich relative to higher latitude and western ocean basins, and this difference in dissolved oxygen levels is expected to widen in coming decades (Figure 9.5B) (Diaz & Rosenberg, 2008; Middelburg & Levin, 2009; Stramma et al., 2010). Coastal waters see increased incidence of hypoxia due to eutrophication caused by atmospheric deposition as well as run-off from dense urban population centres and agriculture (Figure 9.6) (Breitburg et al., 2018).

On a broad scale, this geographic and biophysical profile of ecosystem effects will result in strong latitudinal variation in ecosystem service impacts. People inhabiting coasts adjacent to waters more affected by ocean deoxygenation will generally experience more exposure to resulting hazards, and thus will be more vulnerable than those who are less exposed. However, due to teleconnections between dissolved oxygen levels and climate regulation as well as distribution patterns of goods, others who are not as proximate to hypoxic waters will also likely experience effects

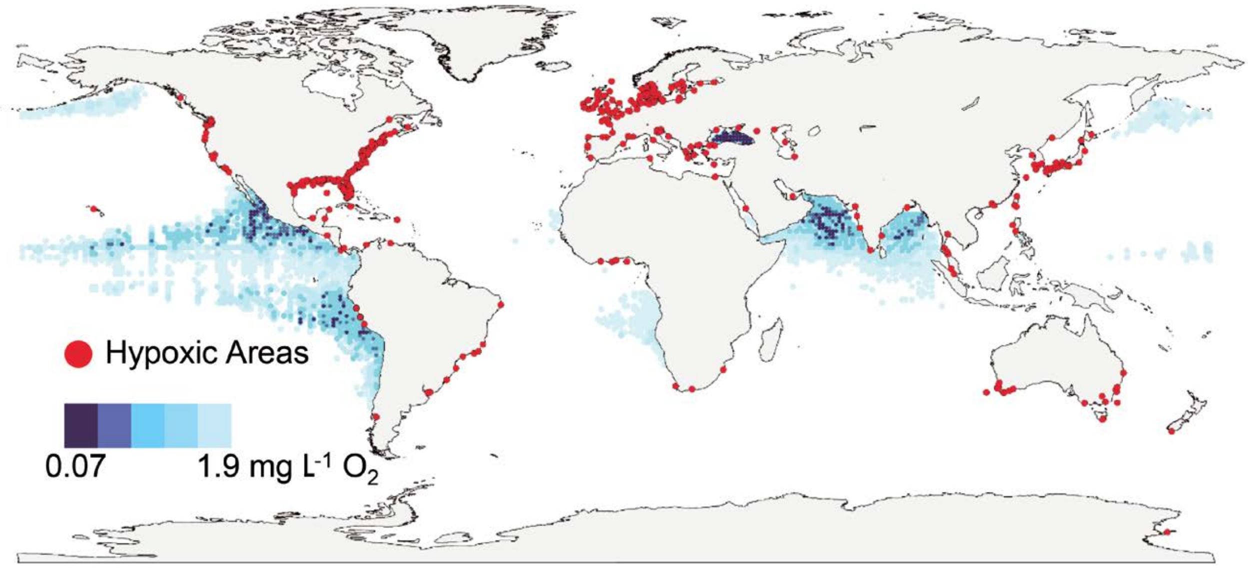

Figure 9.6 Ocean oxygen-minimum zones at 300m depth (blue shaded regions) and coastal hypoxic areas of <2 mg O L^{-1} caused or exacerbated by anthropogenic nutrients (red dots). Figure reproduced with permission from Breitburg et al. (2018) and unpublished data from R. Diaz.

to some degree (Adger et al., 2009; Breitburg et al., 2018). Combined and interacting biogeochemical and ecological processes can result in complex and wide-reaching ripple effects initiated by relatively small areas of hypoxia. Local changes to nutrient-cycling within oxygen minimum zones can be communicated to the wider ocean via circulation (Breitburg et al., 2018) and populations and economic activities far removed from the sea can be impacted by oceanic influences on the global climate system (Allison & Bassett, 2015). These teleconnections link global environmental change, the ocean, and societies (Adger et al., 2009) creating indirect and interacting impact pathways and complicating our ability to isolate impacts of change to one dimension of the larger system.

9.4.2 Temporal and spatial variations

Low oxygen zones can vary in degree of persistence or transience, both spatially and temporally (Breitburg et al., 2018), complicating estimation of impacts over space and time. Several case studies presented here show that ocean deoxygenation can have negligible or even positive effects on ecosystem services in the short-term (e.g. Chesapeake Bay striped bass and Humboldt squid and quahog, respectively), but less favourable or unknown outcomes in the future. There remains a high degree of uncertainty around effects of sustained hypoxia on both the natural and social world (Rabotyagov et al., 2014), making long-term predictions highly challenging. However, researchers highlight that the general trend is toward habitat degradation and myriad negative impacts of altered ecological systems (e.g. Altieri & Witman, 2006; Breitburg et al., 2018). For example, coral reef researchers have suggested that the long-term effects of hypoxia may be "different from, and more substantial than, those of other disturbances" on reefs because reduced oxygen affects taxa throughout the food web including pathogens, habitat formers, and consumers (Altieri et al., 2017). The rate at which changes occur may also affect the ability of species and human communities or sectors to adapt.

9.4.3 Demographics and social change

Different social groups vary in their vulnerability to hazards in many ways, some of which are predictable. Women and children are generally more vulnerable to losses of ecosystem services due to greater nutrition needs and patterns of impacts of reduced resources reflecting societal norms discriminating against women and children (Otto et al., 2017). Mothers, for example, will forego their own nutrition to provide for their children and instances of 'famine marriages,' where "adolescent girls are married off to reduce the number of mouths to feed and/or to generate resources such as cash or cattle" have been documented in Sub-Saharan Africa (Brown, 2012; Marcus & Harper, 2014; Otto et al., 2017).

Groups that are highly reliant on ocean ecosystem services (Figure 9.7) and more exposed to ocean deoxygenation (Figures 9.5 & 9.6) are specifically more vulnerable to reduced DO levels (Dyson & Huppert, 2010). People in lower latitudes are generally more reliant

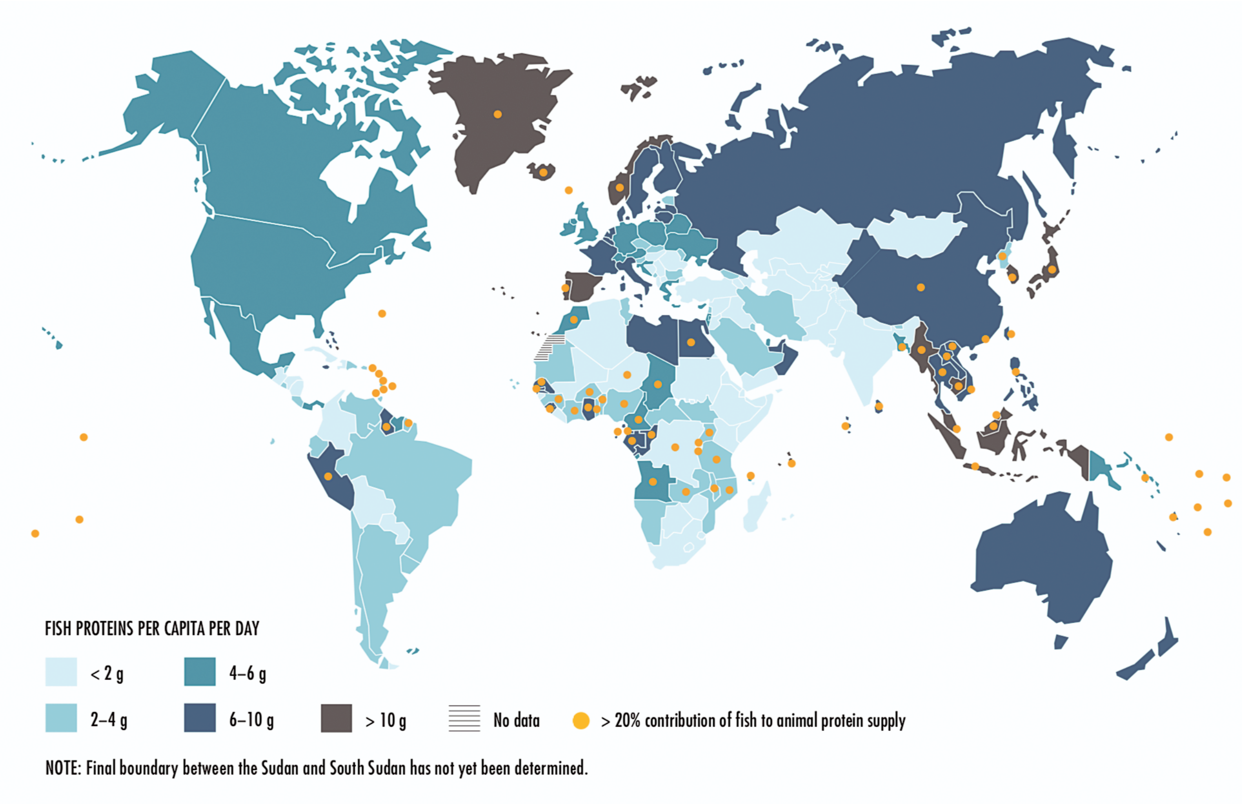

Figure 9.7 Contribution of fish (including wild-caught and farmed fish from marine and freshwater systems) to animal protein supply by country, averaged over 2013-2015 (FAO, 2018).

on access to marine resources for food and livelihoods and experience higher rates of poverty (Figures 9.7 & 9.8). Thus, those in low latitude, low-income developing countries (LIDCs) and in rural coastal areas with less access to credit or wider markets face greater risk from ocean deoxygenation. These groups are more sensitive to loss of marine resources, are more exposed to ocean deoxygenation, and have relatively less adaptive capacity due to systemic and asset-based constraints. Certain regions, such as West Africa, currently experience some of the highest levels of poverty (Figure 9.8), are exposed to low levels of dissolved oxygen (Figures 9.5 & 9.6) and are highly reliant on fish for food (Figure 9.7). Reduced oxygen levels off West Africa are also thought to be lower than current data suggests due to under-sampling (pers. comm. Denise Breitburg). See Chapter 10 for a discussion of the effects of low DO on West African fisheries.

