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Climate Change-Accelerated Ocean Biodiversity Loss & Associated Planetary Health Impacts

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Abstract: A planetary health perspective views human health as a function of the interdependent relationship between human systems and the natural systems in which we live. The planetary health impacts of climate change induced ocean biodiversity loss are little understood. Based on a systematic literature review, we summarize how climate change-induced ocean warming, acidification, and deoxygenation affect ocean biodiversity and their resulting planetary health impacts. These impacts on the planets' natural and human systems include biospheric and human consequences for ecosystem services, food and nutrition security, human livelihoods, biomedical and pharmaceutical research, disaster risk management, and for organisms pathogenic to humans. Understanding the causes and effects of climate change impacts on the ocean and its biodiversity and planetary health is crucial for taking preventive, restorative and sustainable actions to ensure ocean biodiversity and its services. Future courses of action to mitigate climate change-related ocean biodiversity loss to support sound planetary health are discussed.

Keywords: Climate Change, Ocean, Biodiversity, Planetary Health, Natural Systems, Human Systems.

1.0 Introduction

Until recently, science and policy perspectives on the public health of human populations have not necessarily considered the surrounding natural ecosystems (Horton et al., 2014). Ocean biodiversity is core to the Earth's hydrosphere, and thus to the Earth's natural ecosystems: changes and losses therein can have major health impacts on human civilizations. Under the conditions brought about by climate change, Earth systems (i.e., atmosphere, hydrosphere, biosphere, geosphere and anthroposphere) that regulate the stability and resilience of the planet have been rapidly altered by human activity in the modern era (Steffen et al., 2015). These systems are now under significant threat in the Anthropocene epoch (Lewis and Maslin, 2015), and in some cases are leading to accelerated species extinction (Thomas et al., 2004; WHO, 2015) and nature loss and degradation of natural systems. As described in for example, the Rockefeller Foundation-Lancet Commission's report, "*Safeguarding Human Health in the Anthropocene Epoch*," this poses serious threats to human health and wellbeing (Díaz et al., 2015; Whitmee et al., 2015). Indeed, climate change is a key driver of changing earth systems and has been declared the greatest threat to global human health in the twenty-first century (WHO, 2018). The Intergovernmental Panel on Climate Change (IPCC) warned that the world's natural and human systems will face severe challenges if greenhouse gas emissions continue to rise (IPCC, 2018). The impact of climate change has already been significant enough to endanger human health (Watts et al., 2015) both directly and indirectly through the alteration of the Earth's interrelated systems.

The link between human health and the planet's natural systems is core to the concept of *planetary health*, which is now an emergent and powerful framework for redefining human public health in relation to earth's natural systems (Myers et al., 2013; Lade et al., 2020). First declared as a Manifesto in the *Rockefeller Foundation–Lancet Commission on Planetary Health*, planetary health is defined as "… the achievement of the highest attainable standard of (human) health, wellbeing, and equity worldwide through judicious attention to the human systems—political, economic, and social—that shape the future of humanity and the Earth's natural systems that define the safe environmental limits within which humanity can flourish" (Whitmee et al, 2015:1978). *As described by the Lancet editor,* "planetary health is a new science that is only beginning to draw the coordinates of its interests and concerns" (Horton and Lo, 2015:1922). In this review paper, we focus on describing and understanding ocean biodiversity loss and its implications for planetary health.

Oceans cover 70% of the Earth's surface and are a major and essential part of the overall hydrosphere system, playing a crucial role in maintaining planetary health through complex adaptive systems and feedback loops (Santos et al., 2020). The world's oceans influence weather at local to global scales and on medium to longer time scales, while changes in climate can fundamentally alter many properties of the oceans including their biodiversity. As well as these changes, anthropogenic drivers severely affect ocean biodiversity. The Global Assessment Report on Biodiversity and Ecosystem Services found that 66% of the global ocean hydrosphere is impacted by multiple human pressures with "severe impacts" in declining richness and abundance of ocean biodiversity (IPBES, 2019).

The erosion of ocean biodiversity is having multiple effects on ocean-related planetary health (Levin et al., 2015; IUCN, 2017a; IPBES, 2019; Pendleton et al., 2020). For example, the Ocean Living Planet Index, which measures trends in 10 380 populations of 3038 vertebrate species, declined 52% between 1970 and 2010. The OLPI also indicates that the global ocean fish stocks were over-exploited by 29%, ocean species declined by 39% and the world coral reefs decreased by 50% (WWF-ZSL, 2015). Various anthropogenic as well as climate change drivers are responsible for ocean biodiversity erosion. According to Luypaert et al. (2020), among many stressors, climate change bears a 14% responsibility for ocean species threatened to extinction. In this context, the objectives of this paper are: (i) to understand how climate change is decreasing ocean biodiversity and (ii) to identify the planetary health impacts accelerated by ocean biodiversity erosion.

2.0 Methodology

A systematic literature review following the strategy and steps described by Moher et al. (2009) was conducted to create a database and extract relevant information to fulfill the objectives of the paper.

2.1 Database Creation

An intensive literature search was carried out on the *Web of Science* search platform using a combination of keywords to create a database of articles on two nexuses: (Nexus 1) climate change and ocean biodiversity, and (Nexus 2) climate change, ocean biodiversity, and planetary health (see Table 1). A *Google Scholar* search was also conducted to identify potential gray literature. Each nexus was searched separately using each of *Web of Science*, and *Google Scholar*. Table 1 describes the keywords and parameters for the Web of Science search. During this stage, no language or date restrictions were applied.

Table 1. Search strategy in web of science by keywords

Topics	**Keywords**	**No. of studies**
Nexus 1: Climate change and ocean biodiversity	TITLE: (ocean* OR “Atlantic Ocean” OR “Arctic Ocean” OR “Southern Ocean” OR “Antarctic Ocean” OR “Indian Ocean” OR “Pacific Ocean”) AND TOPIC: (“climate change” OR “global warming”) AND TOPIC: (biodiversity*) *Refined by: DOCUMENT TYPES: (ARTICLE OR PROCEEDINGS PAPER)*	294
	TITLE: (ocean* OR “Atlantic Ocean” OR “Arctic Ocean” OR “Southern Ocean” OR “Antarctic Ocean” OR “Indian Ocean” OR “Pacific Ocean”) AND TOPIC: (“climate change” OR “global warming”) AND TITLE: (biodiversity) *Refined by: DOCUMENT TYPES: (ARTICLE OR PROCEEDINGS PAPER)*	35
	TITLE: (ocean* OR “Atlantic Ocean” OR “Arctic Ocean” OR “Southern Ocean” OR “Antarctic Ocean” OR “Indian Ocean” OR “Pacific Ocean”) AND TITLE: (“climate change” OR “global warming”) AND TITLE: (biodiversity*) *Refined by: DOCUMENT TYPES: (ARTICLE)*	3
Nexus 2: Climate change, ocean biodiversity and Planetary Health	TOPIC: (“climate change” OR “global warming” OR “greenhouse gases”) AND TITLE: (ocean* OR “Atlantic Ocean” OR “Arctic Ocean” OR “Indian ocean” OR “Pacific Ocean”) AND TOPIC: (health*) AND TOPIC: (biodiversity*) *Refined by: DOCUMENT TYPES: (ARTICLE OR EARLY ACCESS)*	28
Total articles identified		360

A predefined research protocol which included the steps of identification, screening, eligibility, and included with clearly defined inclusion and exclusion criteria was developed with the guidance of the “Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)” statement (Moher et al., 2009). The first step in the screening phase was exporting the search results to Endnote Online and identifying and eliminating the duplicates. Next, the inclusion and exclusion criteria were applied, and studies were screened by their titles and abstracts.

