Undisturbed
The deep ocean's vital role in safeguarding us from crisis

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Contents

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Cover Image: A squat lobster perches atop a Bubblegum Coral on the San Juan Seamount in the Southern California Borderland. The image was taken by Remotely Operated Vehicle SuBastian as researchers investigated several sites where marine minerals are known (or expected) to occur, while assessing the biological communities living amongst the mineral substrates. © Schmidt Ocean Institute

1. Introduction

Our planet is changing due to our actions. Human-driven climate change is an outsized driver of these planetary changes, affecting nearly every Earth system and process, including those in the ocean. Today, even our planet's most inaccessible realm, the deep ocean, defined as all areas below 200 meters, is not left untouched, and with the 'Blue Acceleration' advancing (Jouffray *et al.*, 2020), the associated impacts could be amplified. That is why it is vital that we look to the future and take actions that recognize and protect the role of the deep ocean in mitigating climate change and build resilience to its impacts.

The urgent need to address the unprecedented changes humanity is causing to the deep ocean is increasingly being recognized, with several decision-making processes underway that could be pivotal to our stewardship of the planet. Annual negotiations are taking place in November 2022 at the 27th Conference of Parties (COP 27) to the United Nations Convention on Climate Change (UNFCCC) to implement the Paris Agreement, with decisions that are critical to getting runaway climate change under control (UNFCCC, n.d.). Fortunately, recent years have seen greater efforts to integrate the ocean into climate change negotiations. At COP 26, the UNFCCC mandated in decision 1/CP.26 that the Subsidiary Body for Scientific and Technological Advice (SBSTA) hold an annual dialogue on Ocean and Climate Change to consider how to strengthen ocean-based action on climate change. This followed the December 2020 Ocean and Climate Change Dialogue, which was the first UNFCCC forum for Parties and non-Party ocean stakeholders to give their perspectives on how the climate regime should address ocean-related climate mitigation and adaptation (Dobush *et al.*, 2021).

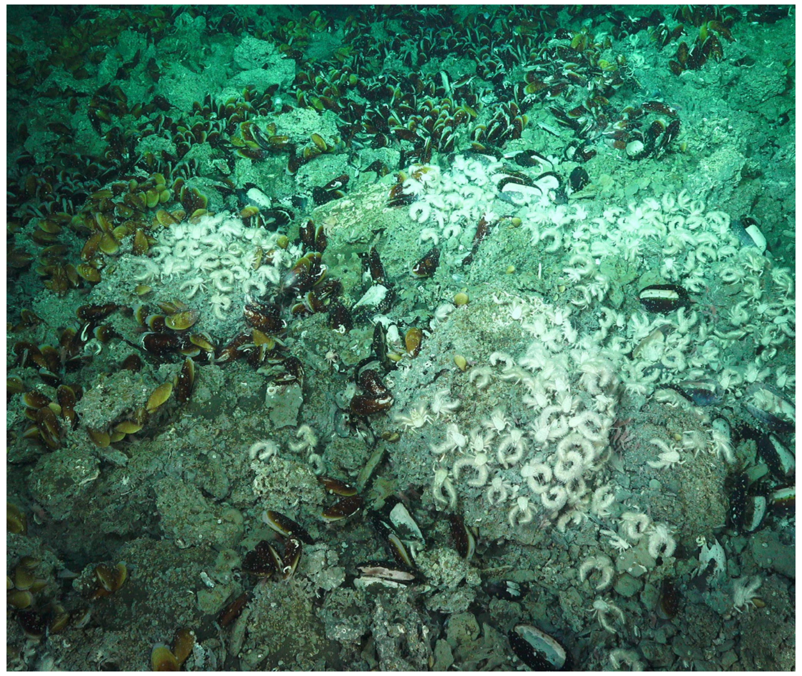
Beyond the UNFCCC, there are several other ocean-related international negotiations that touch on and influence, but do not directly govern, climate change. These include negotiations that are close to heralding a commitment to protect 30% of the ocean by 2030 at the 15th Conference of the Parties to the Convention on Biological Diversity (COP 15) in December 2022 (UNEP, n.d.); negotiations to agree a new global treaty for managing marine biodiversity in areas beyond national jurisdiction at the United Nations (Helm *et al.*, 2021; UN, 2022); and the agreement to eliminate harmful fisheries subsides reached at the World Trade Organization in June 2022 (Sumaila *et al.*, 2021). And, in a process of huge importance to the deep ocean, the International Seabed Authority (ISA) is under pressure to rapidly finalize international regulations by mid-2023 that would subsequently enable deep-seabed mining to begin (Singh, 2022).

In this synthesis report, we highlight the essential planetary roles that the deep ocean plays in the functioning of our planet, including in buffering climate change, and identify the current and impending impacts that human activities are having on this critical ecosystem. We urge others to seize the rare opportunity offered by the international processes listed above, to together take the actions needed to manage this vast and still relatively pristine part of the planet – so vital to Earth's climate and biodiversity and the wellbeing of humanity – via holistic, science- and evidence-based, integrated governance.

Deep water octopus at nearly 1200 meters depth, Ribbon Reef Canyons, 170km northeast of Cairns, Australia. © Schmidt Ocean Institute

2. Why is the deep ocean important for the planet?

The deep ocean accounts for more than 95% of the volume of the ocean. It is essential to a healthy, functioning planet through the provision of multiple ecosystem services (Thurber *et al.*, 2014; Le *et al.*, 2017; Danovaro *et al.*, 2017). The deep ocean also provides a range of vital resources, including marine genetic resources with actual or potential pharmaceutical, industrial, and manufacturing uses, as well as the ecosystems that support commercial fisheries (Thurber *et al.*, 2014; Le *et al.*, 2017). Additionally, the sheer size of the deep ocean means that it plays a critical role in many of Earth's regulatory processes, including elemental and nutrient cycling and waste absorption (Thurber *et al.*, 2014; Le *et al.*, 2017).



Carbon is captured in carbonate rocks and by microbes associated with mussels and yeti crabs at a Costa Rican methane seep. © Schmidt Ocean Institute - Eric Cordes Chief Scientist

Surface waters above shallow-water methane seeps have been found to have twice the rate of atmospheric CO_2 uptake compared to surrounding waters, as primary production is stimulated by cold, nutrient-rich waters that rise to the surface with the methane released from the seafloor, indicating a similar mechanism may exist in the deep sea.