Overall reductions in availability of food resources will lead to increased food prices, which may counteract rent costs of adaptation to change for producers (Sumaila et al., 2011), but persistently high food prices may also result in a global increase in social disruptions (Lagi et al., 2011). The outbreak of violence in Egypt in 2011 is partially attributed by several studies to a food crisis induced by extreme climatic conditions in other regions (Lagi et al., 2011; Sternberg, 2011). Poor households in developing countries typically spend 70-80% of their income on food (as opposed to 10-15% in wealthier country households), so increased prices could have direct effects on health and well-being (Otto et al., 2017). Low income groups in urban areas are recognized as the most vulnerable to the effects of increased food prices, with urban poverty rates in some African cities expected to increase by up to 30% due to climate-related increase in food prices (Otto et al., 2017).

Socio-cultural shifts will affect anthropogenic drivers of ocean deoxygenation and the impact of the stressor on people in an ongoing and dynamic way. Factors such as human population growth, resource use and consumption rates, effects of climate change on the geography of population centres, sanitation and farming practices, and effects of education and income on social processes will influence nutrient discharges and greenhouse gas emissions (Breitburg et al., 2018). Understanding broader social patterns and incorporating them into future models will be essential (Breitburg et al., 2018).

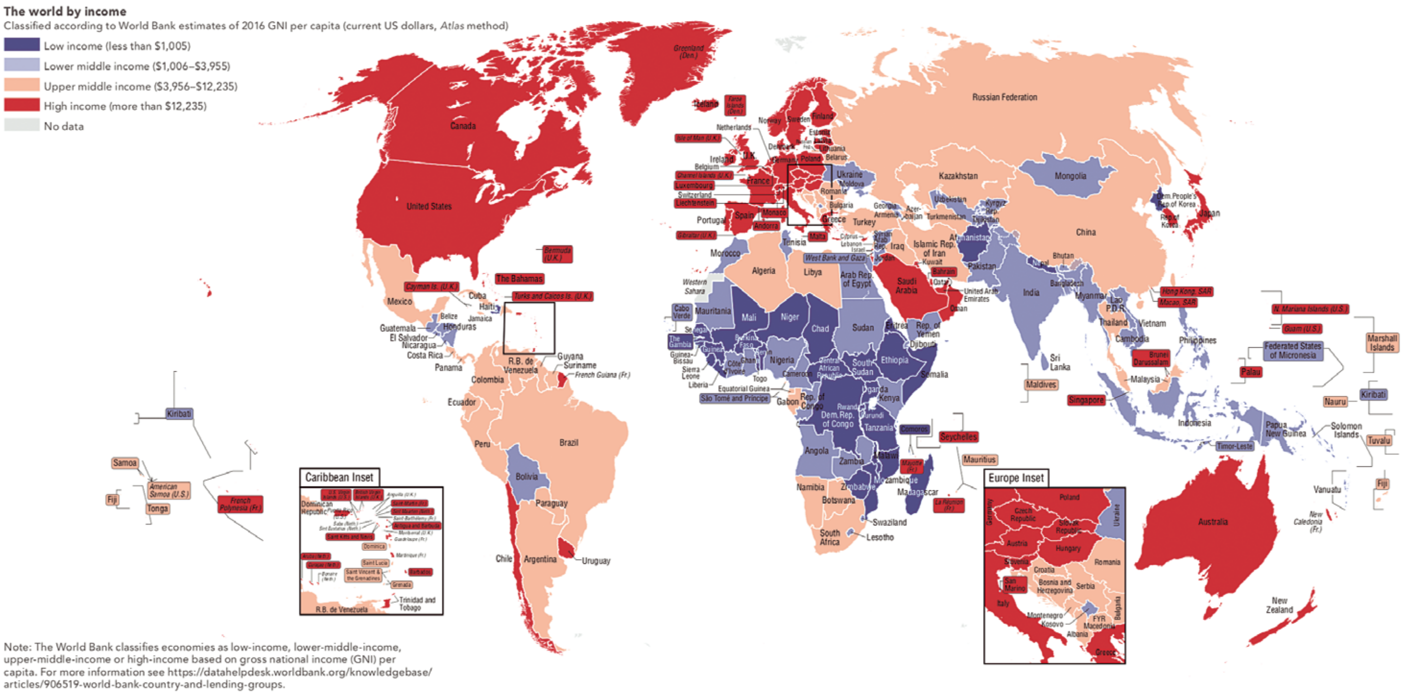

Figure 9.8 Income level by country as an indicator of well-being, vulnerability and adaptive capacity (World Bank, 2017). The World Bank classifies economies into four income groups (low, lower-middle, upper-middle, and high income) using gross national income (GNI) per capita data in U.S. dollars, converted from local currency using the World Bank Atlas method, which is applied to smooth exchange rate fluctuations.

9.4.4 Sensitivity of marine ecosystem subtypes and organisms

Studies have shown non-linear responses to ocean deoxygenation across both marine ecosystem subtypes and species groups. Fish and crustaceans are less tolerant of reduced oxygen levels compared to gastropods and bivalves (Vaquer-Sunyer & Duarte, 2008), so resource use sectors and communities reliant on fish and crustaceans can be expected to see greater impacts on spatial distribution, productivity, and size of stocks (Díaz & Rosenberg, 2011; Stewart et al., 2014). Social groups reliant on gastropods and bivalves may expect to see a range of effects, in the near-term, depending on factors such as the impacts of the suppression of predators on mollusc populations at lower oxygen levels and the physiological optima for different species of molluscs. Examples of improved competitiveness of cephalopods and bivalves can be seen in the Narraganset Bay quahog and Humboldt squid case studies (Sub-sections 9.5.5 & 9.5.6). The effects of low DO on individual organisms are well documented (e.g. Vaquer-Sunyer & Duarte, 2008), so more specific effects are available for researchers or managers addressing particular species of interest.

Similarly, marine ecosystem subtypes are differentially susceptible to negative effects of ocean deoxygenation. Cooley (2012) noted that coral reefs and wetlands and marshes provide a relatively larger magnitude of ecosystem benefits (in number of service types and relative quantity of each) than other ecosystem subtypes and are also more negatively affected by ocean deoxygenation. Some species of coral have been shown to be more tolerant of reduced oxygen than others, however (Altieri et al., 2017). Mangrove-supported systems provide substantial ecosystem services and the trees are relatively tolerant of ocean deoxygenation (Table 9.2) (Cooley, 2012) while associated organisms may show relatively less tolerance (e.g. Gedan et al., 2017). Kelp forests, seagrass beds, rock and shell reefs, intertidal zones, and lagoons and salt ponds provide a relatively smaller magnitude of ecosystem services (Table 9.2) and are less sensitive to negative impacts of ocean deoxygenation (Cooley, 2012). Despite these observed patterns, particular systems will vary in their susceptibility to reduced oxygen based on a variety of biophysical factors (Breitburg et al., 2018).

9.4.5 Multiple and interacting stressors

Deoxygenation is mechanistically linked to other ocean stressors, such as warming, acidification, and pollution, which means ecosystems can experience combined or synergistic effects of multiple stressors (Breitburg et al., 2018, 2019 (Chapter 6 this report) Cooley, 2012; Gruber, 2011). The mechanisms of interactions are complex and not entirely understood (Gruber, 2011; Rabotyagov et al., 2014), complicating the task of identifying effects of one or a set of stressors on people. Some general patterns are known, however. Warmer water has reduced capacity to hold dissolved oxygen, so people in areas experiencing warming will also be subject to the effects of deoxygenation. Acidification sometimes exacerbates the effects of low oxygen, but the extent and magnitude of such interactions is not currently estimable (Gobler & Baumann, 2016).

Certain species and ecosystem subtypes have been shown to be more or less affected by synergistic or combined stressors. Several studies suggest that the effects on fish populations of deoxygenation alone can be small to moderate, but when combined with other stressors the combined effect can be large (Chapter 10). For example, Miller et al. (2016) found that acidification increases the sensitivity of two important forage fishes of the genus *Menidia* to hypoxia. Forage fish are important sources of nutrients for people, play important roles in pelagic food web function, and contribute substantially to aquaculture feed and fish meal (Pikitch et al., 2012; Tacon & Metian, 2009). Research on forage fish impacts is nascent, but the potential for human impact is substantial. Wetlands and marshes and coral reefs again provide a relatively large magnitude of ecosystem services (Cooley, 2012) yet are susceptible to interacting negative effects of pollution, ocean acidification, and ocean deoxygenation (Cai et al., 2011; Feely et al., 2010; Howarth et al., 2011) and respond poorly to all three stressors respectively (Riegl et al., 2009).

Similarly, low DO can interact with biological and anthropogenic stressors, by making stocks more susceptible to predation or capture by fisheries via habitat compression or shoaling. For example, Froehlich et al. (2017) showed increased sensitivity of the Hood Canal Dungeness crab fishery to overfishing when including deoxygenation and other stressors (see 10.6.3). Improved catchability may manifest as increased availability of certain ecosystem services in the near-term, but over the long-term may complicate management and threaten resource-use sustainability.

9.4.6 Ecosystem service categories

Most marine ecosystem services are likely to be negatively affected by reduced dissolved oxygen, although to varying degrees (Table 9.1). Services reliant on living resources are expected to be most negatively impacted and these services generally fall under the categories of provisioning, supporting, and cultural services. Regulating services (air quality, climate, hydrological cycle), transport, fuel and energy, primary production, and food from plants are services thought to be relatively tolerant to ocean deoxygenation (Table 9.1) (Cooley, 2012).