For Nexus 1 of climate change and ocean biodiversity, the inclusion criteria consisted of (i) empirical research using primary or secondary data and (ii) in-situ (in natural environment), in-vitro (in a controlled environment like a laboratory) and modelling research. All review articles and book chapters lacking these criteria were excluded. Articles that focused only on climate change and ocean health but lacked robustness in the biodiversity component or focused on only the biological attributes of a species without explicit linkage to climate change-induced stressors like acidification and warming were also excluded.

For Nexus 2 of climate change, ocean biodiversity and planetary health, only those articles related to human health directly or indirectly were included. Studies related to ocean health, but lacking a human health component, were excluded. Ultimately, 92 and 4 articles were identified as eligible for the first and second nexus, respectively. No further screening was performed as all 96 articles were deemed significant and valuable to ensure robustness in the reporting and synthesis sections of the article. In addition, 47 hand searched articles and reports were also used to further establish the links between the two nexuses.

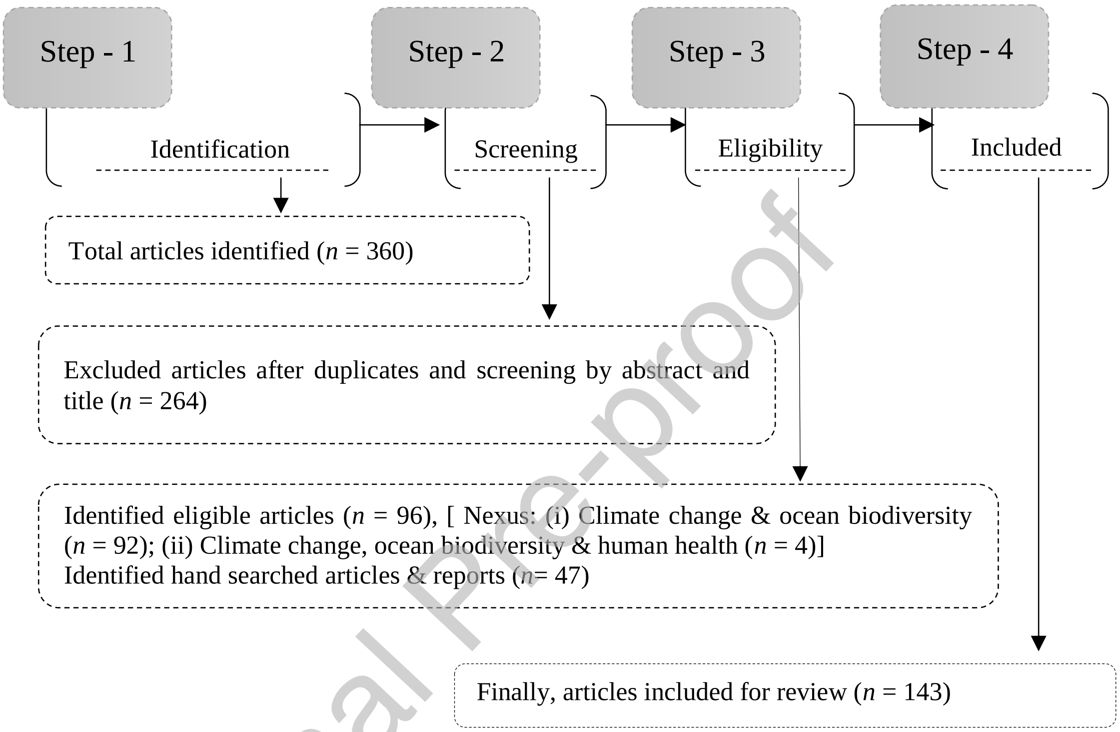


Fig. 1. Four steps of PRISMA flow diagram (Moher et al., 2009) for creating a database by systematic literature review.

2.2 Data Extraction

Data extraction was done using Microsoft Excel. Key variables included (i) location of study, (ii) ocean of interest, (iii) in-situ (in natural environment) or in-vitro (in a controlled environment like a laboratory), (iv) climate change-induced stressor (limited to warming, acidification, and de-oxygenation), (iv) impact on biota (plants and animals) and (v) impact on human health.

Data extractions indicate that Nexus 1 has thus far been researched more extensively than Nexus 2 (94 versus 4 eligible studies), marking the nexus of ocean biodiversity, climate change, and planetary health as an emerging domain requiring more research. As illustrated below in Figure 3[B], the distribution of studies across the five oceans show that most of the research was conducted on the Atlantic and the Pacific Oceans. Our review also shows that two of the three stressors of interest (i.e., ocean warming and ocean acidification) have captured most research interest to date, with de-oxygenation being an emerging stressor of research interest (Fig. 2 [C]). The selected studies covered a wide range of marine life from various taxonomic Phylum [Fig. 2[D]) and marine habitats, including deep-sea (Sunday et al.,2017), sea floor (Ashford et al., 2019; Griffiths et al., 2017) intertidal (Asnaghi et al, 2013) and sea ice fauna (Hop et al., 2020) and the sustained physiological impacts caused by ocean warming, ocean acidification and de-oxygenation.