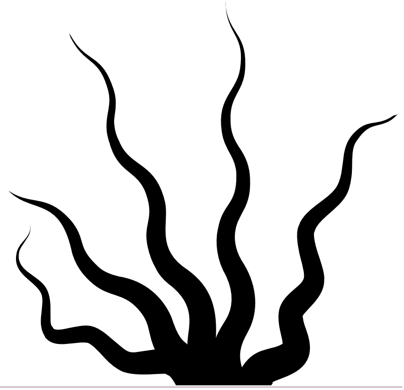
The deep ocean also helps to regulate Earth's climate by absorbing and storing over 90% of the excess heat (Trenberth, 2020) and approximately 38% of the carbon dioxide (CO_2) generated by human activities (Friedlingstein *et al.*, 2019; Gloege *et al.*, 2021; Laffoley *et al.*, 2021). Seawater has the greatest heat capacity of any component of Earth's climate system, which allows huge quantities of solar energy to be stored in the ocean and prevents the Earth's surface from overheating (Faizal & Ahmed, 2011). The ocean can absorb as much as 97% of the solar radiation that hits its surface, whereas land only absorbs about 3% of the heat from global warming, with the atmosphere absorbing even less (Trenberth, 2020). This heat is redistributed from the surface to the depths by ocean currents driven by changes in water density. Marine sediments represent a large and globally important carbon sink, storing twice the amount of carbon in the top meter of sediment on the seafloor compared to terrestrial soils (Atwood *et al.*, 2020). It is estimated that 3,117 gigatons of carbon are stored in marine sediments globally, making the ocean the world's largest pool of sediment/soil carbon stocks, 75% of which is stored within the sediments of the abyss/basin zones (Atwood *et al.*, 2020).

Beyond these seafloor sediments, deep ocean biota and ecosystems also play critical roles in the transport, transformation, storage and sequestration of carbon via carbon dioxide and methane (Hilmi *et al.*, 2021). As mesopelagic fish and zooplankton undertake their daily migration through the water column, they export large quantities of carbon from the ocean's surface layer, where they feed at night, down to deeper waters where they return during the day (Davison *et al.*, 2013; Trueman *et al.*, 2014; Turner, 2015; Steinberg & Landry, 2017; Saba *et al.*, 2021). This diel migration is a major contributor to the export of carbon, with fish alone estimated to contribute 16% of the total carbon flux out of the euphotic zone (Saba *et al.*, 2021). During their lifetime, large marine vertebrates, including whales and large fish such as tuna, billfish and sharks, store vast amounts of carbon (Pershing *et al.*, 2010; Mariani *et al.*, 2020). After their death, this carbon is transported from the euphotic zone to the seafloor as the carcass sinks to the bottom, where it supports deep-sea ecosystems and is incorporated into marine sediments. In addition, whale excrement stimulates primary production through iron fertilization, which in turn enhances carbon export to the deep sea (Lavery *et al.*, 2010).

Methane (CH_4) is a greenhouse gas that is 28 to 84 times as powerful as CO_2 in warming the atmosphere (Myhre *et al.*, 2013). At methane seeps, large amounts of carbon are emitted from the seafloor in the form of methane. This fuels specialized microbial and animal communities that remove, transform or sequester this carbon, preventing it from reaching the atmosphere and exacerbating climate change by serving as sinks for methane-derived carbon (Grupe *et al.*, 2015; Levin *et al.*, 2016; Le *et al.*, 2022). Anaerobic methane oxidation (AOM) performed by a consortium of bacteria and archaea living in seep sediments consumes about 80-90% of the methane at the seafloor (Reeburgh, 2007). A byproduct of this process is the formation of carbonate rock, which can support active microbial communities that represent another key methane sink (Marlow *et al.*, 2014). Many larger seep animals, including some polychaetes, sponges and mussels, host symbiotic aerobic methane oxidizing microbes that also remove methane (Dubilier *et al.*, 2008; Goffredi *et al.*, 2020) and convert the carbon to biomass or carbonate shells. Surface waters above shallow-water methane seeps have been found to have twice the rate of atmospheric CO_2 uptake compared to surrounding waters, as primary production is stimulated by cold, nutrient-rich waters that rise to the surface with the methane released from the seafloor, indicating that a similar mechanism may exist in the deep sea (Pohlman *et al.*, 2017).

Brisingid starfish, sponges and octocorals on San Juan Seamount. © NOAA OER and Ocean Exploration Trust

Despite their huge carbon absorption and storage potential, many of these deep-sea climate mitigation pathways remain unrecognized, unquantified and some may even be undiscovered. However, with the current global push to reduce emissions and enhance carbon sequestration, the conservation of deep-ocean ecosystems and the vital services they provide is taking on added significance and urgency (Le *et al.*, 2022).



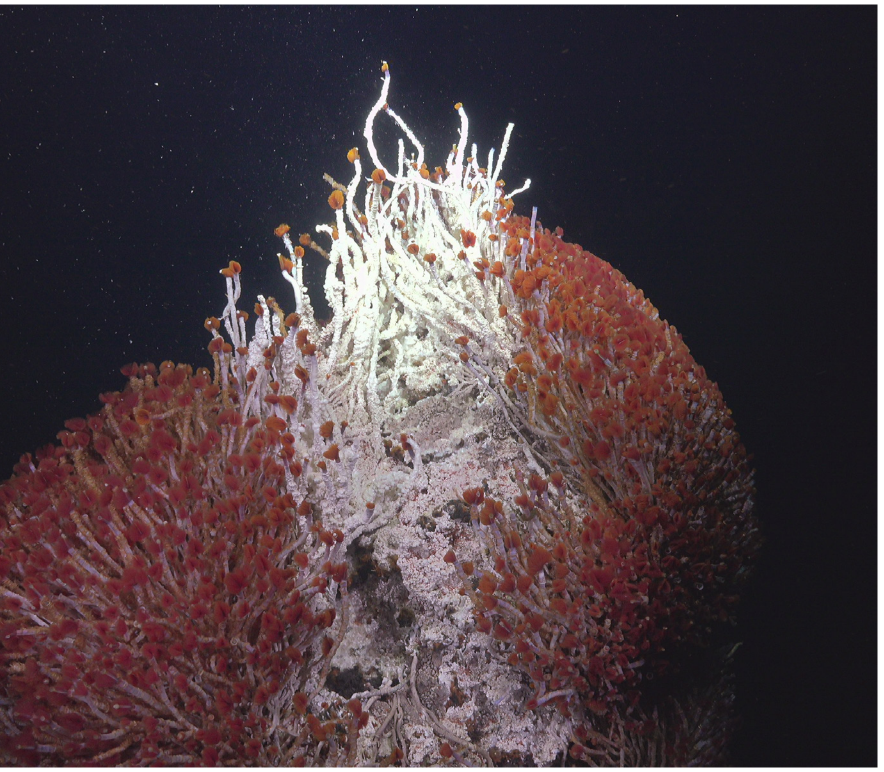
3.

