The Journal of Climate Change and Health 6 (2022) 100114

Contents lists available at ScienceDirect

The Journal of Climate Change and Health

journal homepage: www.elsevier.com/joclim

Review

Climate change-accelerated ocean biodiversity loss & associated planetary health impacts

Byomkesh Talukder[a,*], Nilanjana Ganguli[b], Richard Matthew[c,d], Gary W. vanLoon[e], Keith W. Hipel[f,g], James Orbinski[h,i,*]

[a] Dahdaleh Institute for Global Health Research, York University, Canada
[b] Faculty of Environmental & Urban Change, York University, Canada
[c] Research and International Programs, UC Irvine, USA
[d] Blum Center for Poverty Alleviation, UC Irvine, USA & Urban Planning and Public Policy, and Political Science, UC Irvine, USA
[e] School of Environmental Studies, Queen's University, Canada
[f] Department of Systems Design Engineering, University of Waterloo, Canada
[g] Centre for International Governance Innovation Coordinator, Conflict Analysis Group, Balsillie School of International Affairs, Waterloo, Canada
[h] Dahdaleh Institute for Global Health Research, York University, Canada
[i] Faculty of Health, York University, Canada

A R T I C L E I N F O

Article History:
Received 6 August 2021
Accepted 6 January 2022
Available online 10 January 2022

Keywords:
Climate change
Ocean
Biodiversity
Planetary health
Natural systems
Human systems

A B S T R A C T

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.

Introduction

Until recently, science and policy perspectives on the public health of human populations have not necessarily considered the surrounding natural ecosystems [60]. 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 [131]. These systems are now under significant threat in the Anthropocene epoch [82], and in some cases are leading to accelerated species extinction [137,158] 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 [34,157]. 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 [159]. 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 [63]. The impact of climate change has already been significant enough to endanger human health [147] 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 [77,96]. 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—

* Corresponding author at: Dahdaleh Institute for Global Health Research, York University, Canada.
E-mail addresses: byomkesh.talukder@gmail.com (B. Talukder), orbinski@yorku.ca (J. Orbinski).

https://doi.org/10.1016/j.joclim.2022.100114

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" ([157]: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" ([61]: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 [165]. 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 [64].

The erosion of ocean biodiversity is having multiple effects on ocean-related planetary health [81,64,66,108]. 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% [160]. Various anthropogenic as well as climate change drivers are responsible for ocean biodiversity erosion. According to Luypaert et al. [86], 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.

Methodology

A systematic literature review following the strategy and steps described by Moher et al. [97] was conducted to create a database and extract relevant information to fulfill the objectives of the paper.

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.

A predefined research protocol including the steps of identification, screening, eligibility, and included along 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 [97]. 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.

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 Fig. 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 [134], sea floor [1,48] intertidal [2] and sea ice fauna [59] and the sustained physiological impacts caused by ocean warming, ocean acidification and de-oxygenation.

Fig 1

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.

Results

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 [98], climate change is causing ocean (i) warming, (ii) acidification and (iii) deoxygenation [62]. As illustrated in Fig. 4, The impacts pose major threats to biodiversity at both the individual and population level of marine organisms.

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, [26, 62]. As a result, the upper ocean heat content has increased significantly in recent years (see Fig. 4).

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

Due to the thermal expansion of warming ocean waters, and the melting of glaciers, sea levels are rising globally [28]. In the past decade, this rise has increased coastal flooding [104]. 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 [78].

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 [155]. 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 floods, hurricanes, intense rainfall, and prolonged intervals between rains [163].

Ocean warming is influencing and modifying species diversity [3], abundance patterns and community composition [83,84], driving extinctions [93], and triggering poleward and regional-scale shifts [88] in species distribution causing biogeographical changes [12,47,91,48,50,150,85]. The magnitude of changes in species distribution and of response rate to climate change-induced stressors [132] vary by a series of factors, including: a species' thermal threshold [50]; sessility [65]; population size; habitat alteration and degradation [91,57]; resource availability; competition with invasive species [102,123]; predator-prey dynamics [125]; migration strategy, and light regimes and reproductive fitness [20,71,87,109,50,145,164]. Shifts are likely to become more rapid and erratic instead of gradual and monotonic [50] with resulting non-linear community responses [133].

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 [17]. 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 [151].

Melting of sea ice is causing a negative impact on unicellular sea-ice associated eukaryotes [59] and altering the biodiversity of ciliate microzooplankton [70], 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 [116].