Translation of ecosystem services to human well-being is also likely to vary by category, as the categories are differentially susceptible to social mediation (Figure 9.3). In general, access to certain places is necessary for people to obtain benefits from cultural, provisioning, and, to a lesser degree, supporting services. The potential for access to be mediated by policies and norms, makes benefiting from these service categories more dependent on social factors. On the other hand, controlling access to regulating services is less feasible, so these services are less susceptible to social mediation. Notably, regulating services are the least affected by ocean deoxygenation and access to them is the least dependent on social mediation (Fisher et al., 2013), thus risk due to loss of regulating services is likely to be relatively low generally and more equal across different groups. However, due to existing social factors, some groups may be more exposed or sensitive to changes in regulating services and groups will have more or less capacity to adapt to changes, so a group's vulnerability still plays a role in their level of risk. As a result of these patterns of differential susceptibility and social mediation, ecosystem services that stand to be most affected by ocean deoxygenation are also those that can more readily be taken advantage of by those in power and withheld from those not in power.

9.4.7 Ecological interactions

While ecosystem degradation is commonly understood to lead to reduced biological productivity, ecosystem service provision, and economic output (Altieri, 2008), ecological community dynamics can lead to increased productivity for some species via altered predator-prey or competitive relationships. One mechanism by which a species can benefit from reduced oxygen conditions is via release from predation. As with natural stress gradients, anthropogenically-induced stressors can create uninhabitable areas for some species, thereby releasing their prey from predation pressure (Altieri, 2008). For the organisms released from predation to experience net benefits, however, they must be tolerant of said stressors themselves (Altieri, 2008). The case of the quahog *(Mercenaria mercenaria*) in Narraganset Bay, Rhode Island and Humboldt squid in the eastern Pacific Ocean provide examples of fisheries which may be benefiting from hypoxia.

Despite these examples of benefits from ocean deoxygenation, altered ecological interactions may instead cause a reduction in prey, increased predation, or otherwise altered dynamics that reduce survivorship of certain species. The complexity of impacts on dynamic food web interactions presents a challenge for predicting effects on people. Less beneficial outcomes from the same hypoxia-induced food web alterations described as 'positive' examples are described in Section 9.5 as well: namely, hake in the eastern Pacific Ocean (increased predation by Humboldt squid), and softshell clams and blue mussels in Narraganset Bay (decreased competitive ability). Similarly, Altieri (2008) cautions that a focus on positive outcomes from hypoxia could distract from the reality of continued environmental degradation.

9.4.8 Multiple scales and feedbacks

In many cases, the process of continued ocean deoxygenation may be subject to both social and ecological positive feedbacks at a variety of geopolitical scales, further complicating predictions of human impacts, but also providing important insights into the dynamics of anticipated changes. For example, urbanization may both lead to and be driven by reduced dissolved oxygen levels. Rapid growth of urban centres is associated with environmental degradation, including eutrophication-driven ocean deoxygenation (Moore et al., 2003) and the availability of more resources and job opportunities in cities is a major part of the draw to urban areas (Jiang & O'Neill, 2017). Urbanization is projected to continue under all societal development scenarios analysed (Jiang & O'Neill, 2017) and a reduction of available ocean ecosystem services in rural coastal areas could contribute to the continued trend of cityward movement and further ocean deoxygenation in those areas. Similarly, in semi-enclosed systems, such as the Baltic Sea, enhanced nitrogen fixation in response to deoxygenation has led to undesirable cyanobacteria blooms which then contribute to continued deoxygenation (Conley et al., 2009). These blooms can also be toxic and directly negatively affect people and ecosystems.

Long-term effects at spatial scales of ecosystem service use and stewardship will depend on a wide variety of biophysical and social factors, including and beyond the trends discussed here: extent and synergy of multiple stressors, multi-directional ecological interactions and cascading effects within food webs, multi-directional impact pathways between natural and social systems, vulnerability of communities and groups, trends in root causes and dynamic pressures on vulnerability, and socio-political and economic dynamics from local to global scales.

9.5 Case studies

Six case studies are presented in which the effects of ocean deoxygenation on ecosystem services have

Figure 9.9 (A) Blue crab, (B) striped bass, and (C) Atlantic summer flounder are important commercial fishery stocks in the Chesapeake Bay. © blue crab - wpopp [CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0/)]; striped bass - FishWatch (see Gallery) [Public domain]; Atlantic summer flounder - https://www.capecod.com/newscenter/new-stock-assessments-released-for-summer-flounder-atlantic-striped-bass/).

been assessed for particular systems. The impacts have been valued in monetary units in all but the last two cases, which attribute impacts to low DO, but do not quantify them. Most cases (four) focus on valuing the loss of provisioning services due to hypoxia, primarily related to fisheries, three consider mitigation options (Baltic Sea, North Carolina, and Gulf of Mexico wetlands), two account for adaptation strategies (Chesapeake Bay and North Carolina), and one considers human well-being impacts holistically (rather than valuing a particular ecosystem service) as well as existence values (Baltic Sea).

The cases presented here provide examples of the trends presented thus far, including: effects of differential sensitivity to ocean deoxygenation across species types (Humboldt squid and Pacific hake, and Narraganset Bay quahog), the importance of understanding adaptive capacity of affected human communities as well as temporal variation in outcomes (Chesapeake Bay striped bass and Narraganset Bay quahog), the importance of understanding social dynamics in determining not only the nature of the impacts, but who experiences them (Baltic Sea, North Carolina, and Gulf of Mexico wetlands), the complicating role of interacting stressors (Baltic Sea, Gulf of Mexico wetlands), and the high value of services provided by several marine ecosystems (Baltic Sea, Chesapeake Bay, Gulf of Mexico). Additional case studies that consider impacts of low DO on fisheries are described in Chapter 10.

9.5.1 Chesapeake Bay and nearby coastal bays

Studies from the Chesapeake Bay and other nearby bays on the U.S. east coast have examined potential monetary losses in commercial and recreational fisheries by using economic models to make simplified assumptions about biological responses to low dissolved oxygen. The Chesapeake Bay is a large coastal estuary on the east coast of the United States that experiences low DO levels year-round due to eutrophication (Higgins et al., 2011). Dissolved oxygen ranges between 0 and 12 mg L^{-1}, with substantial temporal and spatial variation (Breitburg, 1992) and fish stocks can be low (or absent) where DO is low. Affected species include the commercially important blue crab (*Callinectes sapidus*), striped bass (*Morone saxatilis*), and Atlantic summer flounder (*Paralichthys dentatus*) with potential for human welfare losses due to further water quality loss demonstrated in all cases (Figure 9.9) (Lipton & Hicks, 2003; Massey et al., 2006; Mistiaen et al., 2003).

Incorporating fishing effort and variable DO levels into two harvest production models, Mistiaen et al. (2003) assessed the potential effects of further reduced water quality on harvest efficiency of blue crabs in the Patuxent, Chester, and Choptank tributaries. Their simulations suggest that a decline in average mid-channel bottom dissolved oxygen in the Patuxent River to 4 mg L^{-1} would result in a 49% decline in harvest and revenue with the same amount of fishing effort. Based on the market price from 2000 of US$1.00 per pound they estimated reduced catch would result in US$228,000 of lost earnings (from a total fishery value of US$465, 306) if the crabbers fished in the same areas with the same effort. However, the authors noted that this would be the upper bound of losses under the assumption that fishermen would likely adjust their fishing behaviour in the case of such a decline in water quality. Furthermore, the authors suggested that the crabs that escaped harvest in the assessed fisheries could move to other harvest areas, effectively redistributing the resource to other crabbers, or could be considered part of the reproducing stock, thus the areas of reduced water quality may act as a refuge. Incorporating fisher behaviour and the ultimate outcome for escaped crabs (i.e. crab stock dynamics) into future models would improve understanding of long-term impacts of reduced oxygen levels.

Similarly, Lipton and Hicks (2003) estimated potential losses for the striped bass recreational fishery in the Patuxent River using Poisson catch rate and random utility models. They estimate that if waters are allowed to deteriorate so that they do not exceed 5 mg L^{-1}, the recreational fishery will see an annual loss of more than US$100,000 in net present value. If waters dip below and do not exceed 3 mg L^{-1}, annual losses would reach US$195,000, and anoxic conditions would result in annual losses around US$300,000. The latter outcome is considered unlikely, however, by current water quality models. These modest estimated total losses reflect that short-term welfare effects would be mitigated by the anglers' ability to adapt by focusing fishing effort on less-degraded areas nearby. Should water quality never exceed 3 mg L^{-1} bay-wide, however, annual losses would be substantially larger around US$145 million net present value. This outcome is not occurring now or projected to occur in the future, but highlights the importance of alternative healthy fishing grounds. The authors also noted that their study addresses a small piece of the puzzle as they analyse only one economically-important fishery in the area and they do not incorporate reproduction effects or the population's long-term health.

In contrast, Massey et al. (2006) considered both long-term effects on reduced survival and reproduction as well as short-term effects on species crowding and abundance to examine potential gains in the recreational Atlantic summer flounder fishery with increased DO levels. Linking a bioeconomic model to a recreation demand model, they estimated that a 25% increase in dissolved oxygen in all bays and estuaries throughout the range of the species would increase catch rates by 20% and result in total annual angler benefits of approximately US$630,000 within the study area and exceeding US$80 million across the range of the species (Massey et al., 2006).

The studies presented here use economic models to examine potential impacts of changes in DO levels on economic earnings of fishermen in a handful of fisheries. They do not comprehensively consider the range of ecosystem services provided by Chesapeake Bay, its tributaries, and nearby coastal waters, nor do they go the next step to consider impacts on human well-being. Non-use and existence values of the blue crab, striped bass, and Atlantic flounder stocks and fisheries have not been incorporated in the analysis, nor has the affected community's vulnerability or resulting level of risk been considered, with exception of the adaptive capacity of recreational striped bass anglers discussed above.

9.5.2 Baltic Sea

The Baltic Sea is home to the world's largest anthropogenically-induced hypoxic zone (Diaz & Rosenberg, 2008). Cod fisheries have seen impacts from eutrophication and the associated hypoxic zone (described in Chapter 10.6.4) and a transdisciplinary research effort has assessed human well-being impacts of the degraded Baltic Sea in the surrounding countries. Turner et al. (1999) studied user preferences to establish benefits of a 50% reduction of nitrogen and phosphorous inputs, estimating an annual economic benefit of around US$10 billion (or SEK70 billion). Their analysis considers potential increases in the Baltic by considering potential improvements in ecosystem services including beach recreation, existence and option values of preserving species and their habitats, and benefits from preserving and restoring wetlands. The authors acknowledge that the exact dollar amount is imprecise and note that the sheer magnitude is telling of potentially large benefits.