What will the increasing impacts of climate change mean for the deep ocean and the planet?

Much of what is known about the impacts of climate change on the ocean comes from the well-studied surface layer, above 200 meters (Brito-Morales *et al.*, 2020). Deep-ocean ecosystems have long been thought to be less impacted by climate change compared to shallower waters, which experience much greater fluctuations in temperature, oxygen, salinity, and food availability (Narayanaswamy & Foley, 2016). However, a growing body of research is revealing that climate change impacts are occurring at unprecedented rates in the deep ocean, over very short timescales. These impacts are leading to a less oxygenated, more acidified, warmer deep ocean, with potentially dire consequences, not only for deep-ocean life but also for the ecosystem services the deep ocean provides (Levin & Le Bris, 2015; Narayanaswamy & Foley, 2016; Sweetman *et al.*, 2017).

Climate change is particularly problematic for the deep ocean because (with a few exceptions) it is an incredibly stable environment where fauna have evolved to survive within a very narrow range of physico-chemical conditions (Danovaro *et al.*, 2004; Danovaro *et al.*, 2017). Although the deep ocean is expected to experience the smallest changes in biogeochemical parameters (oxygen, temperature, and pH) amongst all marine habitats over the 21st century (Bindoff *et al.*, 2019), the impact on its fauna may be greater than in shallow-water environments. That is because many sessile and demersal deep-ocean fauna have physiologically evolved to live within a very narrow temperature range due to limited daily and seasonal variations (Yasuhara & Danovaro, 2016).

The Matterhorn, a hydrothermal vent of Pescadero basin displaying an abundance of red tube worms and white microbial mats Image made during expedition studying the Auka Hydrothermal Vent Field. © Schmidt Ocean Institute



The deep ocean is also particularly sensitive as the majority of its ecosystems rely on the external input of organic matter from the ocean's surface waters as a primary food source (Smith *et al.*, 2008; Danovaro *et al.*, 2017), so the impacts of climate change on surface productivity, processes, and fauna have a direct effect on the deep ocean (Danovaro *et al.*, 2017). Additionally, many deep-ocean species are long lived, have low fecundity, and are late to mature, decreasing their ability to cope with change and increasing their vulnerability to climate change impacts (Levin & Le Bris, 2015; Danovaro *et al.*, 2017; Clark *et al.*, 2019).

Due to the vast size of the deep ocean, the absence of long-term datasets, and the difficulties associated with conducting research in such a challenging and remote environment, the full extent of climate change impacts on the deep ocean remains unknown (Levin, 2021). However, the following sections summarize the major expected impacts.

3.1 Increasing temperatures

The temperature of the deep ocean varies considerably by depth, ocean basin, and water masses, with marginal seas such as the Red Sea experiencing temperatures over 20˚C at 2,000 meters, compared to the global average of 2.5˚C at the same depth (Yasuhara & Danovaro, 2016). Warming of the deep ocean is predicted to vary by ocean basin. According to the models developed in the Coupled Model Intercomparison Project phase 5 (CMIP5), the greatest changes are projected to occur in the Atlantic, Southern and Arctic basins, where water temperatures at bathyal depths (200 m – 3,000 m) may increase by up to 4.4˚C, 1.7˚C and 3.7˚C, respectively, by 2100 relative to present-day temperatures (Sweetman *et al.*, 2017).

Temperature increases, as well as associated oxygen and productivity loss, will impact deep-ocean species, causing those able to move to shift their ranges, while those unable to move (e.g., corals and sponges) may experience impaired health and death. Changes in seawater temperature are a known cue for spawning in some species, including deep-ocean *Calyptogena* bivalves (Fujikura *et al.*, 1998; Fujikura *et al.*, 2007), one of the dominant taxon at some hydrothermal vents and methane seeps. Even a small change in ambient water temperature could therefore affect the reproduction of deep-ocean species. Increases in sea temperature have also caused invasions of deep-ocean habitats by temperature-limited taxa, such as lithodid crabs in the Palmer Deep on the west Antarctic Peninsula shelf, which have been attributed to major modifications of benthic ecosystems and reductions in species diversity (Smith *et al.*, 2012).

Climate change induced temperature changes in the deep ocean are not only altering the distribution of marine species, there are also physico-chemical impacts. For example, the warming of the western North Atlantic caused by changes in the flow and temperature of the Gulf Stream over the last 5,000 years has destabilized 2.5 gigatons of methane hydrate stored in the sub-seafloor (Phrampus & Hornbach, 2012). Further increases in water temperature could release more methane into the water column, and ultimately into the atmosphere, contributing to global warming (Mienert, 2012). Additionally, water temperature has been key to the formation of the mesopelagic zone over the last 15 million years, increasing the efficiency of the ocean's biological carbon pump, and allowing marine life to thrive and diversify (Boscolo-Galazzo *et al.*, 2021). The central role of temperature in the evolution of this vast deep-ocean ecosystem means the mesopelagic may be vulnerable to anthropogenic warming, which has the potential to disrupt the efficiency of the biological pump.

One of the most concerning aspects of temperature rise in the ocean is that, while curtailing emissions and limiting global temperature rise to under 2˚C may limit the large-scale redistribution of marine life in the top 200 meters of the ocean, the deep ocean will continue to warm, leading to potentially major impacts on the deep ocean and its biodiversity (Brito-Morales *et al.*, 2020).

