The Second World Ocean Assessment

WORLD OCEAN ASSESSMENT II

Volume I

United Nations

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Chapter 7M
Abyssal plains

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Keynote points

- The abyss lies between 3 and 6 km water depth and covers more of the Earth's surface than all other habitats combined.
- The present chapter is the first in the *World Ocean Assessment* that is dedicated to the abyss, covering biodiversity, regional differences, biogeography, and changes and impacts as a result of natural stressors and anthropogenic activity.
- Abyssal biodiversity is not well understood, and many gaps exist in the current understanding of abyssal evolution and biogeography, as well as the distributions, connectivity and responses of organisms to changing conditions.
- Fragmentary knowledge of abyssal taxonomy is largely the result of difficulties in sampling the vast and remote area and, hence, limited research effort, which hinders the advancement of scientific knowledge.
- Most abyssal environments support the processes that drive deep-sea and global ecosystem functioning and are linked closely to surface production and pelagic processes.
- Climate change and anthropogenic impacts affect the abyss, despite its remoteness.

1. Introduction

1.1. Situation as recorded in the first *World Ocean Assessment*

The first *World Ocean Assessment* (United Nations, 2017d) contained a brief description of abyssal environments, in chapter 1 (United Nations, 2017a), chapter 36F (United Nations, 2017c) and the chapters on biodiversity in different ocean regions. The dependence of abyssal habitats on the flux of food from above, the possible impacts of climate change and the likely impact of deep seabed mining were noted. There is continued uncertainty about abyssal biodiversity and its potential connections to pelagic and surface water organisms and future changes therein. The first Assessment did not contain the comprehensive description of abyssal biodiversity provided in the present chapter.

1.2. General

The abyssal zone (3–6 km water depth) (Gage and Tyler, 1991) encompasses the largest area on Earth (about 58 per cent of the planet's surface). It mainly comprises vast areas of sea floor plains covered in generally fine sediments, punctuated by sporadic hard substrate at topographic highs in the form of knolls, seamounts, mid-ocean ridges and island arcs, as well as lows in the form of valleys and deeper trenches. The total absence of sunlight penetration and in situ primary production, apart from some chemosynthesis (see chap. 7P), characterize an ecosystem based on a variable rain of material from shallower euphotic zones. Although it is food-limited, with low abundances compared with most deep-sea habitats (Gage and Tyler, 1991), the abyss supports high levels of alpha and beta diversity of meiofauna, macrofauna and megafauna (Rex and Etter, 2010). The quantity and quality of food particles sinking from the ocean surface strongly modulate ecosystem structure and function (Smith and others, 2008; McClain and others, 2012a), but feedback mechanisms through nutrient cycling back into the water column are poorly understood (Thurber and others, 2014). Abyssal regions differ from each other in physical variables, surface water characteristics and biogeographical distinctions, which are reflected in their organisms, communities and biodiversity.

Abyssal biodiversity varies in space (Glover and others, 2002; Woolley and others, 2016; Simon-Lledó and others, 2019a) and time (Ruhl and others, 2008). Despite poorly known biodiversity patterns on regional to global scales, some regions, such as the abyssal Southern Ocean (Brandt and others, 2006; Griffiths, 2010) and the equatorial Pacific (Glover and others, 2002; Amon and others, 2016a), house major biodiversity reservoirs. For the few taxa studied, connectivity appears high (Baco and others, 2016; Taboada and others, 2018), whereas studies of deep-sea functional diversity have just begun (e.g., Chapman and others, 2019), including of the abyssal sea floor (e.g., Christodoulou and others, 2019; O'Hara and others, 2019). Biodiversity knowledge varies by region and, in recent years, interest in seabed mining (see chap. 18) has helped to generate new information for regions such as the Clarion-Clipperton Fracture Zone in the central Pacific (e.g., Dahlgren and others, 2016; Glover and others, 2016a; Amon and others, 2017a, 2017b; Marsh and others, 2018; Wiklund and others, 2019), with evidence of biodiverse, yet vulnerable life (Vanreusel and others, 2016).

Climate change will likely affect the abyss (Yasuhara and Danovaro, 2016; Sweetman and others, 2017). Projections suggest increased abyssal ocean temperatures and acidification, and decreased oxygen concentrations and downward flux of organic matter. Other oceanographic processes will likely respond, increasing stratification and reducing water mass exchange. Given the narrow environmental niches of abyssal biota, such changes could produce geographic shifts and increase the vulnerability of abyssal organisms to other anthropogenic impacts (Levin and others, 2020). The current understanding of anthropogenic impacts on abyssal ecosystems remains poor but highlights a vulnerability that will very likely increase in the future.

2. Shifting baselines and documenting status and change in abyssal biodiversity

The challenges of sampling in remote locations at depths of more than 3,000 m contribute to abyssal undersampling (Glover and others, 2018). Biodiversity records reflect that deficiency (figures I and II). Sampling effort has also focused more on the sea floor than on the highly variable and vast pelagic realm.

2.1. Benthic abyssal biodiversity and benthic-pelagic coupling

Biogenic habitat comprises much of the fine-scale habitat structure on sediments. The patchy food resource also contributes fine-scale structure to the sea floor (McClain and Schlacher, 2015). Characteristically low current speeds result in minimal sediment erosion (Smith and others, 2008) but affect sediment composition (McCave, 2017). Abyssal waters are cold (< 5°C) and relatively constant in temperature (Sweetman and others, 2017), and they are characterized by extremely high hydrostatic pressure.