Assessing the Baltic drainage basin at a regional level, Turner et al. (1999) identified numerous sources of nutrient loading and several social drivers of eutrophication and hypoxia (including air and water pollution externalities, groundwater depletion, overfishing, poor land use policies, and market price interventions). The authors explored the potential for international agreements amongst bordering countries and found that most countries would see a net gain from pollutant reduction. Their model identified that pollution reduction concentrated on areas of high nutrient loads would be environmentally and economically optimal, as opposed to a uniform abatement strategy. Countries containing sub-drainage basins with larger proportionate impacts are also the countries that stand to benefit most from nutrient reduction. Their results suggest that reducing nitrogen and phosphorous loads concurrently via improvement of existing sewage effluent treatment, coastal wetland creation and restoration, and adjustments to agricultural practices would be highly effective. Targeting areas of sub-standard treatment would be more effective than improving already acceptable, if imperfect, treatment facilities.

This study was concerned with potential for coordinated international action, thus its scope was regional in scale and further differentiation of costs and benefits to the level of sector, community, or group was not included in the analysis. The scale of analysis was appropriate for informing policy at the regional level and, based on Turner et al.'s (1999) analysis, Gren (2001) evaluated four policies aimed at reducing nitrogen loading in the Baltic Sea. Her analysis suggested that coordinated actions across countries would be substantially more effective than independent actions by individual countries.

Figure 9.10 Brown shrimp (*Farfantepenaeus aztecus*) is one of the largest fisheries in the U.S. © Smithsonian Environmental Research Center [CC BY 2.0].

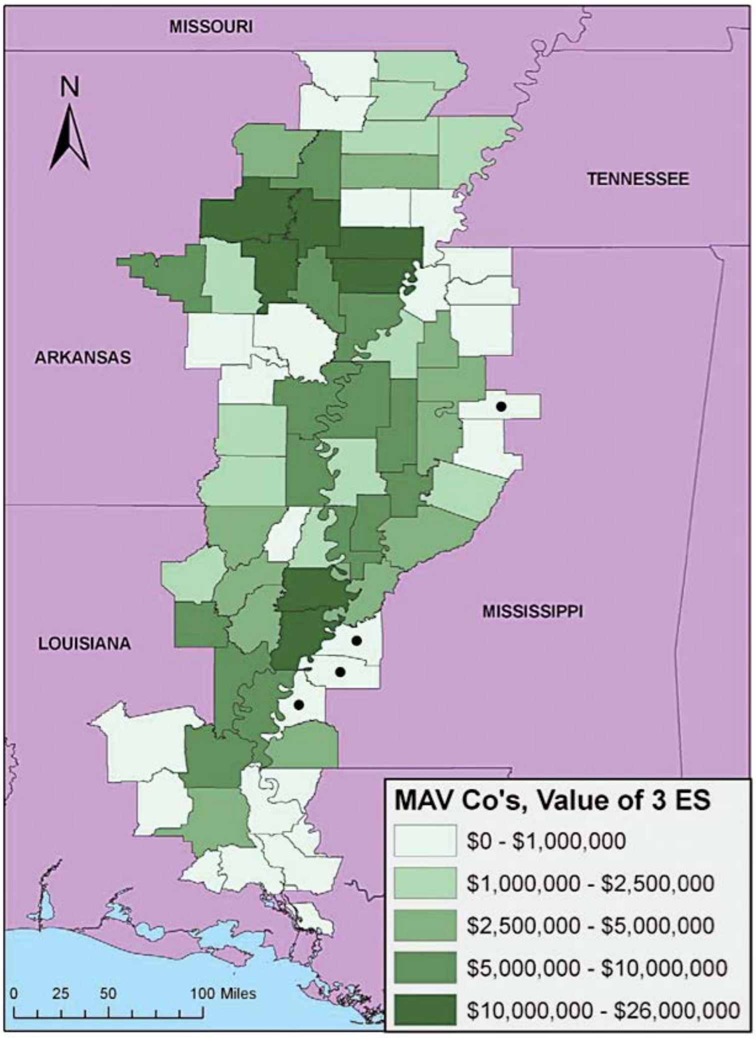

Figure 9.11 Mississippi Alluvial Valley (MAV) counties by annual aggregate social value of the three bundled ecosystem services – greenhouse gas mitigation, nitrogen mitigation, and waterfowl recreation - generated by restored wetlands on Wetlands Reserve Program land (dot indicates insufficient data to construct agricultural baseline for county). Reproduced with permission from Jenkins et al. (2010).

These two studies highlight the utility of interdisciplinary examinations of social-ecological systems at a scale appropriate for management. Ocean deoxygenation is expected to continue in the Baltic Sea under all but the most aggressive nutrient-reduction plans (Meier et al., 2011), making careful assessment of impacts and mitigation options crucial for taking effective action.

9.5.3 North Carolina brown shrimp and blue crab

Several studies in North Carolina have provided insights into the combined effects of hypoxia and social dynamics on fishery sector profits as well as optimal fishery functioning. Huang et al. (2010) estimated an annual loss of US$1.27 million from catch losses during the period 1999-2005 in the Neuse River and Pamlico Sound Estuary brown shrimp (*Farfantepenaeus aztecus*) fishery (Figure 9.10). An important contribution of this study was that their model accounted for lagged effects of hypoxia reflecting cumulative exposure Much of the economic consequences resulted from effects of hypoxia on juvenile shrimp prior to arrival at the fishing grounds. Model results found that losses in Pamlico Sound in perpetuity would amount to US$27,560,000 in lost revenue. Recouping these lost rents would pay for only a fraction of the costs of mitigating hypoxia in the Sound in perpetuity, estimated to be between US$155,000,000 and US$266,000,000 by Schwabe et al. (2001). The authors suggest that the range of ecosystem services provided by the Sound would need to be assessed to justify policy actions to reduce nutrient inputs.. By incorporating shrimpers' behaviour and demand for shrimp into the model, Huang et al. (2012) were able to estimate producer and consumer surplus losses and found that all losses accrued to

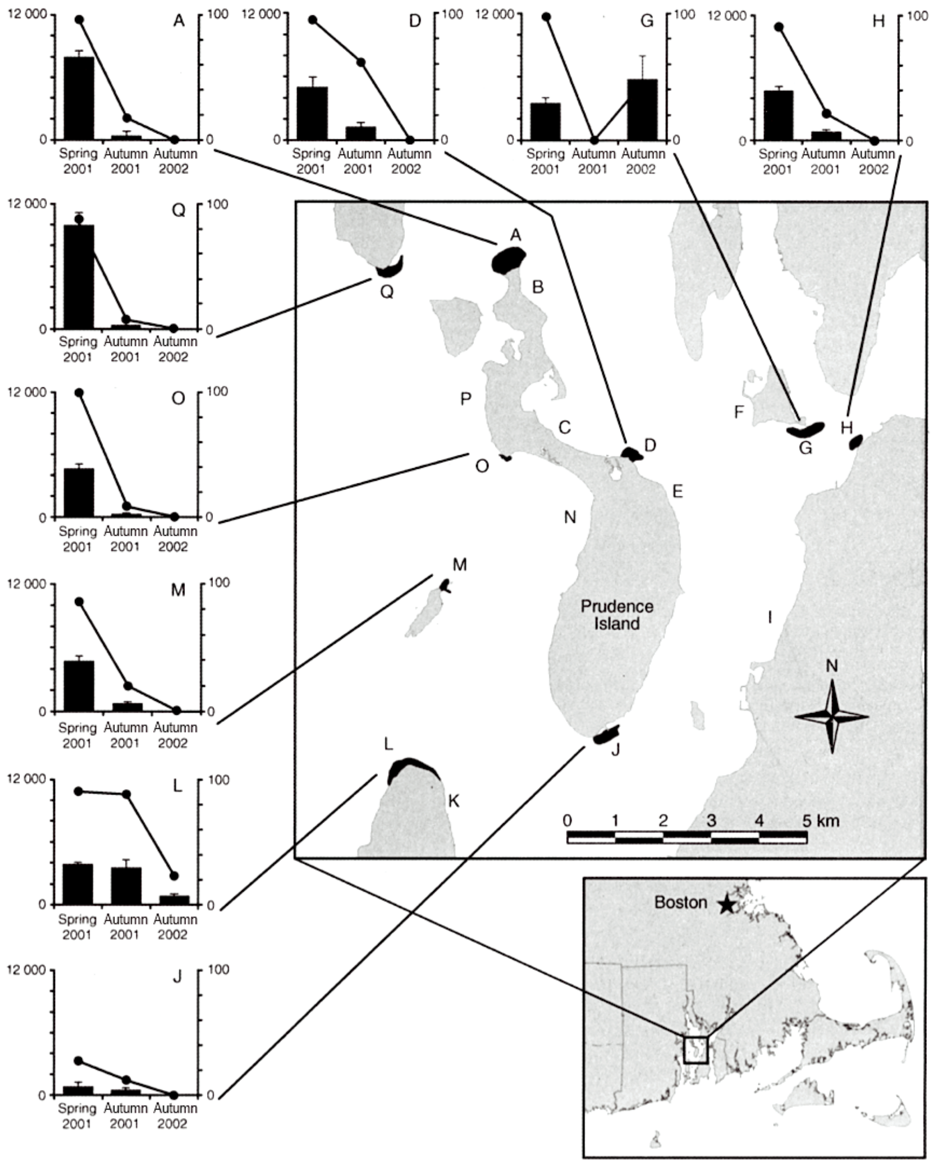

Figure 9.12 Declines in blue mussel density (histograms, mean + SE, count m^{-2}) on the left-hand axis and percentage cover (lines) on the right-hand axis during three sampling periods (before, during, and after the hypoxic event). Study sites: A. Providence Point; B. Bear Cove; C. Potter's Cove; D. Mount Tom Rock; E. Homestead Point; F. Hog Island West; G. Hog Island East; H. Marker 6A; I. Portsmouth Abbey; J. T-Wharf; K. Conanicut Point East; L. Conanicut Point West; M. Hope and Despair Islands; N. Home Beach; O. Pine Hill Point; P. Rossi Farm Backside; Q. Warwick Point. Figure and description reproduced with permission from Altieri and Witman (2006).

producers. In a separate study, Huang and Smith (2011) used a bioeconomic model to find that under hypoxic conditions, optimal harvest occurred earlier in the season.