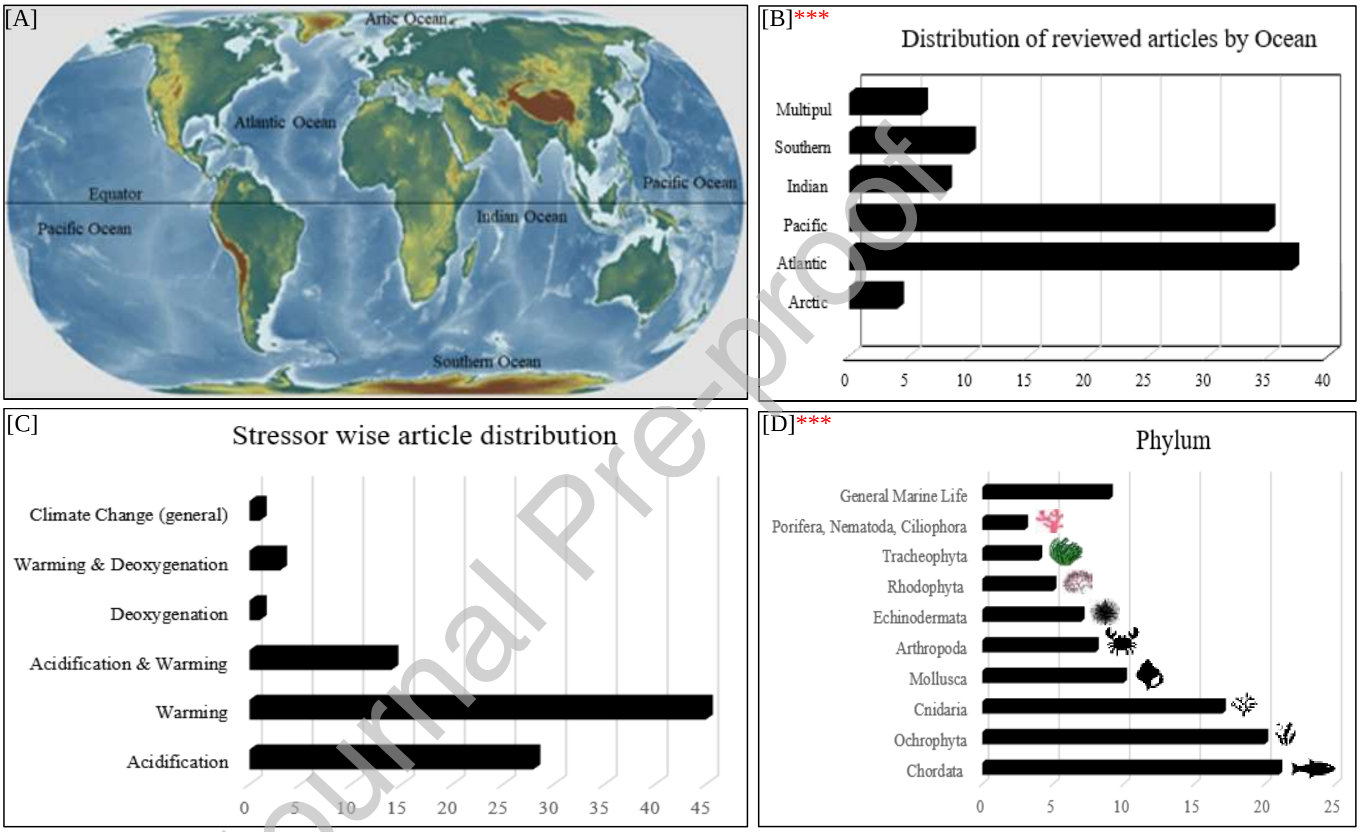
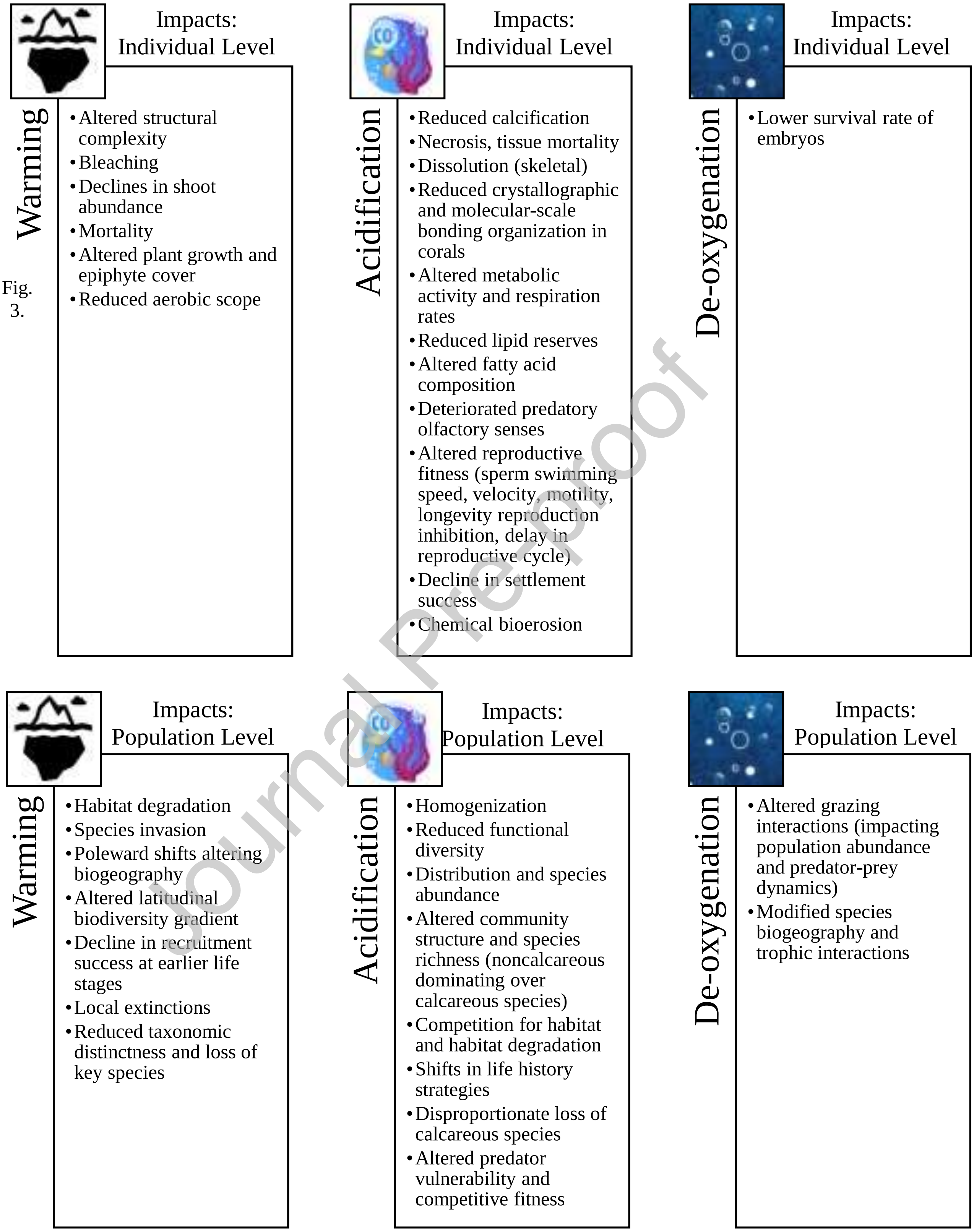


Fig. 2. [A] Map of World Oceans (UN, 2017a), [B] Distribution of reviewed articles across the five oceans, [C] Reviewed article distribution by climate change-induced stressor and [D] Distribution of reviewed articles by Marine Taxonomy. Note: in [B]*** articles covering multiple oceans have been counted as “1” for each category, i.e., articles have been duplicated to maintain consistency in count. In [D]*** Examples of Marine Taxonomic Phylum are: Chordata (Fish), Ochrophyta (Algae, Kelp), Cnidaria (Corals), Mollusca (Sea-snails), Arthropoda (Copepods, crabs, krill), Echinodermata (Sea urchins, Sea star), Rhodophyta (Coralline algae), Tracheophyta (Sea grass), Porifera, Nematoda, Ciliophora (Sponges).