The transfer of organic matter to the abyss occurs mainly through sinking particulate organic carbon, which is largely produced in surface waters through photosynthetic primary production and zooplankton, the latter generating secondary production and by-products (Cavan and others, 2015). In addition, carcasses of marine vertebrates can sink to the abyssal plain within a few days, temporarily increasing local food

(Amon and others, 2016b). Surface export of organic material can reach abyssal depths within a few days but rates fluctuate (Smith and others, 2008). Particle export dynamics, such as summer export from upper layers, can strongly influence abyssal biogeochemical processes (Bouef and others, 2019). However, remineralization throughout the water column results in very low quantities of organic matter reaching the abyssal sea floor (about 0.5–5.0 per cent of surface production) (Lutz and others, 2007; Smith and others, 2008; Smith and others, 2009). The arrival of food influences abyssal communities and their diversity, abundance, density and composition, whereas important microbial groups affect processes such as carbon and nitrogen cycling, and vertical organic matter transport shapes the composition and biogeography of deep ocean prokaryotic (and eukaryotic) communities (Mestre and others, 2018). The low energy availability results in generally low abyssal abundances, biomasses and biological rates (metabolism, growth and reproduction) (Smith and others, 2008; Wei and others, 2010).

The total biomass of all benthic size classes generally declines with increasing water depth, except for bacteria and archaea, which dominate the biomass of the abyssal plain and deeper (Wei and others, 2010). Modelling estimates suggest global prokaryotic biomass on the sea floor of approximately 35 megatons of carbon (Wei and others, 2010). Thus, the activities of microbial communities strongly influence the type and abundance of nutrients released back into the pelagic realm. The microbes also experience top-down forcing from viral populations (Suttle, 2005) and grazing by animals of various sizes (e.g., Howell and others, 2003; Ingels and others, 2010).

Figure I.A
Number of Ocean Biodiversity Information System (OBIS) records plotted against ocean depth

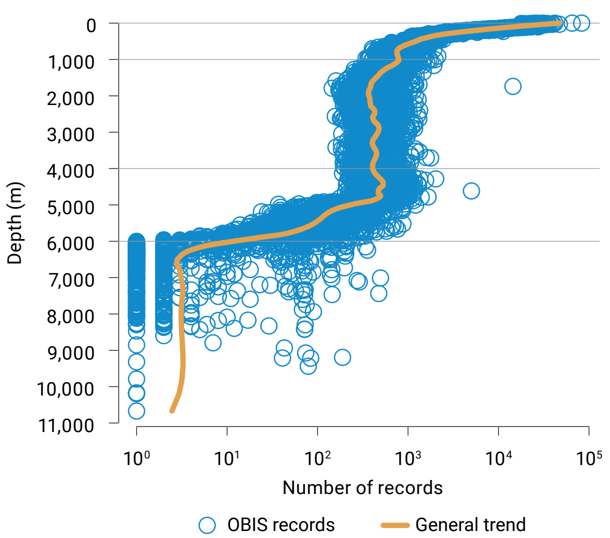
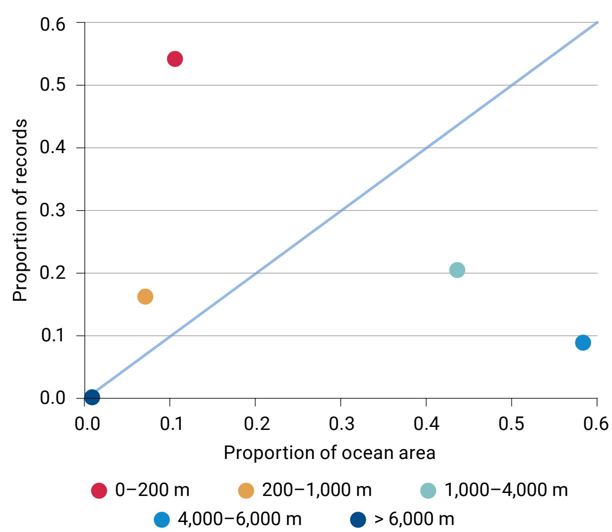


Figure I.B
Proportion of all OBIS records occurring in different depth zones, plotted against the proportion of the global ocean that occurs at those depths



Source: Webb and others, 2010.
Note: The 1:1 line identifies those areas of the ocean with proportionately more (points above the line) or fewer (points below the line) records than expected given their area. The depiction provides a conservative view of under- and overrepresentation based on the volume of each habitat.

Figure II.A
World map of Ocean Biodiversity Information System abyssal records

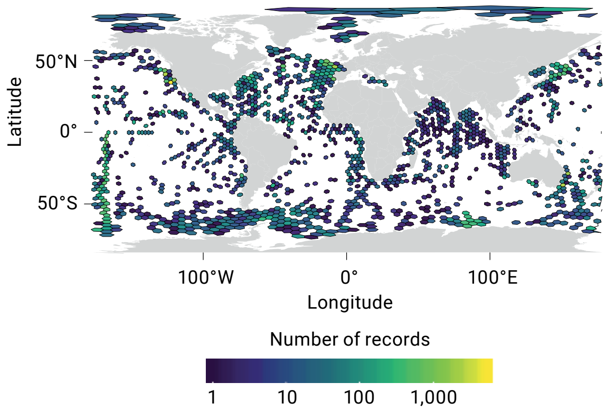
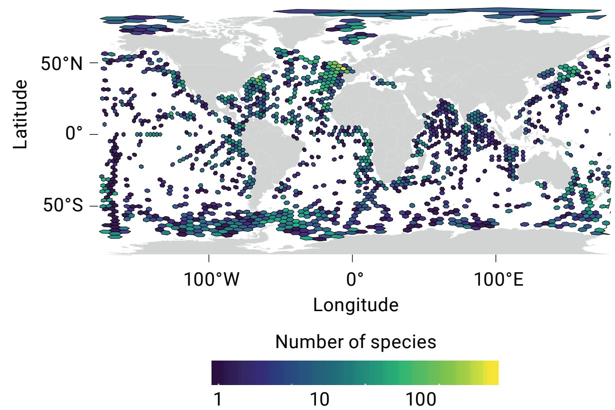


Figure II.B
World map of Ocean Biodiversity Information System species presence between 3,000 and 6,000 m depth



Source: Ocean Biodiversity Information System (OBIS), 16 May 2019; Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization. Retrieved from https://obis.org).
Notes: A: Data available rarely exceed 1,000 records per 75,000 m^2 area; gaps exist, especially in the Pacific Ocean, the South Atlantic Ocean and the South Indian Ocean. B: The North-East Atlantic Ocean has more samples as compared with all other oceans. Note the correlation between records and species presence.