Similarly, Smith (2007) used a bioeconomic model of the Neuse River Watershed blue crab fishery to reflect both biophysical components of the system, such as spatial dynamics of hypoxia and the relationship between hypoxia and population dynamics, as well as social components in the form of different management regimes and regional market dynamics. He estimated total benefits of a 30% reduction in nitrogen and associated reduction in hypoxic conditions to range between US$1 million and US$7 million annually, with the magnitude of benefits depending on management regime.

These studies demonstrate the value of integrated assessments that consider both social and biophysical processes as well as consider differential impacts on groups reliant on particular ecosystem services. The studies are limited to provisioning services accessed through fisheries and do not consider cultural, supporting, or regulating services or non-fishery provisioning services. Thus, the estimates of fisheries

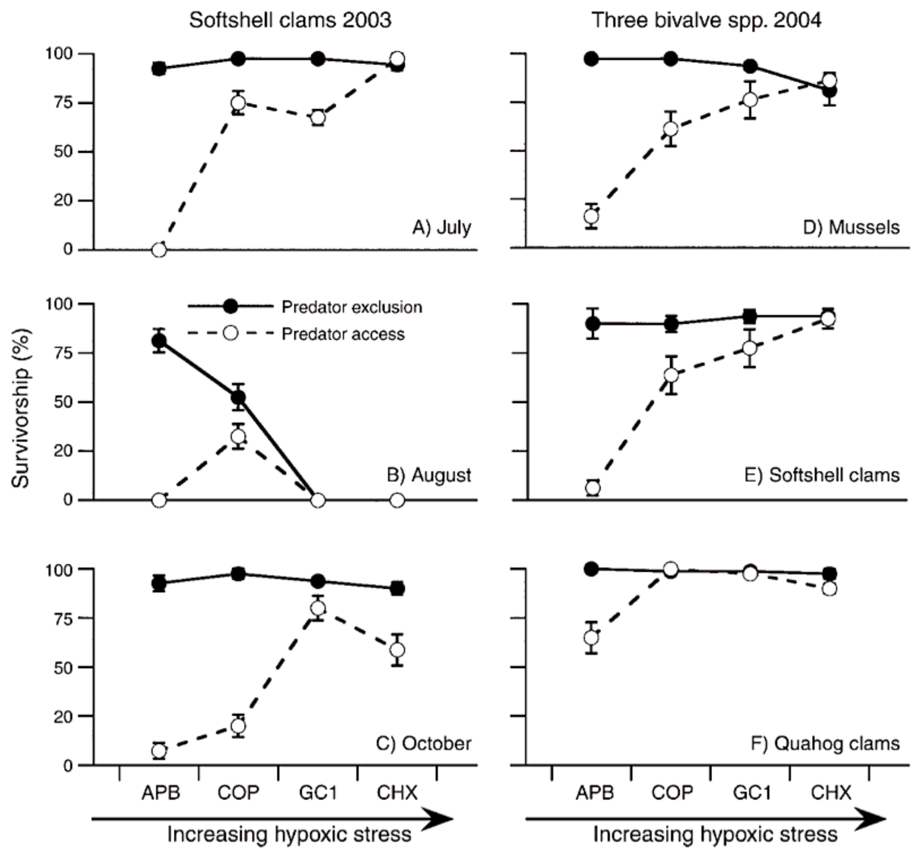

Figure 9.13 Bivalve survivorship along the hypoxic gradient at four hypoxic sites in Narragansett Bay, Rhode Island, USA in predator-exclusion (solid circles) and predator-access (open circles) treatments. There was temporal and spatial variation in net survivorship of softshell clams, exhibiting the interacting hypoxia-driven effects of predator release and physiological stress (A-C). All three species exhibited decreased predation with increasing hypoxic stress (D-F). Differences in survivorship between treatments were assessed with two-way ANOVA. Data were arcsine square-root transformed to meet ANOVA assumptions of normality. Data are survivorship (mean ± SE) in 10 replicates. Sites on the x-axis are in order of increasing hypoxic stress: APB = Arnold Point Bay, CPO = Conimicut Point, GC1 = Greenwich Cove (navigational marker number 1), and CHX = Chepiwanoxet Point. Figure and description reproduced with permission from Altieri (2008).

gains and losses reflect only partial human impacts of hypoxia levels within the system.

9.5.4 Gulf of Mexico wetlands

Effects of ocean deoxygenation on Atlantic croaker and shrimp fisheries in the Gulf of Mexico are discussed in Chapter 10, but other studies have evaluated the benefits of ocean deoxygenation mitigation more generally. As the largest floodplain in the U.S., nutrient loading from the Mississippi Alluvial Valley (MAV), is considered a principal driver of the "dead zone" in the Gulf (Goolsby & Battaglin, 2001). Wetland restoration presents an opportunity for hypoxia mitigation by increasing the ecosystem's provision of pollution and waste control (a regulating service) through denitrification (removal of nitrate) and nitrogen sequestration (Jenkins et al., 2010). In addition to wetland restoration contributions to nitrogen mitigation, Jenkins et al. (2010) evaluated potential social welfare benefits of greenhouse gas mitigation and waterfowl recreation. Despite upfront costs of wetland restoration and reclamation of lands previously converted to agriculture, the estimated social value received from restored wetlands surpasses restoration costs within one year. The study estimates a social welfare value of US$1,435 to US$1,486 ha^{-1} yr^{-1} with annual MAV-level benefits of approximately US$300 million. Most of the value (75%) is supplied by 21 of the 67 counties (Figure 9.11) and the authors note that expanded public programmes or novel ecosystem service markets would be necessary to deliver payments to landowners in order for restoration to be economically rational for that user group. For taxpayers who are not directly invested in agriculture on eligible restoration lands, restoration has a social value well above agricultural use and is economically rational.

The authors note that other services that did not have clear monetary value at the time of publication were not included, suggesting their estimate of social value of

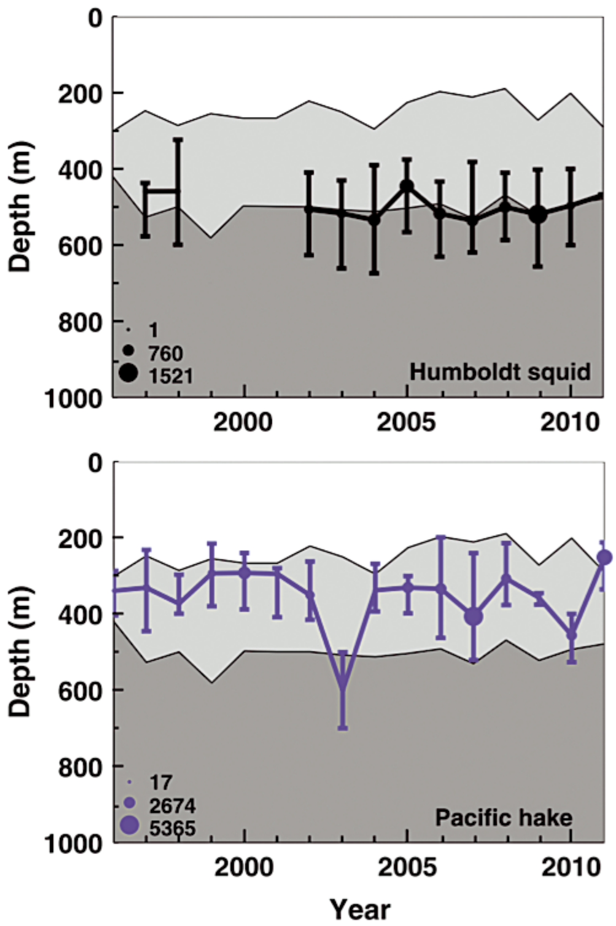

Figure 9.14 Annual depth distributions and abundance of Humboldt squid and Pacific hake in relation to hypoxia. Light grey illustrates the mean depth-range of the oxygen limited zone (OLZ; between 0.5 and 1.5 ml L^{-1} dissolved oxygen concentration); darker grey indicates the mean depth range of the oxygen minimum zone (OMZ; <0.5 ml L^{-1} dissolved oxygen). Circles show relative encounter rates for each species, with actual values indicated. Adapted from Stewart et al. (2014).

restoration is on the conservative side. While nitrogen mitigation accounted for the majority of benefits construed from wetland restoration, inclusion of other ecosystem services highlights the interconnection of biogeophysical processes and the necessity of considering the suite of interacting stressors and mechanisms in considering impacts of large-scale environmental change, such as ocean deoxygenation, on people.

9.5.5 Narraganset Bay quahog and blue mussels

Hypoxia in Narraganset Bay, Rhode Island, USA is chronic and has played a central role in shaping ecosystem dynamics and services within the semi-enclosed system. Altieri and Witman (2006) examined impacts of a severe hypoxic event in the summer of 2001 and found that it led to local extinction of blue mussels, a foundational species in the Bay (Figure 9.12). With mass mortality of blue mussels, the species, bay-wide filtration capacity was reduced by >75% and was still further reduced a year later. Their analysis also found that blue mussel density had a bottom-up effect on predator abundance with their presence enhancing four of seven predator populations, including sea stars (*Asterias forbesi*), rock crabs (*Cancer irroratus*), spider crabs (*Libinia emarginata*), and drills (*Urosalpinx cinereal / Eupleura caudate*), the abundance of those other species fell when mussels succumbed to hypoxia. In contrast, quahogs (*Mercenaria mercenaria*), another bivalve species, benefited from the new low DO conditions (Altieri, 2008). Following the loss of blue mussels and other harvested bivalve species due to declines in dissolved O_2 concentration (Altieri, 2008; Altieri & Witman, 2006; Desbonnet & Lee, 1991; Good et al., 2003; Oviatt et al., 2003), quahogs are currently the most important fishery within Narraganset Bay (DeAlteris et al., 2000). The fishery is now one of the largest quahog clam fisheries in the United States (Desbonnet & Lee, 1991).