Warming – Impacts: Individual Level

- Altered structural complexity
- Bleaching
- Declines in shoot abundance
- Mortality
- Altered plant growth and epiphyte cover
- Reduced aerobic scope

Acidification – Impacts: Individual Level

- Reduced calcification
- Necrosis, tissue mortality
- Dissolution (skeletal)
- Reduced crystallographic and molecular-scale bonding organization in corals
- Altered metabolic activity and respiration rates
- Reduced lipid reserves
- Altered fatty acid composition
- Deteriorated predatory olfactory senses
- Altered reproductive fitness (sperm swimming speed, velocity, motility, longevity reproduction inhibition, delay in reproductive cycle)
- Decline in settlement success
- Chemical bioerosion

De-oxygenation – Impacts: Individual Level

- Lower survival rate of embryos

Warming – Impacts: Population Level

- Habitat degradation
- Species invasion
- Poleward shifts altering biogeography
- Altered latitudinal biodiversity gradient
- Decline in recruitment success at earlier life stages
- Local extinctions
- Reduced taxonomic distinctness and loss of key species

Acidification – Impacts: Population Level

- Homogenization
- Reduced functional diversity
- Distribution and species abundance
- Altered community structure and species richness (noncalcareous dominating over calcareous species)
- Competition for habitat and habitat degradation
- Shifts in life history strategies
- Disproportionate loss of calcareous species
- Altered predator vulnerability and competitive fitness

De-oxygenation – Impacts: Population Level

- Altered grazing interactions (impacting population abundance and predator-prey dynamics)
- Modified species biogeography and trophic interactions

Fig. 3.

Individual and population level impacts of ocean warming, acidification and de-oxygenation.

The results and discussion are based on 147 articles in total. Of these, 96 were identified using the *Web of Science* and *Google Scholar* databases, and 51 were hand-searched articles selected by the authors for their content as core to the context of the study.

3.0 Results

3.1 Nexus 1: Climate Change Related Threats Causing an Erosion of Ocean Biodiversity

While oceans have buffered humans from the worst impacts of climate change by absorbing more than 90% of excess global temperature increase, and about 25% of CO_2 emissions (MBARI, 2019), climate change is causing ocean (i) warming, (ii) acidification and (iii) deoxygenation (IPCC, 2019). As illustrated in Figure 4, The impacts pose major threats to biodiversity at both the individual and population level of marine organisms.

3.1.1 Warming Ocean

Rising greenhouse gases are preventing heat radiated from the Earth's surface from escaping into space as freely as before the modern age. More than 90% of the excess atmospheric heat has passed back and been absorbed by ocean surface waters, (Cheng et al., 2017; IPCC, 2019). As a result, the upper ocean heat content has increased significantly in recent years (see Fig. 4).

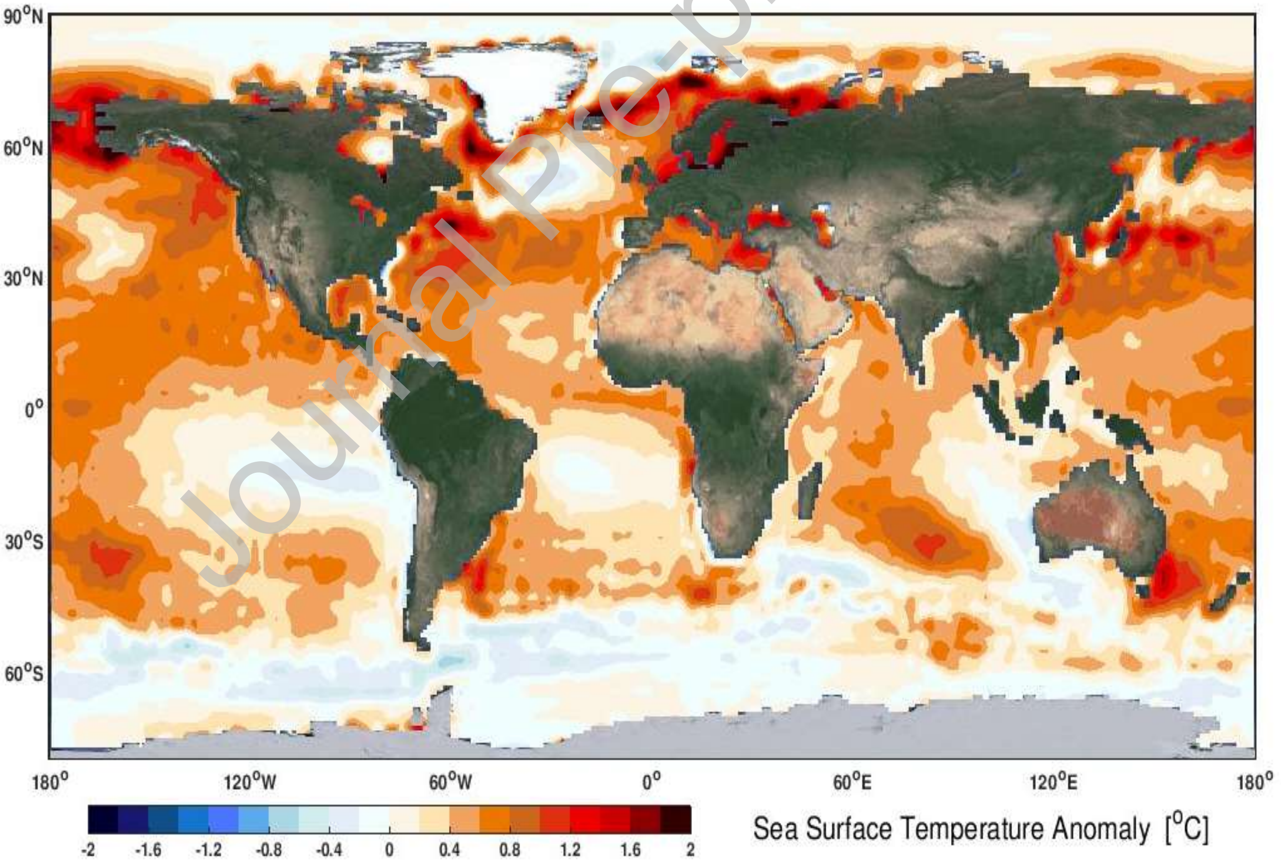


Fig. 4. Satellite observations of sea surface temperature anomalies during the last five years (2015-2019) with reference to the first five years of the data (1982-1986). Source: Adapted from Yang et al. (2020) and AWI and Lohmann (2020) with permission.