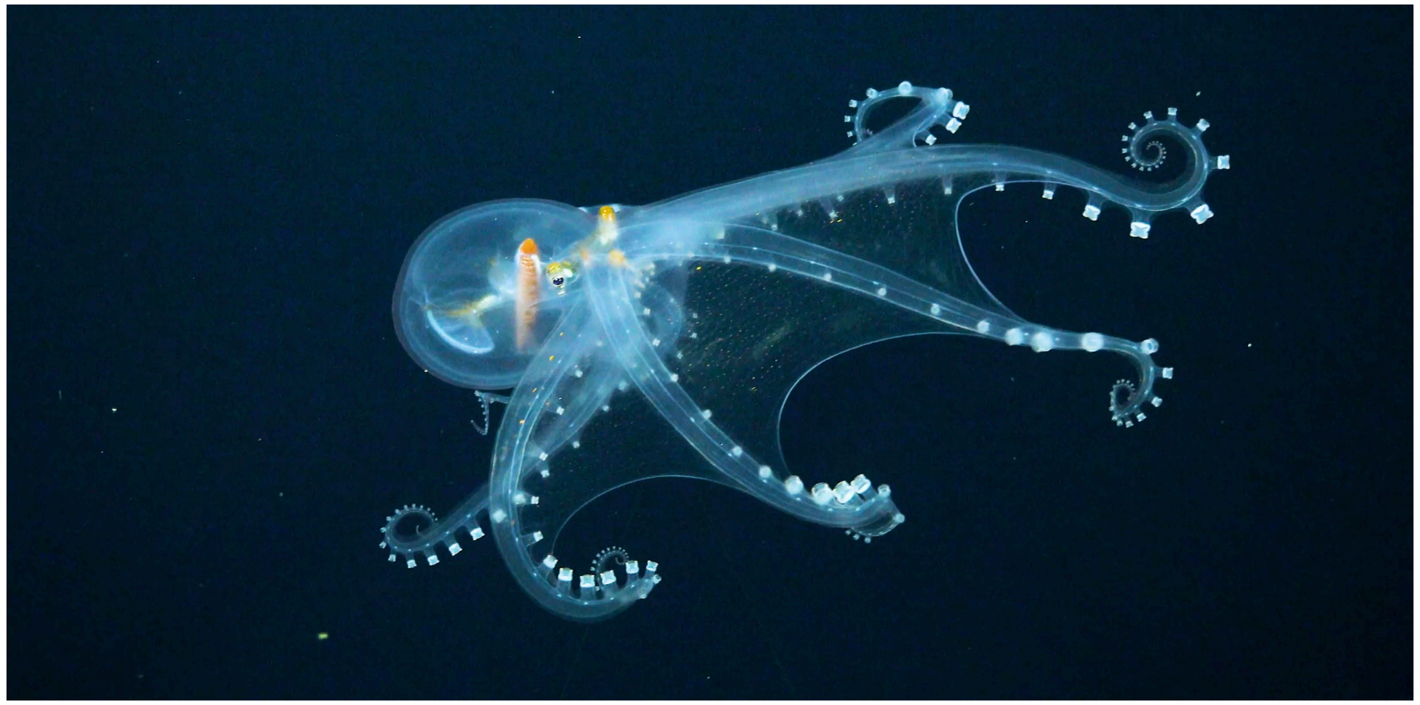
3.2 Increasing acidification

Ocean acidification is a reduction in the pH of the ocean over an extended period of time, caused primarily by an increase in CO_2 being absorbed from the atmosphere. The pH of the surface ocean (<200 m) has declined by 0.1 pH units since the Industrial Revolution, equivalent to a ~26% increase in acidity (IPCC, 2013). And, according to the Shared Socio-economic Pathways (SSPs) used in CMIP6, future projections for the deep ocean do not fare much better: under the more optimistic SSP1-2.6 scenario, the end-of century model mean change (2080–2099 relative to 1870–1899) in bottom-water pH is −0.018 ± 0.001, while under SSP5-8.5, the corresponding change in pH is −0.030 ± 0.002 (Kwiatkowski *et al.*, 2020). Under the most severe warming scenario (RCP8.5), 23% of deep-ocean canyons and 8% of seamounts, including seamounts proposed as marine protected areas, are forecast to experience pH reductions exceeding −0.030 ± 0.002 (Gehlen *et al.*, 2014; Kwiatkowski *et al.*, 2020).

Rapid ocean acidification occurred 66 million years ago, when surface ocean pH declined by 0.25 pH units in the 1,000 years following a meteorite impact, causing a mass extinction of marine life. This resulted in ecological collapse in the ocean due to a decline in primary productivity, which had long-term effects on nutrient export, global carbon cycling, and the climate. Although primary productivity in the surface ocean recovered relatively quickly, the reinstatement of carbon export to the deep ocean took much longer, showing that acidification events can have prolonged and extreme impacts on deep-ocean fauna and functioning (Henehan *et al.*, 2019).

Despite there being limited research into acidification impacts on the deep ocean, it is expected that acidification will result in lower calcite and aragonite saturation states. This will limit calcification and growth in species such as long-lived, habitat-forming cold-water corals, leading eventually to their loss (Roberts *et al.*, 2006; Ross *et al.*, 2020), and dissolve the non-living components of cold-water coral reefs (Bindoff *et al.*, 2019). This impact may be amplified in the deep ocean, given the lower carbonate saturation state at depth, with deep-ocean cold-water coral reef ecosystems even more vulnerable to the effects of ocean acidification than their shallow water counterparts (Roberts *et al.*, 2006). This will likely contribute towards the fragmentation of coral populations by reducing the areas of suitable habitat, thus increasing the risk of extinction (Thresher *et al.*, 2015). Ocean acidification will also affect the structural complexity of the dead reef framework of cold-water corals – which offer a hard substrate for colonization by diverse faunal and microbial communities – by reducing porosity of the skeletons and increasing bioerosion, ultimately affecting the important ecosystem services they provide (Maier *et al*, 2021).

A glass octopus, a nearly transparent species whose only visible features are its optic nerve, eyeballs and digestive tract. © Schmidt Ocean Institute



3.3 Increasing deoxygenation

Oxygen is fundamental to life on Earth. Not only is it essential to respiration, but it fuels biogeochemical cycles of carbon and major nutrients (Keeling et al., 2010; Breitburg *et al.*, 2018). Decreasing oxygen conditions (i.e., deoxygenation) can have significant and pervasive effects on deep-sea marine life, leading to a loss of habitat, biodiversity and biomass (Laffoley & Baxter, 2019), and affect biogeochemical cycles (Breitburg *et al.*, 2018). As ocean temperature increases, oxygen becomes less soluble, resulting in decreased dissolved oxygen content and increased stratification (further accelerating deoxygenation), as well as a slowdown of deep-ocean ventilation (Keeling *et al.*, 2010; Brietburg *et al.*, 2018; Gao *et al.*, 2019; Sallée *et al.*, 2021). The deep ocean is projected to experience declines in oxygen content of up to 3.7% at bathyal depths (200 m to 3,000 m) by 2100 (Sweetman *et al.*, 2017). The Southern Ocean, North Atlantic and equatorial Pacific are projected to experience the greatest declines (Kwiatkowski *et al.*, 2020; Oschlies *et al.*, 2021), but some local regions (e.g., St. Lawrence Estuary, Central and Southern California) have already experienced declines of 20-40% (Levin, 2018).