Using the "chronically hypoxic" bay's seasonal fluctuation in dissolved oxygen levels for *in situ* experiments, Altieri (2008) found that certain levels of hypoxia released quahog, softshell clams (*Mya arenaria*), and blue mussels (*Mytilus edulis*) from predation (Figure 9.13). Common predators of bivalves, such as sea stars, fish, and crustaceans, are highly sensitive to hypoxia and tend to move away from oxygen-depleted waters (Altieri & Witman, 2006; Bell & Eggleston, 2005; Lenihan et al., 2001; Pihl et al., 1991) or stay and become lethargic with reduced predation behaviour (Baden et al., 1990; Bell et al., 2003; Breitburg, 1992; Grantham et al., 2004). However, at still lower levels of dissolved oxygen, gains from reduced predation were counteracted by reduced survival of both the softshell clams and blue mussels (Figure 9.13). Quahog, known as "facultative anaerobes" (Hochachka & Somero, 2002), are highly tolerant to reduced oxygen conditions and were able to survive under the most hypoxic conditions observed (Altieri, 2008). Altieri (2008) noted that, as the most important fishery in the Bay, the success of quahog under hypoxic conditions serves to benefit the community and industry and should be considered in planning for adaptation to sustained hypoxic conditions. He adds, however, that it will be important to consider the dissolved oxygen content threshold of quahog in long-term adaptation strategies.

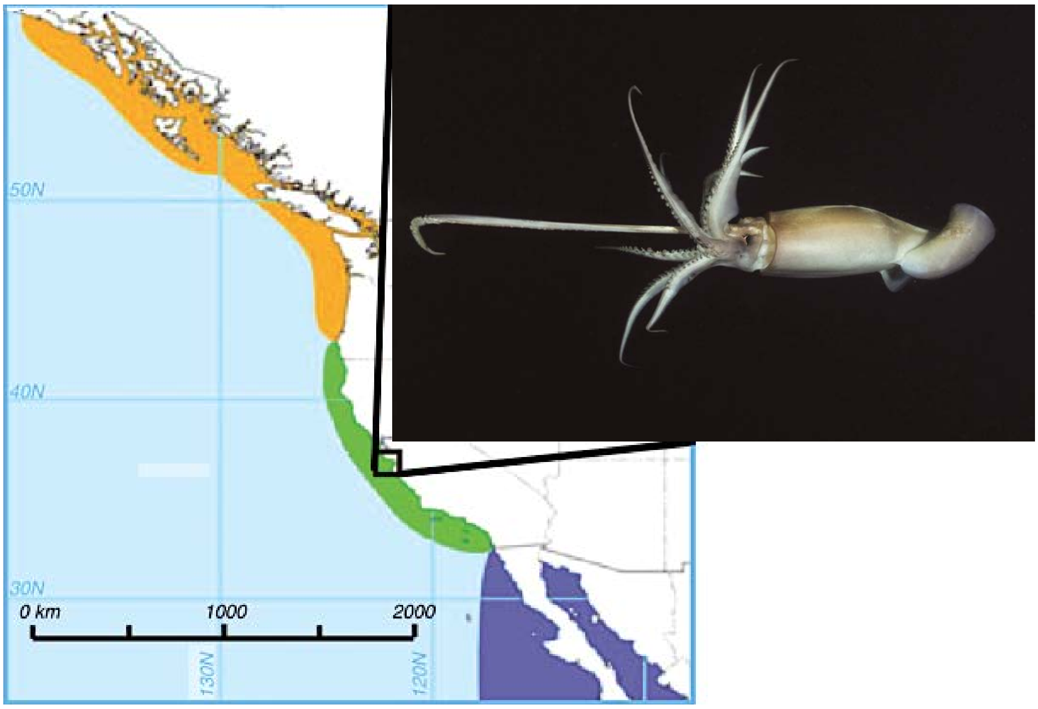

Figure 9.15 Map of Humboldt squid range expansion in the north-eastern Pacific Ocean. Humboldt squid likely came to the Gulf of California and Mexico in the 1970s (blue: Gilly, 2005), were first observed in California and Southern Oregon in 1997/1998 (green: Pearcy, 2002; Zeidberg & Robison, 2007), and further north in 2004-2005 (orange: e.g. Brodeur et al., 2006; Wing, 2006). Adapted from Stewart et al. (2014). Humboldt squid © WaterFrame / Alamy stock photo.

9.5.6 Humboldt squid and Pacific hake

The Humboldt squid (*Dosidicus gigas*) and Pacific hake (*Merluccius productus*) are two commercially important species in the eastern Pacific Ocean thought to be impacted by ocean deoxygenation in different, but interrelated ways. Humboldt squid are cephalopods with relatively high tolerance to low oxygen levels (Figure 9.14) (Stewart et al., 2014), while hake, a pelagic fish in the same taxonomic order as cod and haddock (Gadiformes), are less tolerant of low oxygen conditions (Figure 9.14). Hake is the largest fishery by volume on the continental U.S. and Canada (Thomas et al., 2011) as well as a prey species of Humboldt squid.

Previously not found in north-eastern Pacific waters, Humboldt squid have expanded their range by increasing the distance of their seasonal migration (Figure 9.15) to access prey species whose distribution patterns have changed as a result of shoaling of oxygen minimum zones (Gilly et al., 2013; Stewart et al., 2014). Squid range expansion has consequently had negative impacts on several commercially-important species via increased predation (Field et al., 2007, 2013). Hake, in particular, have seen increased predation by Humboldt squid in both the north-eastern Pacific California Current system (Zeidberg & Robison, 2007) and the Humboldt (or Peru) Current system (Alarcón-Muñoz et al., 2008; Arancibia & Neira, 2008). In addition, increased presence of the predators is disrupting hake schooling structures in the California Current (Holmes et al., 2008) and presents challenges for hake management through increased uncertainty of hake stock estimates due to interfering with acoustic methods used to monitor hake numbers and set national quotas (Holmes et al., 2008; Stewart & Hamel, 2010; Thomas et al., 2011). Additional effects of the OMZ on Peruvian fisheries are discussed in Chapter 10.

As a result of environmental and ecological changes (partially driven by reduced dissolved oxygen and shoaling of oxygen minimum zones), the eastern Pacific Humboldt squid fishery has been the largest invertebrate fishery in the world in most years since 2004 (Gilly et al., 2013; Stewart et al., 2014). Global catch has increased from 19,000 t in the 1980s (Rodhouse et al., 2016) to 1.16 million t in 2014 (FAO, 2016) with most of the catch coming from the Peru Current (Stewart et al., 2014). During this period, the hake fishery saw reduced catch, with Chilean total allowable catch (TAC) reduced by more than half from 40,000 t in 2013, to 15,000 - 19,000 t between in 2014 - 2015 (Plotnek et al., 2016). While the hake fishery losses have not been directly tied to increased squid predation, it appears to be a plausible explanation given the Humboldt squid's opportunistic predation behaviour, high turnover rates, and high consumption rates (Field et al., 2007). Further fisheries impacts are considered likely as Humboldt squid prey include several of the largest fisheries by volume on the U.S. West Coast (Field et al., 2007).

Understanding human well-being impacts resulting from the known or hypothesized changes to provisioning service availability in these two fisheries requires examination of the role each species plays in local, regional, and global markets as well as the ability of communities and relevant groups and sectors to adapt. For example, in Chile, both hake and Humboldt squid are targeted by industrial and artisanal fishing fleets. Distribution of the fishery types varies along the coastline, so geographic regions will be differentially impacted by the growth of the squid fishery and decline of the hake fishery. Specifically, squid fisheries predominate in urban coastal *caletas* (Aburto et al., 2013), which may stand to benefit more from the species' expansion, in the near-term, relative to rural coastal *caletas* that do not generally have developed squid fisheries. The relatively slow rate of change in Humboldt squid distribution may have facilitated adaptation, indicated by the relatively high number (2350) of artisanal fishing boats targeting squid in recent years (Rodhouse et al., 2016) compared to those targeting hake (approx. 400; Plotnek et al., 2016), despite the squid fishery's more recent establishment.

The Humboldt squid case study provides another example of a fishery that has seen improved performance due to ecological interactions being altered by ocean deoxygenation, likely at the cost of hake fishery performance. While expansion of hypoxic zones did not directly benefit Humboldt squid, the effects of reduced oxygen on their prey populations ultimately benefited the squid, highlighting the power of altered ecological interactions in determining the ultimate impacts of ocean deoxygenation on people. This case further highlights the potential for both positive and negative effects of ocean deoxygenation on people via changes to ecosystem service availability, as well as the potential for uneven distribution of impacts across groups due to existing socio-economic structures.