Due to the thermal expansion of warming ocean waters, and the melting of glaciers, sea levels are rising globally (Church et al., 2013). In the past decade, this rise has increased coastal flooding (Oppenheimer et al., 2019). If global average temperature increase rises to 1.5 °C, abnormal localized marine heatwaves are projected to become decadal to centennial events, and if the global average temperature increase rises to 3°C, these are projected to become annual to decadal events (Laufkötter et al., 2020).

Ocean currents have two vital thermally-linked roles within Earth’s systems: (i) storage and seasonal release of heat and (ii) movement of heat via their circulation systems (Winton, 2003). These currents are affected by the warming ocean, and this will lead to alterations in climate patterns around the world as well as more extreme weather events such as flood, hurricanes, intense rainfall, and prolonged intervals between rains (Yang et al., 2016).

Ocean warming is influencing and modifying species diversity (Ateweberhan et al., 2018), abundance patterns and community composition (Lloyd et al., 2011; Linklater et al., 2018), driving extinctions (McClanahan et al., 2021), and triggering poleward and regional-scale shifts (Maharaj et al., 2018) in species distribution causing biogeographical changes (Beaugrand et al., 2013; Gregory et al.,2009; Griffiths et al., 2017; Gupta et al., 2015; Martinez et al., 2018; Wernberg et al., 2011; Lopez et al., 2020). The magnitude of changes in species distribution and of response rate to climate change-induced stressors (Stuart-Smith, 2018) vary by a series of factors, including: a species’ thermal threshold (Gupta et al., 2015); sessility (Isla and Gerdes, 2019); population size; habitat alteration and degradation (Martinez et al., 2018; Hill et al., 2013); resource availability; competition with invasive species (Newton et al., 2013; Sands et al., 2015); predator-prey dynamics (Selden et al., 2018); migration strategy, and light regimes and reproductive fitness (Busseni et al., 2020; Johnson et al., 2011; Madeira et al., 2016; Poloczanska, 2013; Villarino et al., 2020; Yeruham et al., 2020; Gupta et al., 2015). Shifts are likely to become more rapid and erratic instead of gradual and monotonic (Gupta et al., 2015) with resulting non-linear community responses (Stuart-Smith, 2009).

Deep ocean water is no longer a safe haven from surface ocean warming effects, and deep-water biodiversity is at higher risk than surface ocean waters due to velocities in the deep ocean than at the surface, a situation which is further exacerbated by the lack of mitigation options (Brito-Morales et al., 2020). For instance, deep water cetaceans like sperm whales (*Physeter macrocephalus*) and northern bottlenose whales (*Hyperoodon ampullatus*) may see a shift in biodiversity with an increase in ocean of higher latitudes (polar regions) from the tropics (Whitehead et al., 2008).

Melting of sea ice is causing a negative impact on unicellular sea-ice associated eukaryotes (Hop et al.,2021) and altering the biodiversity of ciliate microzooplankton (Jiang et al., 2013), whereas drastic shifts in ice-scouring events (gouging or reworking of seabed in shallow coastal areas caused by drifting sea ice)can cause significant impact on benthic communities dependent on their sessile capabilities (Robinson et al., 2020).

As described in Fig. 3, at an individual level, review results show rising ocean water temperatures impact the biological systems of marine species' in multiple ways, including: digestive and immune physiology in sea urchins (*Lytechinus variegate)* (Brothers et al., 2018), deteriorated respiration and gonado-somatic index (GSI) in the European purple sea urchin (*Paracentrotus lividus*) (Yeruham et al., 2020), shoot mortality, leaf width and the presence of leaf epiphytes in seagrasses (Marba and Duarte, 2010; Peirano et al., 2011), decline in larvae survival in a key fisheries species such as sea bream (*Sparus aurata*) (Madeira et al., 2016), loss of structural complexity in reef corals due to coral bleaching (Graham et al., 2006), and decline in the aerobic scope in coral reef damselfish (*Acanthochromis polyacanthus*) (Rodgers et al., 2019). Warming and eutrophication have also been found to weaken the ability of ocean plants' such as Neptune Grass (*Posidonia oceanica)* to cope with multiple environmental stressors (Pazzaglia et al., 2020).

3.1.2 Ocean Acidification

Ocean absorption of excess CO_2 causes ocean acidification in which concentrations of CO_2 and bicarbonate (HCO_3-) increase while the concentration of carbonate (CO_3^{-2}) ions and pH decrease (Barker and Ridgwell, 2012). Increased sedimentation in coastal waters has also been found to be an enhancer of ocean acidification (Smith et al., 2020).

Ocean acidification impacts the calcium carbonate anatomic structures of calcareous species disproportionately more than non-calcareous species making the former less competitive (Asnaghi et al., 2013). In this way, it alters ecosystem functional diversity including coastal biogenic habitats (Sunday et al., 2017) resulting in homogenization and ecosystem simplification (Brustolini et al., 2019; Harvey et al., 2021; Kroeker, 2013; Porzio et al., 2011). A mesocosm experiment showed molluscs to be the most sensitive to lowered pH and elevated temperatures when compared to annelids and nematodes (Hale et al., 2011; Ricevuto et al., 2015). Several studies have found ocean acidification to affect reproduction and development across taxonomical groups through a range of physiological responses like reallocation of resources in copepods (Fitzer et al., 2012); fertilization rates; sperm motility and velocity in sea stars (Uthicke, 2013); altered metabolic activity and fatty acid composition in predatory snails (Valles-Regino, 2015); modified respiration rates in cold water corals (*L.pertusa*) (Henninge et al., 2014) and altered metabolic capacity and timing of reproduction in Antarctic fish (Todgham and Mandic, 2020). Tolerances to ocean acidification can differ between species from different trophic levels, which may alter species interaction, aid productivity and modify community stability directly or indirectly through changes in resource availability (Cornwall et al., 2012; Nagelkerken et al., 2016). For example, Campanati et al. (2018:66) found that a pH level of 7.4 posed no significant threat to the mortality, abnormality, or growth of the larvae of the rock oyster (*Saccostrea cucullate),* but “increased mortality (up to 30%), abnormalities (up to 60%) and approximately 3 times higher metabolic rates” in the larvae of its key predator, the whelk (*Reishia clavigera)*. McCormick et al. (2013) found a reversal in the competitive outcome for space in two species of fish, (*Pomacentrus moluccensis)* and (*P. amboinensis*) in elevated CO_2 conditions, while Range et al., (2010) found increased survival in juvenile clams (*Ruditapes decussatus*) as a response to ocean acidification.