2.2. Abyssopelagic zone

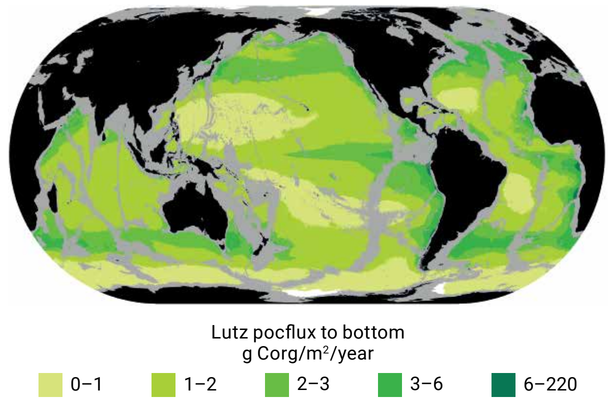
Much less is known about the pelagic fauna that primarily occupy depths between 3 and 6 km and that live more than 200 m above the sea floor. The Ocean Biodiversity Information System shows minimal sampling of those ecosystems, which results in major knowledge gaps spanning over a billion km^3 of habitat – potentially the largest reservoir of unknown diversity on Earth (Robison, 2009). The abyssopelagic zone facilitates the largest carbon sink on the planet, a critical ecosystem service of the global ocean (Atwood and others, 2020). Daily vertical migration between deep-sea pelagic layers can move dissolved nutrients that contribute to primary production in the photic zone (Houghton and Dabiri, 2019), along with long-term deep ocean circulation.

2.3. Key region-specific differences or contrasts

Broad-scale variation in physical and chemical environments (e.g., organic flux, oxygen) in the abyss result in geographic differences in biodiversity. Salinity, however, varies too little to produce such variation. Such geographic differences could also lead to contrasting responses to human impacts within different regions, but the data necessary to evaluate that possibility are lacking.

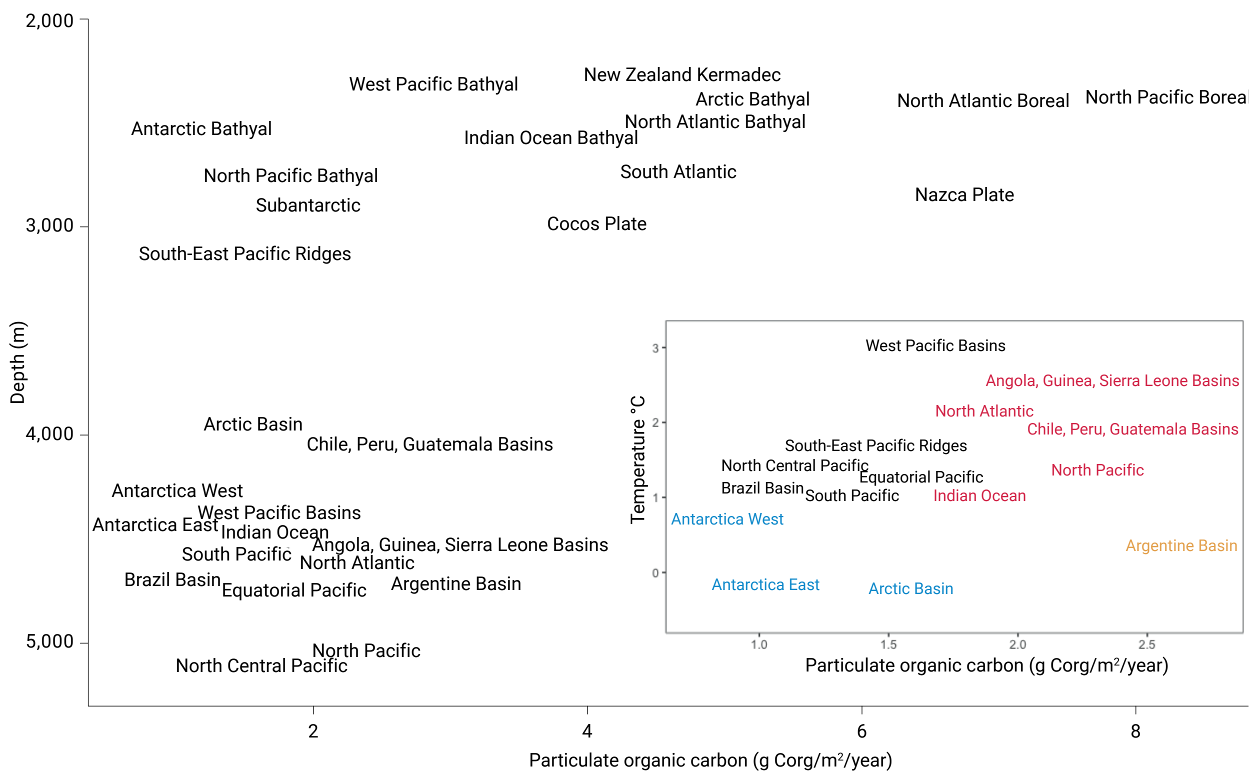
Carbon availability. Numerous studies on carbon availability demonstrate that a variety of processes contribute to particulate organic carbon levels in the abyss, thus shaping communities (Carney, 2005; Smith and others, 2008; Rex and Etter, 2010; McClain and others, 2012a; McClain and Schlacher, 2015; Woolley and others, 2016). Particulate organic carbon flux to the deep varies in time and space (Lampitt and Antia, 1997; Lutz and others, 2007; figure III). Such factors as depth, distance from productive coastal waters and/or upwelling regions can produce considerable local effects, generally limiting particulate organic carbon flux to the deep sea floor. For example, upwelling in the equatorial Pacific results in high levels of particulate organic carbon flux (2–6 g/m^2/year) compared with the extremely low particulate organic carbon (< 1 g/m^2/year) in adjacent regions to the south (Watling and others, 2013). Intense areas of coastal upwelling, combined with narrow continental shelves, place abyssal habitats in the North-East Pacific and the South-East Atlantic closer to productive coastal waters, resulting in higher particulate organic carbon input (Lutz and others, 2007; Lampitt and Antia, 1997). Moderately high particulate organic carbon fluxes also occur in the North Atlantic (6.6 gm^2/year) because of spring bloom pulses (Lampitt and Antia, 1997).