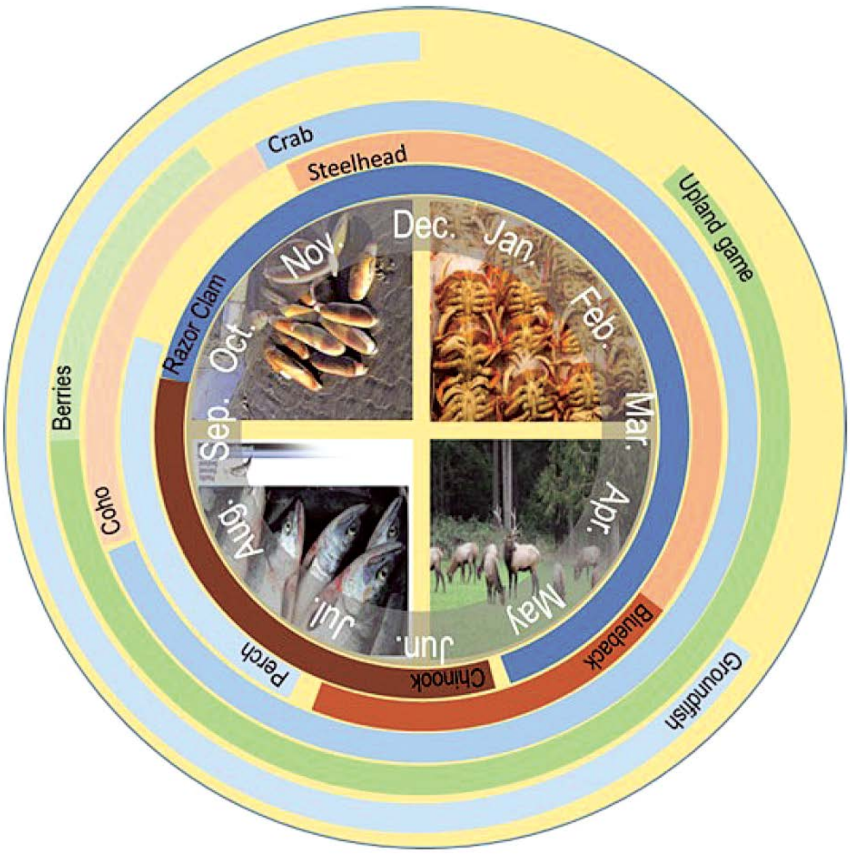

Figure 9.16 Seasonal cycle of the Quinault Indian Nation's harvested food resources. The cycle highlights the reliance on marine resources harvested for subsistence and commercial use and is based on interview data. Reproduced with permission from Crosman et al. (2019).

9.6 Impact pathways

As exemplified by the case studies presented above, assessment of ocean deoxygenation's impacts on people are predominantly focused on valuing specific ecosystem services that are more easily assigned monetary value and are situated in relatively small, bounded systems in more capitalized regions. However, ocean deoxygenation affects people via a variety of complex pathways as shown in trend and case studies described here. Despite challenges, even impossibilities, of calculating the monetary value of such impacts, current knowledge can be used to construct impact pathways to inform adaptation and mitigation policies and actions.

Here we present cases that illustrate two key challenges to comprehensive and quantitative analysis of ocean deoxygenation impacts on human well-being: (a) appropriate inclusion of services that are not readily quantified, such as cultural services (e.g. fish harvest in Native American culture, though this applies to all social-ecological systems), and (b) high risk situations in which numerous interacting stressors and social factors are creating critical and daunting social-ecological problems (e.g. coral reefs). These particularly challenging systems require relatively more research capacity to be appropriately examined.

9.6.1 Native American harvest

For coastal Native American tribes in the Pacific Northwest (PNW) and Alaska, traditional foods such as salmon, clams and crabs represent more than sustenance; they are revered as spiritually fulfilling and central to well-being (Lynn et al., 2013). Traditional foods are central in tribal life through harvest and associated acts (such as preparing, storing, bartering, selling, and consuming the foods) as well as in other facets of life essential for creating and maintaining healthy communities, such as education, ceremonies, and community events (Crosman et al., 2019; Donatuto et al., 2011). For example, Crosman et al. (2019) describe the Quinault Nation's concept of 'clam hunger' as "a deeply felt physical and emotional craving for a traditional food, the harvest of which connects tribal members with traditional places and the eating and sharing of which connects them to their childhoods, their families, and their ancestors" (Figure 9.16). These marine resources that Native American tribes rely on are subject to multiple stressors, including ocean deoxygenation (e.g. Crosman et al., 2019). The upwelling-prone eastern Pacific Ocean boundary current waters adjacent to tribal lands are currently experiencing reduced DO levels and projections predict further reductions (Figures 9.5 & 9.6). With fish and crustaceans particularly vulnerable to negative physiological impacts of ocean

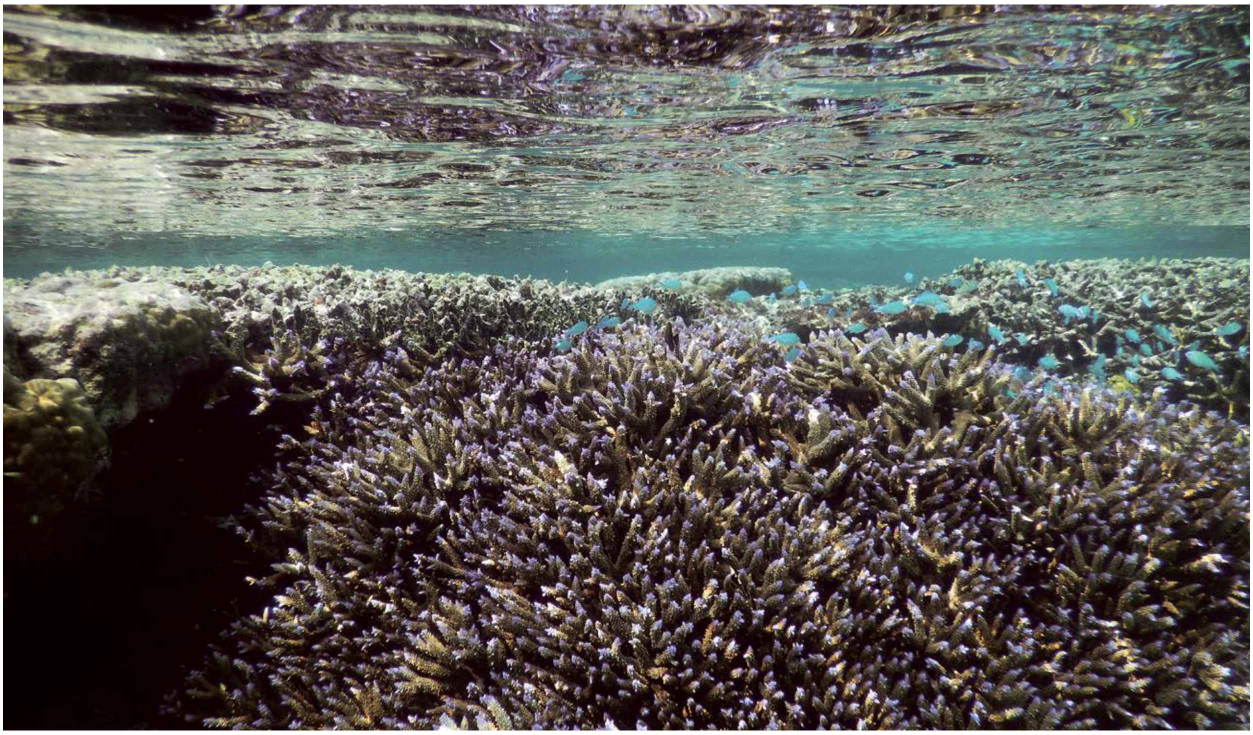

Figure 9.17 Coral reefs provide important ecosystem services, including shoreline protection and provision of nursery habitat for many species. © Rickard Törnblad [CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0)].

deoxygenation, and bivalves to a lesser degree (Chan et al., 2008; Vaquer-Sunyer & Duarte, 2011), reduced fitness of important species is likely to lead to changes in availability and movement patterns of different species. For example Dungeness crab in Hood Canal are an important tribal fishery and hypoxia has been shown to increase catch variability and lower minimum catch returns (Froehlich et al., 2017; Chapter 10). As a result, non-lethal environmental forcing from hypoxia threatens the fishery's ability to continue to provide a range of ecosystem services by increasing its sensitivity to overfishing and other pressures.

Not only are the tribes sensitive and exposed to the hazards presented by ocean deoxygenation, their capacity for adaptation or mitigation actions is limited by political and economic exclusion brought about by historical dispossession and alienation from both culture and nature. Tribal access to resources is strongly influenced by the legal and regulatory relationship with the U.S. federal government (Whyte, 2013) and, in particular, restriction of tribal harvest activities to reservations or "usual and accustomed" areas (Silvern, 1999) prevents tribes from employing traditional responses to resource shifts, such as harvesting different species or in different geographic areas (Berkes & Jolly, 2002). Historical place attachments and economic challenges common to indigenous communities in the U.S. (Cornell & Kalt, 1998) further constrain tribal populations' adaptive capacity.

While the nuanced and geo-temporally-relevant impacts of ocean deoxygenation on marine species important to PNW and Alaska Native Americans are not entirely understood, it can be reasonably hypothesized that Native Americans are, and will continue to be, affected by low DO-driven reductions in availability of the ecosystem goods and services they rely on for food, cultural practice, and spiritual wellbeing.

9.6.2 Coral mortality

As a final example and another exercise in transitive reasoning, here we connect deoxygenation-induced coral mortality to potential effects on people. There are no studies yet that directly connect ocean deoxygenation-induced coral mortality to human well-being impacts, however, potential impact pathways can be inferred from existing knowledge. It is well-established that corals provide a wide range of ecosystem services, including shoreline protection, important nursery grounds for many species harvested commercially, recreationally and in the aquarium trade (Agardy et al., 2011), all cultural services, such as tourism, recreation, education, and aesthetic and spiritual values (e.g. Barbier et al., 2011) and a variety of other services across all four categories (see Table 9.2; Figure 9.17) (MEA, 2005a). Millions of people are highly dependent on the goods and services provided by coral reefs, primarily in developing countries, where there is an especially high reliance on reefs for food provision (Figure 9.7) (FAO, 2018; Teh et al., 2013). It is also established that ocean deoxygenation leads to the decline of corals, though mechanisms of impact and recovery are understudied and not well-understood (Altieri et al., 2017). Studies suggest that coral reefs are one of the ecosystem subtypes most susceptible to multiple and interacting biogeochemical stressors of ocean warming, pollution, and ocean deoxygenation (Altieri et al., 2017; Cooley, 2012; Nelson & Altieri, 2019). Ocean deoxygenation may be particularly harmful for coral reefs over the long-term and compared to other reef disturbances, because hypoxia impacts a wide range of taxa including consumers, habitat formers, and pathogens (Altieri et al., 2017). It also mediates many important processes on the reefs and so interacts with climate change and ocean acidification (Nelson & Altieri, 2019).