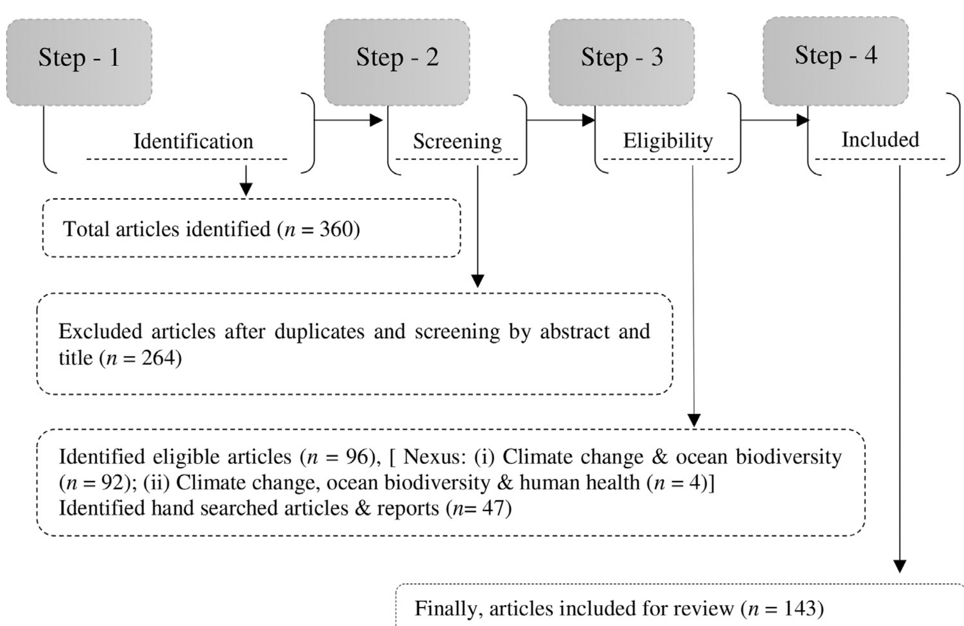

Fig. 1. Four steps of PRISMA flow diagram [97] for creating a database by systematic literature review.