The combined effects of ocean warming and acidification can affect processes like calcification, necroses and dissolution, with often exacerbating effects when acting together as compared to alone. For instance, the mortality of coralline algae (*Lithophyllum cabiochae),* caused by tissue mortality and skeletal dissolution (Diaz-Pulido et al., 2012) increased 2 to 3 times under high pCO_2 and temperature, with major consequences for the biogeochemistry and biodiversity of ecosystems dominated by these species like the Mediterranean coastal ecosystems (Martin and Gattuso, 2009). Ocean acidification and warming can impact ocean biodiversity by influencing species diversity, abundance, predator detection (Dixson et al., 2010), distribution, and competitive fitness (Caldwell, 2011; Rölfer et al, 2021; Santora et al., 2017). Acidification also appears to be reducing the amount of reduced sulfur species flowing out of the ocean into the atmosphere, where they are oxidized to form SO_4^{2-}. This reduces the reflection of solar radiation back into space, resulting in even more global warming with more severe consequences for ocean components including biodiversity (Barford, 2013).

The combined pressure of ocean acidification and ocean warming can limit the scope of polar acclimatization. For example, warmer temperatures have been associated with the modification of gene expression in an Antarctic pteropod by upregulating the transcripts responsible for increasing membrane fluidity (Johnson and Hofmann, 2020). Coral reefs are especially vulnerable to ocean warming and acidification through exaggeration of bioerosion rates by recycling calcium carbonate skeletal material (Wisshak et al., 2013); compromising coral growth and structural integrity by weakening reef bases and lowering their effectiveness as "load-bearers" (Hennige et al., 2015; Wilkinson, 2008); negatively impacting the health and survival of recruits (Bahr et al., 2020) and reducing the metabolic performances of these ecosystems (DeCarlo et al., 2017). Species that are accustomed to large environmental fluctuations like those in the natural rock pool communities (comprised of coralline algae, fleshy algae, and grazers) will have a physiological advantage for coping with multiple stressors like ocean acidification and warming (Legrand, 2018).

3.1.3 Ocean Deoxygenation

Warmer ocean water retains less oxygen and is more buoyant than cooler water. As a result, a warmer ocean loses its capacity to blend oxygenated water close to the surface with deeper waters that contain less oxygen. The oceanic O_2 flux and exportation are highly dependent on particulate and organic matter produced by photosynthesis, which is directly regulated to a larger extent by the plankton communities that are threatened by ocean warming (Richardson and Bendtsen, 2017). Apart from this, ocean-dwelling organisms demand more oxygen in warmer waters as a consequence of increased metabolic rates (Boscolo-Galazzo et al., 2018; Deutsch et al., 2015). De-oxygenation has also been associated with increases in oceanic N_2O production and this potent greenhouse gas adds its contribution to climate change (Babbin et al., 2015). Because of these dual effects, less oxygen is available for ocean life. Apart from warming, ocean deoxygenation is also taking place due to excessive growth of algae through eutrophication (IUCN, 2019).

Respiratory responses to deoxygenation have been found to be complex and to vary across species and body sizes, the latter consistently indicating higher vulnerability among creatures that have large body sizes like the giant Antarctic marine invertebrates (Spicer and Morley, 2019). Deoxygenation has also been found to alter species interactions; for example, short-term exposure to low oxygen levels decreased grazing interaction by threefold over a short timescale in four common grazers of juvenile giant kelp (*Macrocystis pyrifera*) in an aquarium facility at the Hopkins Marine Station (HMS) (Ng and Micheli, 2020).

The combined impact of warming and hypoxia negatively impact the survival and growth of catsharks (*S. canicular*) – the former stressor leading to a reduction in the length and body mass of a newly hatched shark and the latter, negatively impacting the survival rate of the embryos (Musa et al., 2020).

3.2 Nexus 2: Climate Change, Ocean Biodiversity and Planetary Health

The erosion of ocean biodiversity has multiple planetary health impacts. As shown in Fig. 5, these can be divided into six groups: (i) ecosystem services, (ii) food and nutrition security, (iii) livelihood, (iv) biomedical and pharmaceutical, (v) disaster risk and (vi) pathogenic organisms.

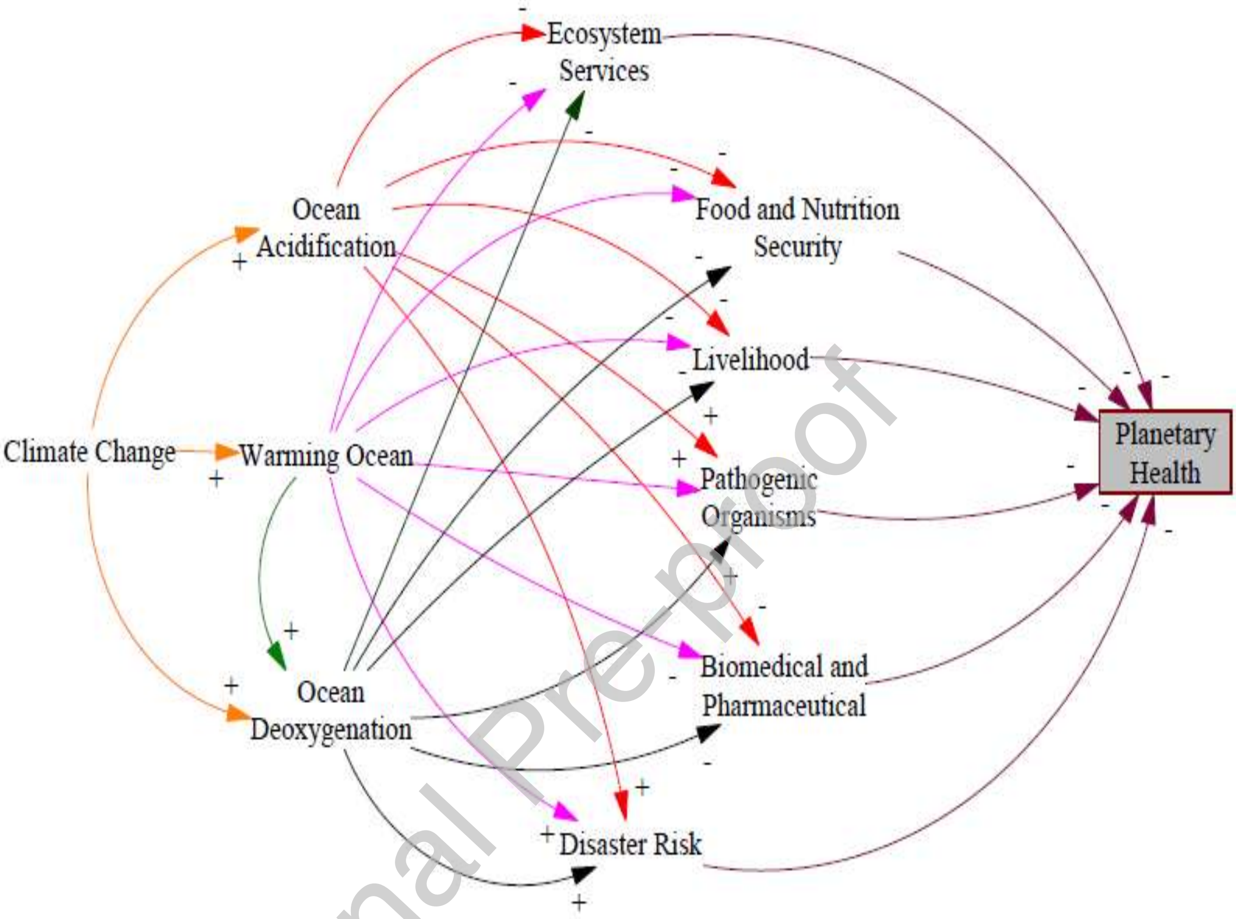


Fig. 5. Causes of ocean biodiversity erosion and their planetary health impacts. Note: “+” = increase; “-” = decrease.