Figure III.A
Particulate organic carbon flux to the bottom at depths between 3,500 and 6,500 m



Source: Data from Lutz and others, 2007; adapted from Watling and others, 2013.

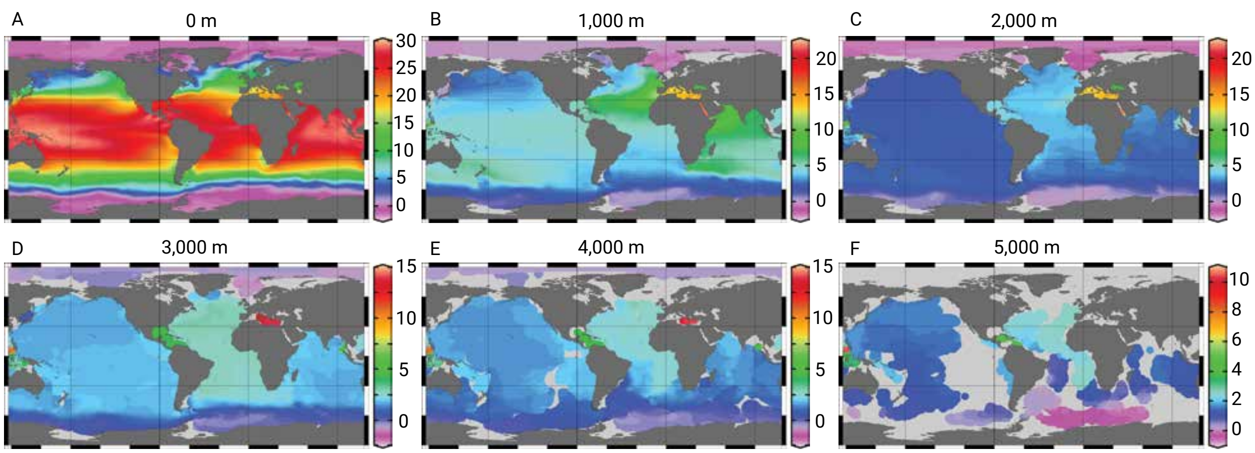
Figure III.B
Depth-particulate organic carbon plot illustrating differences in particulate organic carbon flux and flux variability between bathyal and abyssal regions (main) and variability between abyssal regions (temp-particulate organic carbon flux) (insert)



Source: Based on data from Watling and others, 2013.

Temperature. Temperature often shows a statistically significant relationship with diversity in the abyss (Cronin and Raymo, 1997; Hunt and others, 2005; Yasuhara and Danovaro, 2016). Temperature may also limit the biogeographic distribution of some species (McClain and others, 2012b). Temperatures above 10°C occur in the Mediterranean, even on its abyssal plains. Higher temperatures in some other marginal seas, such as the Gulf of Mexico and the Sulu Sea, also exceed those at open ocean abyssal depths. Slightly colder abyssal temperatures occur in the Pacific than in the Atlantic, with substantially colder polar sea abyssal temperatures (see figure IV; Yasuhara and Danovaro, 2016). Gebbie and Huybers (2019) recently reported a significant difference between Pacific (continuing to cool as a result of the Little Ice Age) and Atlantic (beginning to warm because of recent climate change) circulation. The changes may alter carbonate compensation depths (water depth at which carbonate supply and dissolution are equal) within the different basins. Regional differences result from influences of depth and bottom-water formation, downwelling and other water mass exchanges.

Figure IV
Global temperature distributions at different water depths (°C)



Source: Adapted from Yasuhara and Danovaro, 2016; data available at www.nodc.noaa.gov/OC5/WOA09/pr_woa09.html.
Notes: The map was created using Ocean Data View, available at http://odv.awi.de.

Oxygen. Dissolved oxygen concentrations affect the ecology and distributions of deep-sea animals (Levin, 2003; Stramma and others, 2010) and may determine the presence and absence of species in specific regions and restrict species dispersal. Oxygen can vary between 1 and more than 6 ml per l in the abyss (Watling and others, 2013). Well-oxygenated Antarctic Bottom Water moving northward increases dissolved oxygen concentrations in the extreme south Indian Ocean, the Pacific Ocean and the Atlantic Ocean (3–4 ml/l). Likewise, the southward-flowing North Atlantic Deep Water oxygenates the North Atlantic Ocean (5.5–6.5 ml/l), resulting, with the Antarctic, in some of the most oxygenated abyssal waters on Earth (Watling and others, 2013).