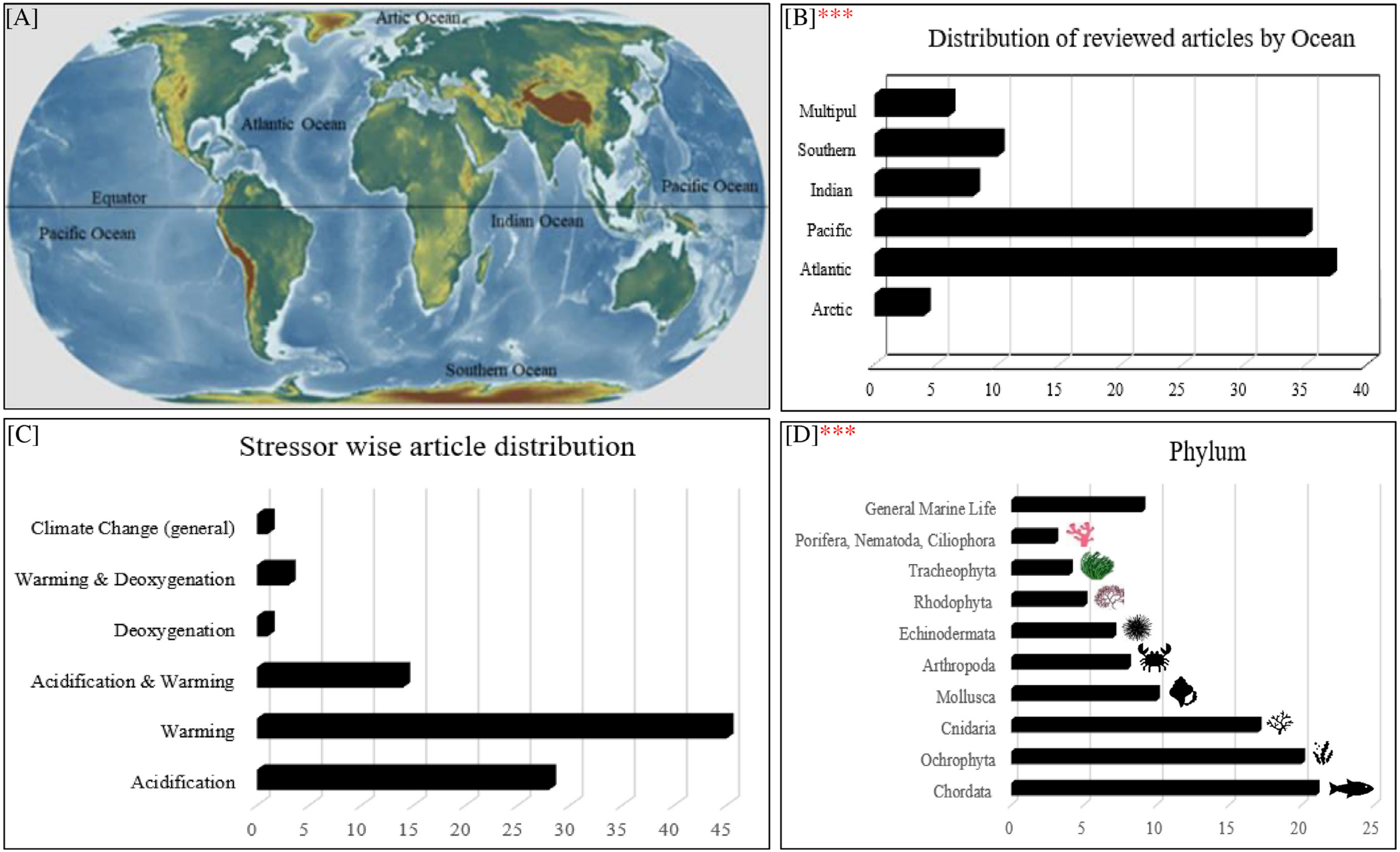

Fig 2. [A] Map of World Oceans [139], [B] Distribution of reviewed articles across the five oceans, [C] Reviewed article distribution by climate change-induced stressor and [D] Distribution of reviewed articles by Marine Taxonomy. Note: in [B]*** articles covering multiple oceans have been counted as "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).

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) [18], deteriorated respiration and gonado-somatic index (GSI) in the European purple sea urchin (Paracentrotus lividus) [164], shoot mortality, leaf width and the presence of leaf epiphytes in seagrasses [89,106], decline in larvae survival in a key fisheries species such as sea bream (Sparus aurata) [87], loss of structural complexity in reef corals due to coral bleaching [45], and decline in the aerobic scope in coral reef damselfish (Acanthochromis polyacanthus) [119]. 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 [105].