3.2.1 Ecosystem Services

The elements of biodiversity - including all life forms, habitat environments, and all form of genes and species- are the basic properties of an ecosystem. Biodiversity plays a fundamental role in maintaining and defining a healthy ocean ecosystem (Cochrane et al., 2016). However, climate change-related impacts as described in Section 2.0 deteriorate ocean biodiversity and leads to the decay of provisional (refer to section 3.2.2) and regulatory ecosystem services (Sandifer and Sutton-Grier, 2014; Levin and Le Bris, 2015).

Coastal ecosystems such as mangroves, salt marshes and seagrass meadows which support storm and shoreline protection are weakening as a result of sea level rise (Oppenheimer et al., 2019), thereby accelerating coastal flooding and drowning of coastal wetland habitats (Sandifer and Sutton-Grier, 2014). Additionally, increased ocean temperature and altered precipitation impact, the ability of coastal water areas to sequester carbon (Ward et al., 2016).

Ocean acidification can also compromise the quality of air by the release of toxins, causing respiratory illnesses in coastal areas. A warm and more acidic ocean threatens the production pattern of phytoplankton, which during its growth emits much of the oxygen that permeates our atmosphere and transfers energy for higher trophic levels in the marine ecosystem (Falkowski, 2012; Winder and Sommer, 2012).

3.2.2 Food and Nutritional Security

Ocean ecosystems and biodiversity provide food and nutrition (Sandifer and Sutton-Grier, 2014), but climate change-related threats hamper the ocean ecosystems and biodiversity necessary to supply food and nutrition (IUCN, 2017a). For example, as described below increased ocean acidification compromises the growth and structural integrity of coral reefs, which in turn damages the food supply and food-related health outcomes of 500 million people worldwide (Wilkinson, 2008).

Loss of ocean biodiversity will heavily affect the food, animal protein and essential micronutrient consumption for billions of people around the world, especially in developing countries (UNEP, 2006; Branch et al., 2013; Hicks et al., 2019; Falkenberg et al., 2020). Since 1961, global fish consumption has increased by 3.1% per year. This is more than the increase in consumption of all other animal-based protein sources such as meat, eggs, and milk, which is 2.1% per year. In particular, the world’s least developed countries have doubled their fish consumption since 1961 (FAO, 2020). Declines in ocean fish diversity will hamper global fish consumption and ultimately human health of the community depend on ocean fish. This can occur through three potential pathways (i) lack of fish availability due to collapsed food webs (ii) reduced affordability due to increase in fish price caused by lower fish availability and livelihood loss and (iii) lack of dietary diversity as fish species which differ in type of nutrients (for example: consuming smaller fish is associated with higher intake of micronutrients, especially iron, zinc, calcium and vitamin A, primarily as they are consumed whole) (Kaimila et al., 2019). Seafood quality and its resulting impacts on the health and safety of human health is also a matter of concern as described by Barbosa et al.'s study on the impacts of temperature on the nutritional quality of a commercial seabass species (*Dicentrarchus labrax*) (Barbosa et al., 2017)

3.2.3 Pathogenic Organisms

Warmer ocean water, ocean deoxygenation as well as ocean acidification create favorable conditions for larger and more frequent blooms of toxic algae, leading to sickness and poor overall health for fish, birds, ocean mammals and humans (Backer et al., 2003; Berdalet et al., 2016; IPCC, 2019; Laufkötter et al., 2020; Riebesall et al., 2018). Seafood such as shellfish contaminated by harmful algae can cause sickness ranging from diarrheal illness to neurotoxic effects (CDC, 2017). Ciguatera (a type of human food poisoning affecting gastrointestinal, neurological and cardiovascular processes causing paralysis, coma and death in severe cases) caused by Ciguatoxins produced by *G.toxicus* attached to dead corals is expected to increase in marine food chains as a result of ocean warming induced coral bleaching and hurricanes (Lehane et al., 2000). In addition, harmful algal blooms can trigger mass fish mortality by disturbing trophic transfers of organic matter and reducing water quality (DiLeone and Ainsworth, 2019; Riebesall et al., 2018).

3.3.4 Livelihoods

The ocean is essential for many aspects of human wellbeing and livelihoods, but the erosion of ocean biodiversity and ecosystems particularly threatens the livelihoods of local communities, especially those most dependent upon natural resources (UNEP, 2006; Bindoff et al., 2019). For example, 80% of all tourism is based near the sea (Honey and Krantz, 2007), but the destruction of coral reefs is affecting coral reef-based tourism and recreation (Pendleton, 2019). Coastal ecosystems dependent on wind-based upwelling of deep seawater, like those in East & Southern Africa and Northwest coast of North America popular for tourism are highly vulnerable to future climate scenarios (Jones et al., 2018; McClanahan et al., 2007). Climate change related modifications to oceanic conditions are impacting the intensity of upwelling impacts with consequences on reef fish assemblages. This further impacts several sources of livelihood, such as, recreational fishing, tourism, and diving (Eisele et al., 2020). Climate change-driven ocean fish migration could lead to a resurgence or collapse of fisheries depending on latitude (Weatherdon et al., 2016; Tai et al., 2019), which could damage the livelihoods of about 3 billion people globally who depend on ocean and coastal biodiversity (UN, 2017b). In addition to direct effects on fish, rapid shifts in other ocean floral species, like temperate to tropical *Sargassum* species in western Japan have been found to have serious implications on regional fisheries (Yamasaki et al., 2014). Livelihood and health are inseparably connected, while sound livelihoods are important to maintain the conditions of good health such as food security, health facilities, and education, they are also important for mental health as lack of livelihoods in the form of loss of a job opportunity could cause depression and ecoanxiety, and solastalgia can occur communities that depend on ocean biodiversity.

3.2.5 Biomedical and Pharmaceutical

Ocean biodiversity is a source of food supplements, enzymes, and biomaterials such as artificial bone from corals and silica, chitin, and collagen from sponges (Ehrlich et al., 2007; Venugopal, 2008; Green et al., 2014; Jesionowski et al., 2018). Biodiversity of genes and molecules in ocean creatures and plants has value for various biomedical and pharmaceutical purposes such as cancer treatments as well as antibacterial, antifungal, antiviral and anti-inflammatory uses (EU, 2013), but ocean biodiversity erosion is causing the loss of these genes and molecules. Biodiversity loss in oceans will reduce the potential human benefits of ocean biodiversity and also hinder medical research.