Depth. The minimum depth at which the abyssal plains begin varies regionally, with shallower abyssal plains in both the Gulf of Mexico (3,000–3,900 m) and the Mediterranean (average depth, 1,500 m; maximum, 5,267 m) than in other regions. The average depth of the Arctic Ocean and the Chile, Peru and Guatemala basins approach 4,000 m, in contrast to average depths closer to 5,000 m in the northern and central Pacific. Greater depth, ceteris paribus, reduces particulate organic carbon flux. Depth, as a proxy for pressure, may also limit biogeographic distributions (Somero, 1992; Carney, 2005). Regional abyssal depth differences may thus cause taxonomic compositional shifts and influence biodiversity. Nonetheless, despite broad biogeographic differences among regions, little evidence points to depth as a strong correlate of diversity within abyssal plains.

Topography. Topographic features can impede exchange of individuals between deep-sea populations and influence biogeographic classification (McClain and Hardy, 2010). The Pacific and Atlantic share only 15–20 per cent of species (Vinogradova, 1997). The Strait of Gibraltar limits colonization of the relatively species-poor Mediterranean by Atlantic fauna (Sardà and others, 2004). Mid-oceanic ridges may also limit dispersal on the abyssal plains. Half of the known species of deep-sea bivalves are restricted to either the eastern or western Atlantic (McClain and others, 2011), likely because of the Mid-Atlantic Ridge.

Researchers recently recognized that abyssal hills rising less than 1,000 m off the sea floor create topographic, depth and sediment differences that support different taxonomic assemblages and higher biomass levels (Yesson and others, 2011; Durden and others, 2015) than in flatter abyssal sediments.

Sediment and substrate. Sediment types can vary dramatically in composition within different abyssal regions. Most diatom oozes occur at abyssal depths but radiolarian oozes occur, inter alia, in the Southern Ocean, the equatorial Pacific and the Peru basin. Sponge spicules form a major component of sediments in the Australian-Antarctic basin. Clay dominates large seabed regions off South America and in the Indian Ocean, and it dominates the South Australian basin (Dutkiewicz and others, 2015). Sediment diversity affects biodiversity, but linkages between sediment type and biodiversity patterns remain underexplored. In abyssal plain sediments, polymetallic nodules can also affect biodiversity. Assemblages on nodules differ fundamentally from both near-bottom seawater and sediment communities (Shulse and others, 2017; Simon-Lledó and others, 2019a). Increased nodule presence promotes increased megafaunal and xenophyophore abundance (Simon-Lledó and others, 2019b). Thus, increased habitat complexity generated by polymetallic nodules increases diversity in all levels of abyssal biota.

Riverine influences. Riverine input can influence the abyss through: (a) input of terrestrial carbon; (b) creation of a dispersal barrier, thus affecting biogeography; and (c) disturbance that alters deep-sea sediments. Significant discharges are shown in table 1.

Table 1
Riverine influences

Recipient	River	Megatons carbon/year
Indian Ocean	Ganges and others	30.0
South-East Atlantic	Congo and others	30.0
South-West Atlantic	Amazon	37.6
North-West Pacific	Yangtze, Yellow and Mekong	16.2
Arctic	Siberian rivers	12.8
Gulf of Mexico	Mississippi	3.6
South-West Pacific	Indonesian rivers (with high annual rainfall)	90.0

Sediments from large rivers may also deliver substantial loads of anthropogenic contaminants, with unknown effects on abyssal biodiversity (Davies and Moore, 1970). Organic matter influx from large rivers to the continental margins, slopes and canyons is easily channelled through various processes to the abyss, where it may disturb and drive sea floor biomass and community diversity.

Ice cover. Polar ice cover influences primary production and thus particulate organic carbon flux to the abyss. Permanent ice cover reduces or prevents surface production, thus limiting biodiversity and biomass in the Arctic Ocean, where known species richness of polychaetes may be lower than in other, similar-sized basins (Bodil and others, 2011). Summer ice absence can bolster surface production and increase biodiversity and biomass (Wlodarska-Kowalczuk and Pearson, 2004).

Geological age. Geological changes likely affected the distribution of abyssal biodiversity by altering connectivity among ocean regions, including those shown in table 2.

Table 2
Connectivity among ocean regions

Connection	Opening	Closing	Source
	Millions of years ago (approximately)		
Mediterranean/Atlantic Ocean and Indian Ocean (Tethys Seaway)		19–14	Harzhauser and others, 2007
Drake Passage	30		Lawver and Gahagan, 2003; Livermore and others, 2007; Scher and Martin, 2006
Central American Seaway		3	Schmidt and others, 2007; O'Dea and others, 2016; Schmidt and others, 2016
Bering Strait (Arctic/Pacific)	4.8–7.4		Marincovich and Gladenkov, 2001; Hu and others, 2012
Fram Strait (Arctic/Atlantic)	10–20		Engen and others, 2008; Ehlers and Jokat, 2013

Source: Yasuhara and others, 2019a.

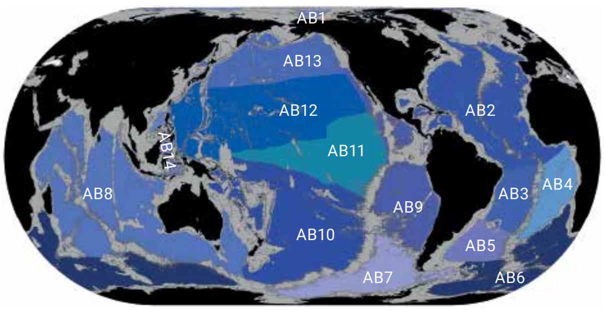
2.4. Abyssal biogeography

In contrast to well-recognized boundaries among benthic assemblages on continental margins, uncertainty remains as to whether such abyssal boundaries exist (Carney, 2005). Researchers have attempted to establish biogeographic realms below 3,000 m. Some early attempts based on temperature, topography or faunal similarities suggested Atlantic, Indo-Pacific, Antarctic and Arctic divisions; others linked the Arctic and Atlantic, or questioned such linkages and split the Indian Ocean and Pacific Ocean or proposed more subregions (Menzies and others, 1973; Vinogradova, 1979, 1997; Carney, 1994).