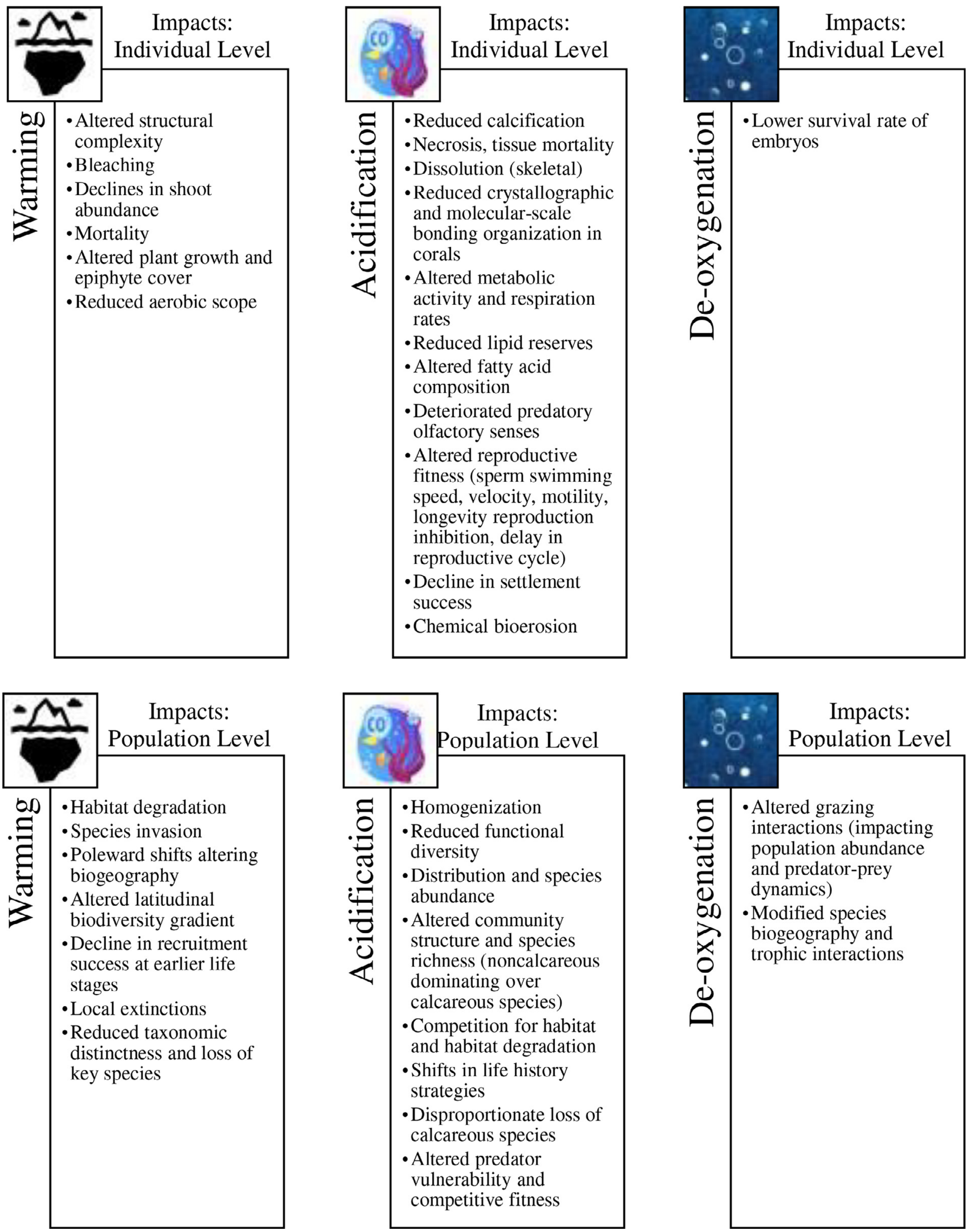

Fig 3. Individual and population level impacts of ocean warming, acidification and de-oxygenation.