Deoxygenation leaves less oxygen available for the basic physiological functions and processes necessary to sustain populations (Pauly & Cheung, 2018), leading to structural shifts in communities (Clarke *et al.*, 2022), and in some instances direct mortality. The lethal threshold of hypoxia varies across taxa, reflecting differences in their ability to adapt to oxygen-depleted conditions (Vaquer-Sunyer & Duarte, 2008). Some species are tolerant of severe hypoxia and can even thrive, reaching high density aggregations (Pineda *et al.*, 2014), however this is not the case for most marine species (Levin & Gallo, 2019). Lower oxygen conditions can directly impact the physiology of marine organisms, reducing growth rates (Pauly, 2021), and deoxygenation has been linked to a decrease in the body size of commercially important fish species (Orio *et al.*, 2022). Under a high-emission scenario, fish maximum body weight could decline by 14-20% between 2000 and 2050 due to a warmer, less-oxygenated ocean (Cheung *et al.*, 2012). Studies have also found reproduction in marine fishes to be impaired by low oxygen conditions (Wu *et al.*, 2003; Wang *et al.*, 2016; Thomas & Rahman, 2018). The consequences of reduced growth and reproduction as a result of deoxygenation include an increased risk of predation, reduced survival, reduced recruitment, and altered population demographics (Claireaux & Chabot, 2019).

Tubeworms and iridescent scale worms documented on an exploratory dive to a suspected hydrothermal feature detected during seafloor mapping surveys between Auka and the JaichMaa 'ja'ag Vent Fields. © Schmidt Ocean Institute

Since the 1960s, oxygen minimum zones (OMZs) between 200 and 700 meters depth have expanded both vertically and horizontally throughout the tropical and subtropical ocean (Stramma *et al.*, 2010). The expansion of OMZs is known to restrict species' depth distributions by reducing their usable habitat. This expansion not only impacts species' presence and community composition through crowding, forced departure from preferred habitats, altered migration routes, and increased mortality risks from both natural predation and fishing pressure, but also affects the ecosystem services provided (Ramirez-Llodra *et al.*, 2011). For instance, commercially important species, such as sharks, marlin, tuna and sailfish, have been pushed into shallower depths, thereby potentially increasing their vulnerability to overexploitation (Prince & Goodyear, 2006; Prince *et al.*, 2010; Stramma *et al.*, 2012; Vedor *et al.*, 2021). Observations in areas with naturally low oxygen conditions lead us to expect that deep-ocean communities will show reduced diversity (Levin, 2003; Ramirez-Llodra *et al.*, 2011; Sperling *et al.*, 2016).

Low oxygen concentrations can also disrupt biogeochemical cycling, resulting in fundamental changes to the productivity of the ocean, by altering the sources, sinks and cycling of key biological elements (Conley & Slomp, 2019). Fundamental changes in nitrogen cycling have been observed under severe ocean deoxygenation, including during past oceanic anoxic events, because ammonium, rather than nitrate, becomes the main component of fixed nitrogen and the fixed inventory relative to phosphorus collapses. These changes are particularly pronounced in the deep ocean, which becomes highly depleted in readily bioavailable nitrogen relative to phosphorus (Naafs *et al.*, 2019).

3.4 Changes to deep-ocean food supply

Deep-ocean benthic ecosystems, with the exception of cold seeps and hydrothermal vents, are reliant for their food supply on particulate organic carbon (POC) produced in the ocean's sunlit layer, which sinks through the water column to the seabed (Danovaro *et al*., 2017; Smith *et al.*, 2008). Areas of the abyssal seafloor where POC levels are high are often hotspots of biodiversity and support microbial communities that are crucial to ocean carbon cycling and sequestration (Smith *et al*., 2009).

Increased warming of surface waters and continental margins, along with decreased nutrient supply and increased stratification, will likely reduce productivity and phytoplankton size and species diversity, leading to a reduction in POC flux to the seafloor (Yool *et al.*, 2013; Yool *et al.*, 2017). Under scenario RCP8.5 (with regional variations), by the end of the century there will be a projected decrease in upper ocean export of POC to the deep seafloor, resulting in a loss of animal biomass on the deep seafloor by between 5.2 and 17.6% compared to present (2006–2015) levels (Bindoff *et al.*, 2019). Based on the models developed as part of CMIP5, there could be as much as a 40% reduction in POC flux at the abyssal seafloor and 55% at the bathyal seafloor by 2100 (Sweetman *et al.*, 2017). This will affect deep-ocean benthic biomass, leading to both overall declines and a size-shift towards small organisms. For example, reductions in carbon export flux to the mesopelagic and deep-sea ecosystems could lead to the biomass of abyssal meio- and macrofauna declining (by 2081–2100 relative to 1995–2014) by −9.8% under SSP1-2.6, and by −13.0% under SSP5-8.5 (Cooley *et al.*, 2022).

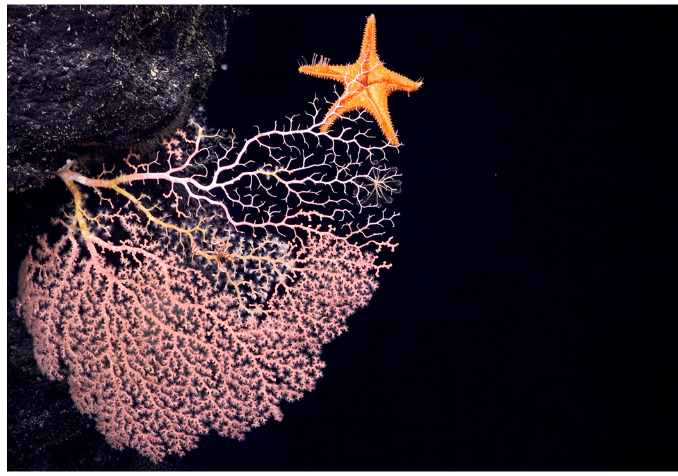
Globally, more than 80% of deep-sea biodiversity hotspots, including cold-water coral reefs, seamounts and canyons, are projected to experience declines in biomass (Jones *et al.*, 2014). Under RCP8.5, reduced particulate food supply is projected to be experienced by 95% of cold-water coral ecosystems by 2100 relative to the present , leading to a very likely 8.6% (± 2%) biomass loss (Bindoff *et al.*, 2019). The abyssal and hadal zones are expected to experience the greatest changes in biomass as these environments are already food limited (Jones *et al.*, 2014). These changes will have major consequences for deep-seafloor ecosystems, causing local extinctions and altering the provision of ecosystem services including carbon burial, deep-water fisheries, and nutrient cycling (Smith *et al.*, 2008; Jones *et al.*, 2014; Sweetman *et al.*, 2017).