Applying transitive reasoning, ocean deoxygenation-induced decline of corals could lead to a decrease in or loss of the services listed above and thus create hazards for reef-dependent and reef-associated human communities. Coral reef social-ecological systems may face some of the highest levels of hazard and risk from ocean deoxygenation due to relatively high sensitivity of the natural system to interacting and multiple stressors (Nelson & Altieri, 2019) and relatively high vulnerability (high sensitivity and low adaptive capacity) of associated human populations. Coral reef social-ecological systems are further disadvantaged by the lack of research addressing the role of ocean deoxygenation in coral reefs and a dearth of historical data on oxygen concentration on reefs due to traditional data collection protocols in reef systems (Altieri et al., 2017). Despite appearing to play a major role in coral mortality, recent research suggests that low-oxygen events on reefs are likely under-reported, in part bwcause the effects of hypoxia may be confused with other factors (Altieri et al., 2017; Nelson & Altieri, 2019). The lack of research and management capacity in affected areas reflects the crux of the problem when high levels of hazard meet low levels of adaptive capacity.

Table 9.3 Select examples of potential impact pathways of ocean deoxygenation (OD) on human well-being assembled using transitive logic to link knowledge from disparate disciplines.

ES Category	Biophysical process, resource, or habitat	(A) Effect(s) of OD on biophysical process, resource, or habitat	(B) Select ecosystem service(s) affected	(C) Potential effect(s) on human well-being
Provisioning	Fish	Decrease in biomass (Breitburg, 2002)	Food, income (Agardy et al., 2011)	A reduction in fish body size can lead to a reduction in food providence and income; fishers will need to catch more small fish to equal the same pay and food provision as catching fewer larger fish. (Díaz & Rosenberg, 2011)
	Fish	Decrease in abundance, survival and availability (Diaz et al., 2013)	Food, income (Agardy et al., 2011)	Fewer fish and lower fish availability may result in lower income for fishers, less food available for communities, and more conflict over limited resources. (Dubik et al., 2018; Smith et al., 2017)
	Fish	Constrains and compresses fish habitat (Hughes et al., 2015; IPCC, 2014)	Food, income (Agardy et al., 2011)	Shrinking of fish habitat reduces the suitable area for fishers to fish and could put further economic strain on them by inducing the need to travel further or switch gears to catch the same type and amount of fish as previously. (Díaz & Rosenberg, 2011; Dubik et al., 2018; Pecl et al., 2017)
	Fish	Habitat expansion (Stewart et al., 2014)	Food, income (Agardy et al., 2011)	Habitat expansion can provide new fishing opportunities as species move into new areas and become a newly available resource for fishers. (Pecl et al., 2017)
	Coral reefs	Coral bleaching and mass mortality (Altieri et al., 2017)	Shoreline protection (Agardy et al., 2011)	Coral mortality will result in a weakening and/or loss of shoreline protection (Gattuso et al., 2015)
Cultural	Fish	Decrease in survival, availability and abundance (Chan et al., 2008)	Spiritual (Lynn et al., 2013)	Indigenous groups who rely on shellfish and finfish harvest for cultural and spiritual well-being are more negatively affected by declines in availability of culturally important species. (Lynn et al., 2013)
	Fish	Decrease in fish catch (Lipton & Hicks, 2003)	Recreation	Decrease in recreational fish catch results in economic losses for those who profit from that fishery and loss of cultural services. (Lipton & Hicks, 2003)
	Coral reefs	Coral bleaching and mass mortality (Altieri et al., 2017)	Education and recreation (Agardy et al., 2011)	Coral die-offs result in an absence or reduction of educational, recreational and research opportunities, and people who make a livelihood from these activities will be more negatively affected. (Gattuso et al., 2015; Mora et al., 2013)
Supporting	Coral reefs	Coral bleaching and mass mortality (Altieri et al., 2017)	Nursery and essential fish habitat (Agardy et al., 2011)	Declines in nursery and essential fish habitat (supporting services) may result in fewer fish available as resources for fisheries, tourism, recreation, and other provisioning and cultural services.
	Biodiversity	Decrease in fish species richness (Hughes et al., 2015; Pecl et al., 2017)	Invasion/perturbation resistance, Recovery from fish collapse, Recreation, Waste removal (microbial diversity), Habitat protection (Palumbi et al., 2009)	Reduced resilience to invasive species and fishery collapse; loss of recreation potential, waste removal and habitat protection.
Regulating	Oxygen Minimum Zones (OMZs)	Increased carbon sequestration in OMZs (Cavan et al., 2017)	Carbon sequestration	Increased carbon storage in the ocean could potentially counteract effects of greenhouse gas emission on people to some degree, though this mechanism of change is understudied at present.

The transitive method of thinking can be applied to better understand other impacts of ocean deoxygenation on people that follow pathways yet to be holistically researched, but for which reliable knowledge exists (scientific, indigenous, or otherwise) about each string of arguments; further examples of such cases are given in Table 9.3.

9.7 Continued ocean deoxygenation: anthropogenic hazards with human solutions

Effects of ocean deoxygenation on people remain understudied and inherently challenging to assess. In particular, non-use and existence value as well as cultural services are underdeveloped in the ecosystem services literature (Fisher et al., 2013; Rabotyagov et al., 2014) and, indeed, within the context of ocean deoxygenation. Spiritual, therapeutic, and aesthetic values of ecosystems are difficult to quantify and, thus, challenging to incorporate into the empirical framework of ecosystem services. Even the more readily assessed welfare losses associated with ocean deoxygenation have only been addressed by a relatively small number of studies and examinations of effects on humans are limited by gaps in knowledge of the biophysical mechanisms and impacts of reduced dissolved oxygen levels (Rabotyagov et al., 2014).

Despite the lack of extensive research on the topic, current knowledge based in both the natural and social sciences, as well as the humanities, offers useful insights into what can be expected from continued ocean deoxygenation. Reductions in dissolved oxygen are expected to disrupt functioning of ecosystems which support a range of services that human communities, groups, and economic sectors currently rely on for well-being. Documented and anticipated biophysical impacts are generally negative, including habitat degradation and decreased fitness and survival of species, emigration of species from certain areas, and loss of critical habitats. People reliant on certain species and in certain regions may benefit from reduced DO levels, if only temporarily, and generally in association with losses to other species. Coral reefs and wetlands and marshes are most susceptible to negative effects of ocean deoxygenation and are considered to provide the largest magnitude of ecosystem services. Low latitude, coastal urban and rural populations, and poor households in developing countries are most vulnerable to the impacts of ocean deoxygenation. These represent systems of priority focus and regions and communities where they overlap are uniquely at risk, such as coastal communities in West Africa and low income developing countries (LIDCs).

Social factors will play a critical role in how biophysical changes are experienced by different groups and communities. A group's social role and characteristics will determine their level of vulnerability to ocean-deoxygenation-induced or -exacerbated hazards and changes based on their ability to adapt to, mitigate for, and possibly take advantage of altered ecosystem services. Owing to the variability of biophysical effects and disparate capacities of social groups to adapt to and mitigate for environmental changes, effects of reduced DO levels on different communities will be highly variable with outcomes generally exacerbating existing inequalities and reinforcing social-ecological poverty traps (Cinner et al., 2018). Any resulting benefits will largely accrue to those in power who have greater capacity to take advantage of new opportunities, while those in positions of less power will generally have less access to newly available or increased ecosystem services. Similarly, negative impacts will disproportionately affect those with less power, who are more reliant on ecosystem services, more vulnerable to hazards, and have less adaptive capacity to respond to changes. Conversely, those in power, will experience hazards to a lesser degree due to their reduced vulnerability and greater adaptive capacity.

Improved understanding of nuanced impact pathways of ocean deoxygenation to human well-being outcomes will be of critical importance for effective planning in response to ocean deoxygenation and other large-scale environmental changes going forward. Anticipating both long- and short-term biophysical and social changes under continued ocean deoxygenation is both essential and challenging. Further studies should endeavour to better understand the nature of non-linear responses of both natural and social systems to slow-onset hazards driven by ocean deoxygenation as well as biogeochemical interactions with other stressors. Analyses of ecosystem services should consider the entire range of service types (e.g. Ash et al., 2010; Landsberg et al., 2012), even where not quantifiable, in order to provide the depth and accuracy of information needed for proper planning. Transdisciplinary approaches to assessing systems holistically present promising means for achieving nuanced and policy-relevant knowledge of complex and dynamic social-ecological system dynamics. Adaptation plans should include consideration of species and habitats that are relatively tolerant of hypoxia in order to bolster their utility in providing ecosystem services. However, attention should remain on these near-term benefits as indicators of overall habitat degradation (Altieri, 2008).

The ultimate consequences of reduced oxygen levels in the ocean will result from complex interactions between natural and social systems, yet the opportunity to minimize negative impacts lies squarely within the social system alone. Efforts to reduce human vulnerability, increase adaptive capacity, mediate conversion of ecosystem services into human well-being, and mitigate for impacts of ocean deoxygenation on ocean systems must all come from actions of people and social institutions and maintain a focus on equity. An effective way for society to reduce the impacts of any environmental change, including deoxygenation, is to reduce the vulnerability of at risk groups and individuals by targeting ultimate and proximate causes of sensitivity, exposure, and capacity to adapt to hazards. In preparing to mitigate for and adapt to impacts of ocean deoxygenation, attention should be paid to the central role that social institutions play in mediating access to ecosystem services and the inherent inequities in the ways in which humans experience natural hazards.

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“Coral reefs, wetlands and marshes, and fish and crustaceans are most susceptible to negative effects of ocean deoxygenation, so people reliant on these systems will be particularly at risk of negative impacts.“

Chapter 9 authors

“The extent of the deoxygenation effects on fisheries is anticipated to increase because the areas of the ocean that will show increasing deoxygenation overlap with the coastal and oceanic regions that support high fisheries production.“

Chapter 10 authors