A scheme sponsored by the United Nations Educational, Scientific and Cultural Organization, the Global Open Oceans and Deep Seabed (GOODS) biogeographic classification, used environmental parameters, including temperature, salinity, dissolved oxygen, carbon flux, primary production, bathymetry and plate boundary layers, to delineate biogeographic provinces, resulting in 14 abyssal provinces (Briones and others, 2009).[1]

A more recent proposal revised the 14 abyssal provinces (figure V) by giving greater weight to hydrographic patterns, particulate organic carbon flux, dissolved oxygen and the effects of cold Antarctic waters and warmer North Atlantic waters (Watling and others, 2013).

Figure V
Proposed biogeographical regions



AB1: Arctic basin
AB2: North Atlantic
AB3: Brazil basin
AB4: Angola, Guinea, Sierra Leone basins
AB5: Argentine basin
AB6: Antarctica East
AB7: Antarctica West
AB8: Indian
AB9: Chile, Peru, Guatemala basins
AB10: South Pacific
AB11: Equatorial Pacific
AB12: North Central Pacific
AB13: North Pacific
AB14: West Pacific basins

Source: Based on Watling and others, 2013.

2.5. Documented change in abyssal biodiversity

2.5.1. Evidence from palaeoecological studies

Fossil records from deep-sea sediment cores provide the only time series data longer than a few decades (Yasuhara and others, 2017, 2019b), and those palaeoecological records clearly point to long-term impacts of climatic change on abyssal biodiversity. Abyssal diversity correlates positively with bottom-water temperature over 1,000–10,000 years (Cronin and Raymo, 1997; Cronin and others, 1999; Yasuhara and Cronin, 2008; Yasuhara and Danovaro, 2016). Dynamic deepwater circulation and associated temperature changes have occurred even at multi-decadal–centennial timescales (Yashayaev and others, 2007; Hoffmann and others, 2018; Thornalley and others, 2018; Yasuhara and others, 2019b). Researchers infer great stability in abyssal biotic and environmental conditions compared with those at bathyal or shallower depths. Over larger timescales, fossil data show that present-day deep-sea fauna were established during the Miocene epoch, approximately 13 million years ago (Thomas and others, 2000; Thomas, 2007). Latitudinal diversity gradients in the deep sea that were established during the late Eocene epoch, approximately 37 million years ago, persist today (Thomas and Gooday, 1996).

2.5.2. Evidence from long-term observatories

Few long-term research programmes have obtained sufficient data to draw conclusions regarding long-term natural versus anthropogenic changes. Those that do indicate a strong connection between surface production and abyssal sea floor communities, often with a high degree of dynamism. The studies suggest that one-time or short-term investigations in the abyss cannot adequately assess biological community changes mechanistically, in particular in the context of deep-sea stewardship.

The monitoring studies of Station M off central California since 1989 strongly correlated surface ocean processes and particulate organic carbon supply to the abyss, where fluctuations affect community structure and processes. Short-term variations in Station M abyssal communities (Kuhnz and others, 2014) link to inter-annual variation in climate (El Niño/La Niña) (Ruhl and others, 2014), but long-term consequences are poorly understood. Sporadic, intense food pulses to the abyss could provide food surplus following many years of undersupply.

[1] See Intergovernmental Oceanographic Commission, IOC Technical Series, No. 84 (IOC/2009/TS/84 and Corr.).

Porcupine Abyssal Plain Sustained Observatory. Sustained observations at a depth of 4,850 m in the North-East Atlantic have produced high-resolution surface-to-sea floor data since 1989. Dramatic community and abundance shifts occur in response to organic matter influx changes (e.g., Billett and others, 2001), resulting from the tight correlation between surface productivity and export fluxes (Frigstad and others, 2015). The shifts (1989–2005) dramatically alter carbon storage. Most abyssal biota respond to food influx, environmental change and competitive interactions (Gooday and others, 2010; Kalogeropoulou and others, 2010; Lampitt and others, 2010; Soto and others, 2010). Biogeochemical results show that the partial pressure of CO_2 (pCO_2) has decreased with increasing anthropogenic CO_2 emissions (Hartman and others, 2015).

Long-term ecological research observatory Hausgarten. Data from the observatory (Fram Strait, Arctic, 250–5,500 m depth, since 1999), point to seasonal forcing of communities related to regional sea ice and hydrodynamic conditions (Soltwedel and others, 2005, 2016). Fifteen years of pelagic and benthic data indicate rapid responses of the entire ecosystem to water column changes. However, uncertainty remains as to whether trends should be attributed to anthropogenic changes or natural multi-year variability.

3. Major natural and anthropogenic pressures

3.1. Natural pressures

Natural disturbances in the form of near-bottom currents, sediment resuspension or settling food particles can dramatically alter benthic communities (Hessler and Jumars, 1974; Snelgrove and Smith, 2002). In the Atlantic, the mass movement of sediment downslope can affect the transport of organic matter to adjacent abyssal basins (Levin and Gooday, 2003). Similar processes occur during dense shelf-water cascading through canyons and slopes to abyssal depths, triggered by increased salinity and winter cooling (Carney, 2005; Company and others, 2008). Such disturbances may increase organic matter transport to abyssal depths (Canals and others, 2006; Ulses and others, 2008; Palanques and others, 2011).