3.5 Indirect impacts

Increasing temperatures, deoxygenation and acidification, as well as changes to deep ocean food supplies and productivity, will have profound impacts on biodiversity and ecosystem functioning and lead to indirect impacts on the size and distribution of important global fish stocks.

Climate velocities, which estimate the rate and direction at which species need to shift their ranges to remain within their preferred temperature range, are commonly used to estimate how climate change will affect species distribution (Loarie *et al.*, 2009; Brito-Morales *et al.*, 2018; 2020). Under future climate change scenarios, the rate of deep-ocean climate velocities will increase. For example, even under RCP2.6 CMIP5 models, by 2100 the climate velocity in the mesopelagic layer (200 m to 1000 m) would be seven times higher than current levels, and four times the rate currently experienced at the surface (Brito-Morales *et al.*, 2020).

The daily vertical migration of mesopelagic fauna makes them a vital component of global biogeochemical cycles. By feeding in the surface layer at night and excreting their waste at depth during the day, mesopelagic fish transport organic carbon from the ocean's surface to the deep and represent a trophic link between plankton and higher predators (Irigoien *et al.*, 2014). The extent of the climate change impact on mesopelagic fishes and oceanic carbon cycling is unknown, but given that mesopelagic fishes also constitute a major food source for other marine animals (Naito *et al.*, 2013; Goetsch *et al.*, 2018), changes to their biomass could have additional knock-on effects, including on oceanic food webs and on a number of highly profitable fisheries, such as tuna (Droplaug, *et al.*, 2016; Laptikhovsky *et al.*, 2021), billfishes and squid (Markaida, 2006; Dunn, 2009).



A corallivorous deep-sea sea star *Evoplosoma* eats live precious coral (*Corallium*) at a depth of 2,004 meters on a previously unexplored high seas seamount. © Schmidt Ocean Institute

Distributional changes in fish stocks are anticipated due to oceanographic changes associated with climate change. A poleward shift in many species is already underway as a result of consistent warming of sea temperatures and changes in circulation (Nye *et al.*, 2009). Species are also moving into deeper waters as temperatures rise. Commercially important deep-sea fishes in the North Atlantic are projected to experience a reduction in suitable habitat and a shift towards higher latitudes due to climate change. By 2100, under RCP8.5, the suitable habitat is projected to decrease by 30% - 50% for American plaice (*Hippoglossoides platessoides*) and Atlantic Cod (*Gadus morhua*), by 10% - 15% for Greenland halibut (*Reinhardtius hippoglossoides*), and by 2% - 25% for round nosed grenadier (*Coryphaenoides rupestris*) (Morato *et al.*, 2020). By contrast, for some commercially exploited deep-sea fish species, such as Blackbelly rosefish (*Helicolenus dactylopterus*) and beaked redfish (*Sebastes mentella*), climate change is projected to lead to an expansion of suitable habitat by 2100 (Morato *et al.*, 2020).

Cheung *et al.* (2022a) examine the population viability under climate change for 32 species of exploited demersal deep-sea species across the global ocean, combining a fuzzy logic expert system with species biogeographical data to assess the risks of climate impacts. Their findings show that climatic hazards are projected to exceed historical variability for all habitats studied by 2050. High risk from climate impacts and fishing are identified for Antarctic toothfish (*Dissostichus mawsoni*), rose fish (*Sebastes norvegicus*), roughhead grenadier (Macrourus berglax), Baird's slickhead (*Alepocephalus bairdii*), cusk (*Brosme brosme*), and Portuguese dogfish (*Centroscymnus coelepis*). Demersal fish populations in the northern Atlantic Ocean and the Indo-Pacific region are found to be most at risk. Cheung *et al.* (2022a) suggest that Regional Fisheries Management Organizations (RFMOs) have an obligation to incorporate climate change in their deliberations.

Indirect impacts from climate change will also be experienced on and within the seafloor. For example, the distributions and abundances of benthic animals profoundly influence the cycling and storage of carbon and other elements in marine systems, and will likely experience changes (Bianchi *et al*., 2021).

4. Climate change and the increasing use of the deep ocean

Deep-sea habitats are not only under threat from climate change stressors but are also at risk from increasing human activities. Extractive activities such as deep-sea fishing and oil and gas extraction have already been underway for decades, a nascent deep-sea mining industry could be targeting minerals from hydrothermal vents, abyssal plains and seamounts as soon as 2023, and ocean-based climate interventions that affect the deep sea are being proposed with greater frequency. The disturbance caused to the deep sea by these activities will interact with climate change stressors, further reducing the resilience of deep-sea organisms and ecosystems, and exacerbating impacts (Sweetman *et al.*, 2017; Levin *et al.*, 2020). And all this is further complicated by a lack of scientific information about the deep ocean, about how these impacts will synergize, and about the potential mitigation routes. These deep-sea activities are summarized in more detail below.

4.1 Deep-sea oil and gas extraction

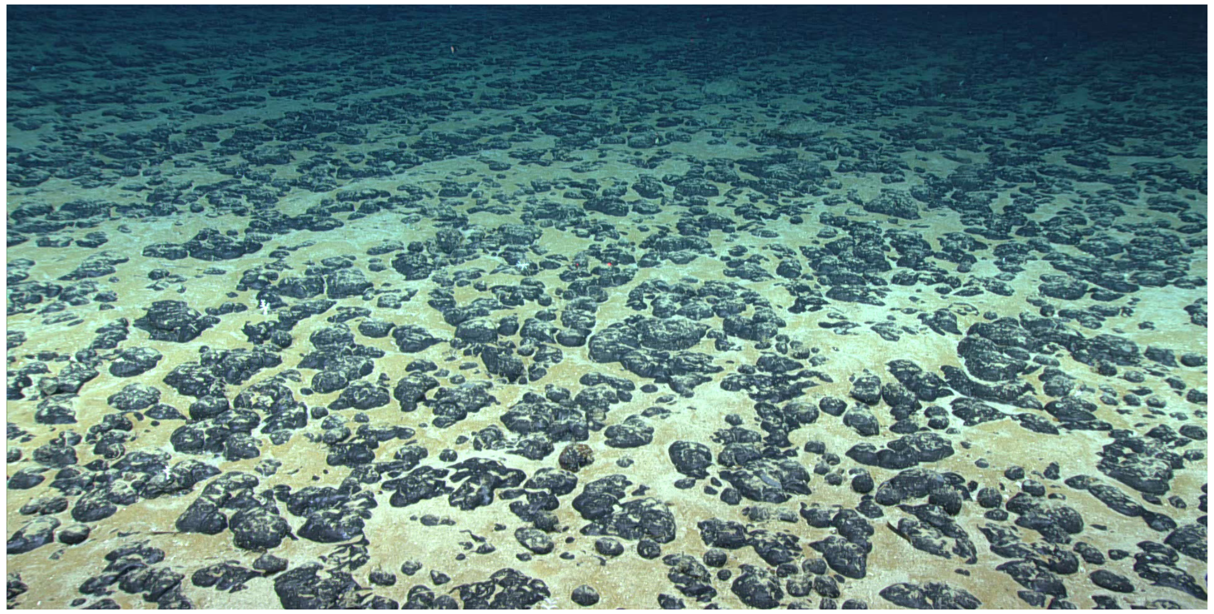
Increasing deep-sea oil and gas extraction on a global scale is challenging for a number of reasons (Cordes *et al.*, 2016). Not only does it reduce deep-sea resilience by exacerbating climate change through the extraction and subsequent burning of oil and gas, and the associated increase in emissions, but there are additional direct impacts to deep-sea biodiversity, ecosystems and functioning from the extraction process itself, as well as from spills and blowouts. Infrastructure installation, including sediment resuspension and burial by seafloor anchors and pipelines, as well as discharges of water-based and low-toxicity oil-based drilling muds and produced water, all have physical and ecological impacts (Cordes *et al.*, 2016). The direct impacts, although on a relatively small scale, may persist in the deep sea for many years or even centuries, especially in more fragile ecosystems, such as cold-water corals.