3.2.6 Disaster Risk Protection

A warmer ocean also creates bigger and stronger storms generating waves that can reach up to 60 feet high and can affect ocean habitats 300 feet below the surface. Waves can topple rocks and coral damaging the structure of coral reef habitats and affecting ocean floor life (NCCOS, 2017). Shoreline erosion caused by accelerating sea-level rise, poses significant threat to coastal cities and communities (Cantin et al., 2010; Sandifer and Sutton-Grier, 2014). Deteriorated coastal ecosystem services as a result of ocean biodiversity loss can no longer provide protection against damages from inundation or flooding or short bursts of precipitation due to storm activity (Wilkinson and Salvat, 2012). Further, there is less natural protection against encroaching salinity caused by sea-level rise (Smyth and Elliott, 2016) Encroaching salinity caused by sea-level rise can impact human health through ground water contamination and food and livelihood insecurity caused by loss of agricultural productivity (Vineis et al., 2011).

4.0 Discussion

The ocean is the planet’s primary heat reservoir, oxygen supplier and carbon sink (Winton, 2003; Cherchi, 2019). Ocean biodiversity is central to maintaining these services, but due to climate change impacts, these services are deteriorating as ocean biodiversity is becoming critically endangered or vulnerable (Luypaert et al., 2020). The Global Assessment Report on Biodiversity and Ecosystem Services showed that 66% of the ocean is facing human pressures and the diversity and abundance of ocean ecosystems is weakening, which limits the ocean’s capacity to supply various ecosystem services including food security and protection against climate change (IPBES, 2019). In addition, ocean biodiversity erosion will accelerate the decline of the overall biodiversity, one of the nine planetary boundaries (Rockstrom et al., 2009), and this will have further wide-ranging and accelerated consequences for the planet.

The United Nations' *Sustainability Development Goals (SDGs)* make direct reference in SDG 14, 'Life Below Water', to the importance of protecting ocean biodiversity. Several targets in this goal are related to maintaining ocean health such as reducing ocean acidification, engaging in sustainable fishing practices, protecting coastal environments, and reducing ocean pollution. However, the literature indicates that these targets are unlikely to be met (Nash et al., 2020), as there are no targets for long-term sustainability for ocean biosphere dependent communities. For example: fishing may cause progress in reducing poverty by increasing food security (SDG 2), while being destructive to SDG 14 through overfishing and reductions in ocean biodiversity. Singh et al. (2018) provide a framework which illustrates the linkages between Goal 14 and the success of all other goals. Here, reducing overfishing is identified as a precondition necessary to achieving the largest number of targets among the full suite of SDGs (except SDG 17: Partnership for the Goals).

The Global Assessment Report on Biodiversity and Ecosystem Services (IPBES, 2019) warned that one million species might disappear within the next few decades. The planet has already seen five large extinctions; the sixth may be happening now, this time driven by human activities and anthropogenic climate change. While higher biodiversity can reduce impacts of acidification on highly vulnerable key organisms by 50 to >90% (Rastelli et al., 2020), the reality of human-driven exploitation of ocean biodiversity, and loss of ocean biodiversity due to climate change will almost certainly accelerate this sixth mass extinction (Barnosky et al., 2011).

Ramirez et al. (2017) analysis of ocean biodiversity loss hotspots illustrates the areas globally that are most vulnerable to climate change. Their study mapped the distribution of 2183 oceanic species (1729 fish, 124 ocean mammals, 330 seabirds) in order to identify key focus areas for conservation. The results indicated that the areas of highest oceanic biodiversity are most affected by stressors from climate change and fishing pressure. These areas include the central-western Pacific (Indonesia, Malaysia, Philippines, Papa New Guinea) and the western Indian Ocean (S. Africa, Mozambique, Tanzania, Kenya and Madagascar) (Ramirez et al., 2017). While there is an ever-growing necessity of mariculture to feed the growing global population facing imminent risks from food insecurity and freshwater shortages, (Duarte et al., 2009) these biodiversity loss hotspots must be protected, and protection measures can be effective. Sala et al. (2021) showed that ocean protection helps to protect biodiversity, increase fish yield, and ensure carbon sequestration.

While ocean biodiversity loss hotspots have been identified and the role of life in our oceans is valued enough by humans to have SDG 14 dedicated to its preservation, ocean biodiversity is under at least as much threat as life on land. Climate change-related threats to the ocean will have to be addressed holistically through international coordination and collaboration. Healthier oceans will benefit planetary health by ensuring the integrity of the ecosystems and their services for humankind. The health of oceans can only be ensured through coordinated effort. Sala et al. (2021) have claimed that at least 30% of oceans will have to be protected to effectively address planetary health issues.

Natural solutions, transboundary management and species-centered studies (Hernández et al., 2020) should be further explored (Henriques et al., 2018). Examples of the former can be co-culturing species which can co-benefit each other like Pacific oyster (*Crassostrea gigas*) and eelgrass (*Zostera marina*) to combat the impacts of ocean acidification (Groner et al., 2018), and harnessing host resilience through microbial-host interactions (Cavalcanti et al., 2018). Tools such as Health Impact Assessments

(HIA) can integrate ocean conservation with human public health by identifying and tackling specific indicators of human health through conservation (Jenkins et al., 2018). Human stakeholder-informed ecosystem modelling strategies have also shown promise in addressing multiple anthropogenic and environmental stressors on complex ocean systems (Koenigstein et al., 2016). The rising threat from global warming has prompted many potential solutions including deep sea CO_2 sequestration. However, it is crucial that prior to implementation, wider consequences are appropriately vetted, which can include a significant mortality impact of sequestered CO_2 on deep-sea infauna (Thistle et al., 2005).

5.0 Conclusion

Climate change is driving major changes and loss in ocean biodiversity, with major impacts for planetary health. As well as other anthropogenic factors, climate change is making oceans more vulnerable by increasing ocean temperatures and acidity and decreasing oxygen, causing the erosion of ocean biodiversity. Deteriorating ocean biodiversity due to climate change diminishes the ocean’s ability to support human health and wellbeing. Ocean biodiversity is vital to planetary health, and healthy ocean ecosystems are crucial for human life. Understanding the causes and effects of climate change impacts on the ocean and its biodiversity and planetary health is crucial for taking preventive, restorative and sustainable actions to ensure ocean biodiversity and its services. Advanced research and collective action will be vital to understanding the underlying causes of the loss of ocean biodiversity due to climate change and identifying appropriate measures to combat it. Lastly, understanding the connection between climate change-accelerated ocean biodiversity loss and the resulting planetary health impact will allow better decision making and planning related to the protection of ocean biodiversity and reduce the impact of climate change.

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