Similarly, heterogeneous sea floor topography can modify the composition and abundance of species, as well as carbon remineralization rates. Such abyssal hills likely play a significant role in Pacific deep-sea communities and organic matter cycling, given their large number and the limited continental sediment supply (Smith and Demopoulos, 2003).

3.2. Anthropogenic pressures

3.2.1. Climate change

Climate change will affect abyssal physical (e.g., salinity, temperature), biogeochemical (nutrients, CO_2, oxygen (O_2), sedimentology) and biological processes and functions (Mora and others, 2013; Sweetman and others, 2017). Abyssal temperatures could increase by 1° over the next 80 years, whereas abyssal sea floor habitats beneath regions of deepwater formation may experience reductions in water column oxygen concentrations by as much as 0.03 ml per l by 2100. Such changes could affect food supply and sediment transport (Cheung and Levin, 2019; Food and Agriculture Organization of the United Nations (FAO), 2019). Climate-induced changes in ocean circulation and hydrodynamics may affect abyssal connectivity by altering distributions of the pelagic larvae of abyssal organisms (acknowledging that larvae of some abyssal taxa do not reach the upper ocean). Questions persist about how such changes impact deep ocean communities but decadal studies in the northern Pacific demonstrate significant linkages (Ruhl and others, 2008). Assessments of climate change impacts, as well as synergistic or cumulative impacts with other anthropogenic activities, must therefore consider abyssal ecosystem responses (Smith and others, 2008; Levin and Le Bris, 2015; Sweetman and others, 2017).

The food-limited nature of abyssal ecosystems suggests high sensitivity of all biota, from microbes to megafauna, to changes in phytoplankton community structure and productivity and the quantity and quality of export flux (Ruhl and Smith, 2004; Ruhl and others, 2008; Billett and others, 2010; Smith and others, 2013). Climate warming will likely increase ocean stratification, reduce primary production, increase acidity and shift dominant phytoplankton community structure, driving biotic changes over major regions of the abyss, such as the equatorial Pacific (Smith and others, 2008; Levin and others, 2020). Predictions of significant decline in organic matter flux to the deep sea floor in most oceans (Sweetman and others, 2017) contrast with predictions of increased production of water column and sea floor biomass in polar seas (Jones and others, 2014). Threats to abyssopelagic environments also include the deepening of oxygen minimum zones.

3.2.2. Plastics and other forms of pollution

Pollution has long affected abyssal depths (Chiba and others, 2018). High levels of plastic debris have been found, along with benthic organisms contaminated with organic pollutants, even at ocean depths of over 10,000 m (see chaps. 11 and 12). Few studies have documented interactions of abyssal life with debris and other pollutants but the research topic is rapidly gaining interest. Other examples of abyssal pollution include the dumping of nuclear waste prior to 1983, as described in chapter 24, section 3, of the first Assessment (United Nations, 2017b).

3.2.3. Mining

In the past few decades, interest in mineral reserves at abyssal depths has grown considerably. The future extraction of sea floor minerals, in the form of polymetallic nodules, cobalt-rich crusts, and polymetallic sulphides, pose a significant potential threat to abyssopelagic and benthic communities, directly and indirectly (Christiansen and others, 2020). Chapter 18 of the present Assessment discusses the environmental, social and economic aspects of seabed mining.

3.2.4. Anthropogenic pressures on abyssopelagic biodiversity

Although currently rare, bioprospecting and oil extraction activities on abyssal plains pose additional threats to the health of abyssopelagic and benthic habitats. Commercial fishing and fish farming on the high seas could threaten abyssopelagic diversity if poorly managed nationally and internationally. Poor management of both activities can reduce prey populations, affect food downflux and undermine biodiversity, including targeted and non-targeted resources. Although currently rare, bioprospecting and oil extraction activities on abyssal plains pose additional threats to the abyssopelagic environment.

4. Consequences of the changes on human communities, economies and well-being

Despite its apparent remoteness and inhospitality, the deep ocean plays a crucial role in human social and economic well-being through its ecosystem functions and services on a regional to global scale (Van den Hove and Moreau, 2007; Armstrong and others, 2012; Thurber and others, 2014; tables 3 and 4).

Table 3
Susceptibility of the abyssal sea floor and abyssopelagic zone to climate change-affected environmental drivers and pressures

	Abyssal sea floor impacts	Abyssopelagic impacts
Changes in temperature, acidity, salinity and oxygen patterns	Medium to high	Low
Changes in sea level	Low (through terrestrial influence)	Low (through terrestrial influence)
Changes in severity of storms and intensity of extreme events	Low	Low
Changes in ultraviolet radiation	Low, indirect through benthopelagic coupling	Low, indirect through benthopelagic coupling
Changes in the physical and chemical aspects of the ocean	Low	Low
Food input	Medium to high	Medium to high

4.1. Impacts on abyssal ecosystem services

Compared with other deep-sea habitats, abyssal plains provide ecosystem services that are limited in scope but important in magnitude and reach. Few abyssal services, such as mineral resources, could directly benefit humans, whereas most abyssal environments support the processes that drive deep-sea and global ecosystem and Earth climate system functioning on such vast scales that they influence the entire Earth system.