4.2 Deep-sea fishing

Technological innovations have resulted in fishing occurring with greater intensity and in deeper waters. This has impacts on climate resilience in four main ways. First, the expansion of fisheries is preventing blue carbon sequestration in the deep ocean for thousands or even millions of years by removing the carcasses of large marine fish and other species from the ocean (Mariani *et al.*, 2020). Second, government subsidies have enabled fishing fleets to travel vast distances and burn large amounts of fossil fuels to reach remote fishing grounds in the high and deep seas, therefore emitting many millions of metric tons of atmospheric carbon dioxide (Mariani *et al.*, 2020; Sumaila *et al.*, 2021). Third, these subsidies sustain fishing activities even when fish stocks and catch rates are low because of overexploitation, or unsustainable in the case of most deep-sea stocks.

Deepwater drilling ship in operational condition at oil field. © M.Afiqsyahmi/ Shutterstock

Seafloor explored during the 2019 Southeastern U.S. Deep-sea Exploration - covered with manganese nodules. © NOAA Office of Ocean Exploration



Finally, deep-sea trawling in particular is known to be extremely damaging from both biodiversity and climate perspectives. The effects of trawling on deep-seafloor habitats and communities can be severe, especially as many fishing grounds correspond with vulnerable marine ecosystems (VMEs) and/or ecologically and biologically significant areas (EBSAs), which are home to long-lived and fragile habitat-forming animals, such as deep-sea corals and sponges (Williams et al., 2010; Ramirez-Llodra *et al.*, 2011; Clark *et al.*, 2016). Furthermore, marine sediments are the largest pool of organic carbon on the planet and a crucial reservoir for long-term carbon storage, locking away carbon for millennia if left undisturbed (Estes *et al.*, 2019; Atwood *et al.*, 2020).

Disturbance of these carbon stores by trawling and other activities can remineralize sedimentary carbon to CO_2, which is likely to increase ocean acidification, result in a decline in the buffering capacity of the inorganic carbonate system, and reduce the ocean's ability to absorb atmospheric CO_2 (Sala *et al.*, 2021; Epstein & Roberts, 2022). This could lead to a positive feedback mechanism whereby the ocean's role in buffering global climate change reduces, while ocean acidification accelerates. This process is expected to occur much more rapidly with the expansion of human activities in the deep ocean, as demonstrated by industrial bottom trawling, which is estimated to result in one gigaton of aqueous CO_2 emissions every year on average due to carbon sediment remineralization (Sala *et al.*, 2021). As well as disturbing marine-sediment carbon stores, trawling can also lower rates of carbon sequestration on the deep seafloor by reducing deep-sea biodiversity and biomass, given the critical role played by deep-sea pelagic and benthic life.

4.3 Deep-sea mining

The nascent industry of deep-sea mining (DSM), if permitted to go ahead, would lead to biodiversity loss and disruption of ecosystem services on an enormous spatial and temporal scale (Amon *et al.*, 2022a). This would be through the direct removal and destruction of seafloor habitats along with their unique fauna. Sediment plumes created from seafloor disturbance and the return of sediment-laden wastewater will extend the impacts of DSM horizontally and vertically for tens to hundreds of kilometers. Additionally, there will be contaminant releases, changes to water properties, and increases in noise and light in the deep ocean.

A recent study showed that, 26 years after simulated disturbance from deep-sea mining, carbon cycling in benthic food webs, biogeochemical cycling, and rates of organic matter remineralization had still not recovered (Stratmann *et al.*, 2018; Vonnahme *et al.*, 2020). As microbial communities form the very basis of the benthic food web, benthic fauna that depend on microbial biomass production, either directly or indirectly, will take even longer to recover. These changes will impact biogeochemical cycling and potentially alter carbon sequestration rates in the deep ocean (Vonnahme *et al.*, 2020).

Our limited knowledge of deep-sea life and their roles in the processes which govern deep-sea carbon cycling make it difficult to quantify the magnitude of mining effects (Levin *et al.*, 2020; Amon *et al.*, 2022b). For example, only 1.1% of scientific categories recently assessed across regions with exploratory deep-sea mining licenses had enough scientific knowledge to enable evidence-based management (Amon *et al.*, 2022b). However, given the disturbance mining will cause to the seabed, it is clear that there is potential for significant effects on carbon cycling and storage in the deep.

New England and Corner Rise Seamounts. © NOAA

Not only would deep-sea mining activities affect the seabed, the resuspension of seafloor sediments and discharge of dewatering effluent would generate huge sediment plumes that could remain suspended in the water column for several years. Sediment plumes would affect pelagic taxa in numerous ways, potentially leading to population-wide effects due to changes in community composition and mortality. This in turn could impact vital ecosystem services such as fisheries and carbon cycling and sequestration (Drazen *et al.*, 2020). There is insufficient scientific evidence to understand and manage mining impacts on deep pelagic ecosystems, which is why a precautionary management approach should be adopted to prevent harm to deep midwater ecosystems (Drazen *et al.*, 2020).

It is also estimated that the impacts of deep-sea mining would synergize with the deep-sea effects of climate change (Levin *et al.*, 2020). For instance, climate velocity in the abyssopelagic layer (depths greater than 4000 m, where nodule mining is prwedicted to take place) is projected to reach 5.5 times the rates currently experienced at the surface by the end of the century (Brito-Morales, *et al.*, 2020). This is further complicated by a lack of scientific information about the deep ocean, how these impacts would synergize, and the potential mitigation routes.