The "biological pump" provides the most important supporting and regulating ecosystem service of the abyssopelagic zone by accelerating the transfer of carbon, nutrients and other compounds from surface waters to the deep sea. Changes in fauna, trophic links or community composition, or physical alterations in water masses (e.g., stratification, warming, deoxygenation, acidification), can disrupt associated biological processes, with abyssal impacts through benthic-pelagic coupling. Stress imposed by low oxygen, acidification or elevated temperature can reduce species and ecosystem resilience through shifts in organism tolerance (Pörtner and Farrell, 2008; Pörtner, 2010), thus retarding recovery from disturbance caused by human activities, such as seabed mining. Climate change effects could exacerbate anthropogenic impacts and compromise deep-sea ecosystem structure and function and, ultimately, their benefits for human welfare (Mora and others, 2013).

Table 4

Threats and pressures on abyssal ecosystem services and their importance in the abyss

	Abyssal plain threats	Abyssopelagic zone threats
Provisioning services		
Fisheries	Currently none	Currently none
Oil and gas	Currently some; also indirect impact through dispersal from shelf and bathyal activity	Currently none, but indirect impact through dispersal from shelf and bathyal activity
Methane reserves/potential for gas hydrate extraction	Gulf of Mexico, potentially other areas	Not applicable
Hydrogen generation and subseabed storage for future carbon capture and disposal	Presently unknown	Not applicable
Mining (metal-rich sediments, polymetallic nodules, rare earth metals, massive sulphides)	Moderate to high in future (potential)	Moderate to high in future (potential) through mining waste and processing water discharge
Waste disposal	High (widespread)	Moderate to high (present)
Bioprospecting	Present, potentially high	High potential, unknown
Military activities and use	Unknown	Unknown
Other energy provision	Currently none	Currently none
Supporting services		
Habitat	Low to moderate and high in the future	Low to moderate and high in the future
Nutrient cycling	Moderate	Moderate
Water circulation and exchange	Moderate	Moderate
Chemosynthetic primary production	Moderate	Moderate
Resilience	High	High
Regulating services		
Gas and climate regulation	Moderate	Moderate
Waste absorption and detoxification	Moderate	Moderate
Biological regulation	Moderate	Moderate
Nutrient cycling	Moderate	Moderate
Cultural services		
Scientific knowledge	Moderate	Moderate
Educational value	Moderate	Moderate
Economic benefits	Potentially high	Potentially high
Aesthetic, inspirational, ethical, indigenous	High	High
Climatic record in deep-sea sediments	Moderate	Not applicable

5. Outlook

Many unknowns remain regarding abyssal ecosystems, but related research has increased significantly in the past decade, with more anticipated, in particular given the increasing interest in deep-sea mineral extraction. The United Nations Decade of Ocean Science for Sustainable Development (2021–2030) also includes plans for more deep-sea research.

The emergence of potential deep seabed mining to exploit polymetallic nodules poses a risk to abyssal ecosystems. However, data collected during current exploration activities may increase deep-sea knowledge in several regions over the next 10 years. Researchers frequently lament the substantial lack of taxonomic biodiversity data for most abyssal fauna. Work to collect such data is under way, but it will require much more time and resources (Glover and others, 2018).

Studies demonstrate the sensitivity of the abyss to climate change. Despite the difficulties of predicting precise climate change effects over the next 10–20 years, rising temperatures, declining oxygen concentrations, shallowing of the aragonite saturation horizon and changes in benthopelagic coupling can be expected (Rogers, 2015; Sweetman and others, 2017). Considering the slow growth rates of organisms and the fact that they are well adapted to the abyssal conditions of cold, high pressure, stability and food poverty, the impacts of predicted changes on abyssal communities will likely be more severe than those at shallower depths. Predictions of significant decreases in the flux of organic material to the deep sea floor in most oceans may be especially problematic for abyssal areas. Future research will enhance abyssal biodiversity knowledge and increase our understanding of how climate change and anthropogenic activities will affect abyssal ecosystems.

Globally, the protection of abyssal environments may increase. The Convention on Biological Diversity classification of ecologically or biologically significant areas (Secretariat of the Convention on Biological Diversity, 2008) includes those environments, and further efforts are under way through the regional environmental management plans of the International Seabed Authority in connection with seabed mining, as well as legislative developments to manage biodiversity beyond national jurisdiction.

6. Key remaining knowledge gaps

Despite recent advances in the knowledge of abyssal ecosystems, many gaps exist in understanding abyssal biodiversity, evolution, biogeography and the distributions, connectivity and responses to changing conditions and anthropogenic impacts.

The current poor state of taxonomic, natural history and biodiversity knowledge of the fauna on abyssal plains limits environmental impact monitoring and exposes the need for baseline studies that provide species lists and numbers. Given that more than 95 per cent of species in planned mining areas are undescribed, current monitoring protocols are inadequate. Despite ongoing efforts to create the necessary faunal catalogues and taxonomic knowledge (Dahlgren and others, 2016; Glover and others, 2016b; Wiklund and others, 2017), future efficient monitoring requires sustained resources.

Very few studies have examined abyssal hard-bottom habitats and, although some megafauna information exists, there is almost no information available on associated microbes, protists, meiofauna or macrofauna.

Vast areas of the abyssal sea floor remain completely unsampled. Records in international databases (e.g., the Ocean Biodiversity Information System), suggest particularly severe undersampling of the southern Pacific Ocean, as well as the deep Indian Ocean and Bay of Bengal.

Knowledge about species geographic ranges, connectivity patterns or the resilience of assemblages to climate stressors or direct human disturbance in the abyss is limited. The effective management of human activities to sustain deep-sea biodiversity hinges upon such information. In addition, poor characterization of abyssal contributions to ecosystem goods and services limits the availability of appropriate tools to value human benefits adequately (Jobstvogt and others, 2014a, 2014b; Thurber and others, 2014).

The lack of documentation on and relating to the management of human impacts on such a vast, dynamic space, almost all of which is located beyond national jurisdictions, may represent the single most important knowledge gap.

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