As well as changes to the seafloor and water column, deep-sea extraction would also cause impacts above the sea surface due to emissions of greenhouse gases and other air pollutants from vessel fuel combustion over hundreds of nautical miles. For example, a hypothetical manganese nodule mining operation in the Clarion-Clipperton Zone at 5,000 meters depth with an annual production of 3 million dry tons has been estimated to emit between 81,294 and 474,479 tons of CO_2 (Heinrich *et al.*, 2019), demonstrating that deep-sea mining operations will generate considerable greenhouse gas emissions. This highlights the urgent need to integrate emissions from deep-sea extractive activities into the regulatory regimes concerned with climate change, air pollution and shipping, despite the exact quantity of emissions remaining uncertain (Heinrich *et al.*, 2019).

4.4 Ocean-based climate interventions

Ocean-based climate interventions (OBCI) that remove carbon dioxide, manage solar radiation, or produce alternative forms of electricity are increasingly being considered as potential pathways to mitigate climate change. OBCI approaches include ocean fertilization, seaweed culture and crop waste sinking, ocean alkalinity, CO_2 deepwater and subsurface injection, ocean thermal energy conversion, and artificial upwelling, to name a few (Teng & Zhang, 2018; DOSI, 2021a; 2021b; DOSI, 2022a; Levin *et al.*, 2022). However, there are numerous concerns about the associated impacts on deep-sea physics, chemistry, ecology and ecosystem services, including oxygenation, acidity, aragonite saturation and trace elements, turbidity, food supply and food web structure, substrate characteristics, and pelagic and benthic communities (Levin *et al.*, 2022). As OCBIs are not yet being implemented, there is still an opportunity for a precautionary approach to be taken, and for these activities and all their impacts on the ocean to be comprehensively studied and factored into decision making and governance.

Sea cucumber *Amperima* sp. on the seabed in the eastern Clarion-Clipperton Fracture Zone. co2© Craig Smith and Diva Amon, ABYSSLINE Project, NOAA Office of Ocean Exploration and Research

5. Looking to the future

To help mitigate climate change and increase our resilience to its impacts, the deep ocean must be taken fully into account. Below is a non-exhaustive list of ways to do this:

1. **Pause all human activities that disturb the deep seafloor and lead to biodiversity loss,** including deepwater oil and gas extraction, deep-sea trawling, and deep-sea mining. There are no known substitutes or replacements for ecosystem services, such as climate regulation, that operate over large distances and long timescales. That is why all human activities that risk disruption of irreplaceable ecosystem services that we all depend on warrant precautionary measures to avoid their loss and ensure our continued benefits.
2. **Increase deep-sea research independent of extractive agendas.** Given the challenges and costs of deep-sea research, there are persistent gaps in knowledge that impact our ability to preserve ecosystem services, including those related to climate regulation. These knowledge gaps create uncertainty about the impacts – including cumulative impacts – of human activities on deep-ocean ecosystems, their functions and services, and their potential for recovery from disturbance (Levin *et al.*, 2020). There is a need for robust baseline data collection that can inform climate modeling, ideally uncoupled and independent from extractive motives, as well as for the application of a precautionary approach.
3. **Expand climate-smart Marine Protected Areas (MPAs).** Ecosystem structures and functions that deliver ecosystem services, such as climate regulation, need to be protected for us to continue receiving nature's benefits. The predicted variation in the rate of climate change throughout the open ocean creates challenges for designing climate-safe MPAs (Brito-Morales *et al.*, 2020) and the effectiveness of deep-sea Area-Based Management Tools is likely to be severely limited by climate change (Johnson *et al.*, 2018). To optimize opportunities for climate adaptation among deep-ocean communities, future open-ocean protected areas must be designed to retain species moving at different speeds at different depths under climate change, while also managing non-climate threats, such as fishing and mining (Brito-Morales *et al.*, 2020; Quieros *et al.*, 2021). Climate resilience should become a standard environmental goal in the design of all deep-sea protected areas in the context of fishing, biodiversity, and shipping (Dunn *et al.*, 2018; LeBris & Levin, 2020).
4. **Introduce policies that support the protection of deep-ocean ecosystem services and take precautionary approaches to avoid irreversible losses of those services.** For example, strategic environmental assessments with robust baseline data at a regional-scale, followed by risk analysis and mitigation strategies of ecosystem services, should be part of project-specific environmental impact assessments. Such requirements can be incorporated into all stages of management.
5. **Develop climate strategies that conserve carbon and avoid significant or irreversible damage to the deep sea.** The IPCC has indicated that active climate intervention will be required to limit warming to 1.5°C. Most newly proposed ocean-based climate interventions designed to sequester more carbon (e.g., iron fertilization, seaweed culture and sinking, crop waste disposal, alkalinity, artificial upwelling) will exacerbate one or more of the key climate challenges impacting the deep ocean, while also causing smothering, contamination and/or other risks to ocean life. Managing deep-sea impacts is essential to the vetting and scaling up of CO_2 removal practices.
6. **Manage fisheries for climate, and vice versa.** More consideration should be given to the role of fish in carbon transport and storage, with future management of fish stocks incorporating climate-induced changes in fish habitat, production and distributions. For instance, limiting blue carbon extraction by fisheries, particularly in unprofitable areas, could reduce CO_2 emissions by burning less fuel, while also strengthening a natural carbon pump as a nature-based solution through the rebuilding of fish stocks and the increase of carcass deadfall (Mariani *et al.*, 2020). And from the other side, without strong actions to mitigate climate change, global fish stocks will not be able to recover to sustainable levels, further impairing their biogeochemical connections with the deep ocean and their future viability (Cheung *et al.*, 2022b).
7. **Develop and implement international agreements and regulations that jointly address biodiversity conservation and climate change mitigation/adaptation,** recognizing these must go hand in hand. Most biodiversity conventions, treaties and agreements are heavily siloed such that climate change is rarely considered. Current treaty negotiations on marine Biodiversity in areas Beyond National Jurisdiction (BBNJ agreement) reflect limited concern for climate change and carbon conservation (Elsler *et al.*, 2022), mining regulations do not directly incorporate climate change into environmental management (i.e., in Areas of Particular Environmental Interest design, Environmental Impact Studies, etc.) (Levin *et al.*, 2020), and the RFMO impact assessments of deep-sea fisheries do not address the climate change consequences of management (DOSI, 2022b).

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