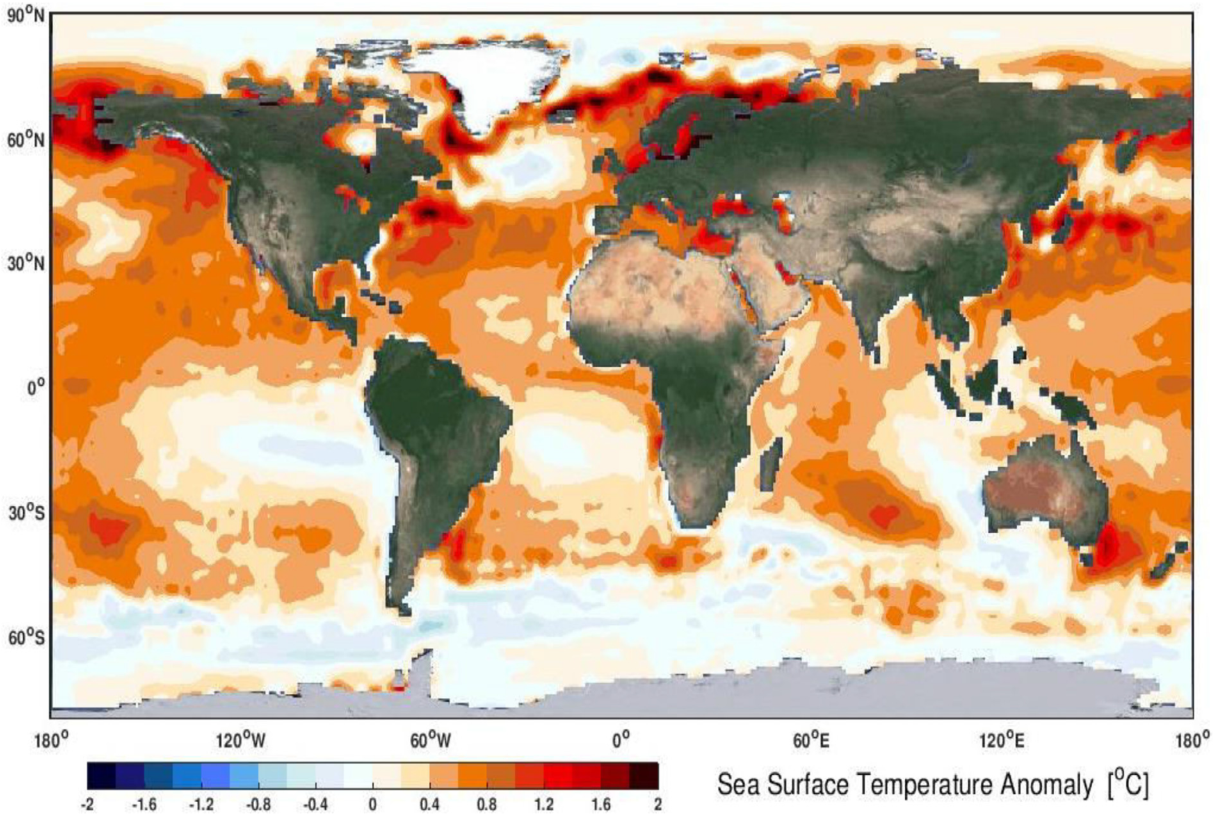

Fig. 4. Satellite observations of sea surface temperature anomalies during the last five years (2015−2019) with reference to the first five years of the data (1982−1986). Source: Adapted from Yang et al. [162] and AWI and Lohmann [4] with permission.

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 [8]. Increased sedimentation in coastal waters has also been found to be an enhancer of ocean acidification [129].

Ocean acidification impacts the calcium carbonate anatomic structures of calcareous species disproportionately more than non-calcareous species making the former less competitive [2]. In this way, it alters ecosystem functional diversity including coastal biogenic habitats [134] resulting in homogenization and ecosystem simplification [19,52,76,110]. A mesocosm experiment showed molluscs to be the most sensitive to lowered pH and elevated temperatures when compared to annelids and nematodes [51,114]. 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 [44]; fertilization rates; sperm motility and velocity in sea stars [142]; altered metabolic activity and fatty acid composition in predatory snails [143]; modified respiration rates in cold water corals (L.pertusa) [53] and altered metabolic capacity and timing of reproduction in Antarctic fish [138]. Tolerance 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 [30,99]. For example, Campanati et al. [[22]: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. [94] 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., [111] 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 [33] increased 2−3 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 [90]. Ocean acidification and warming can impact ocean biodiversity by influencing species diversity, abundance, predator detection [36], distribution, and competitive fitness [21,119, 124]. 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 [9].

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 [72]. Coral reefs are especially vulnerable to ocean warming and acidification through exaggeration of bioerosion rates by recycling calcium carbonate skeletal material [156]; compromising coral growth and structural integrity by weakening reef bases and lowering their effectiveness as "load-bearers" [53,153]; negatively impacting the health and survival of recruits [6] and reducing the metabolic performances of these ecosystems [31]. 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 [79].

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. 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 [115]. Apart from this, ocean-dwelling organisms demand more oxygen in warmer waters as a consequence of increased metabolic rates [15,32]. De-oxygenation has also been associated with increases in oceanic N_2O production and this potent greenhouse gas adds its contribution to climate change [5]. 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 [67].

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 [130]. 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) [103].

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 [95].

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.

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 [29]. However, climate change-related impacts, as described in Section 2.0, deteriorate ocean biodiversity and lead to the decay of provisional (refer to section 3.2.2) and regulatory ecosystem services [123,81].

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 [104], thereby accelerating coastal flooding and drowning of coastal wetland habitats [122]. Additionally, increased ocean temperature and altered precipitation impact the ability of coastal water areas to sequester carbon [148].

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 [42,154].

Food and nutritional security

Ocean ecosystems and biodiversity provide food and nutrition [122], but climate change-related threats hamper the ocean ecosystems and biodiversity necessary to supply food and nutrition [66]. 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 [153].

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 [16,41,56,141]. 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 [43]. Declines in ocean fish diversity will hamper global fish consumption and ultimately human health in some communities depends 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) [74]. 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) [7]

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 [10,13,62,78,113] . Seafood such as shellfish contaminated by harmful algae can cause sickness ranging from diarrheal illness to neurotoxic effects [25]. 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 [80]. In addition, harmful algal blooms can trigger mass fish mortality by disturbing trophic transfers of organic matter and reducing water quality [35,113] .

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 [14,141]. For example, 80% of all tourism is based near the sea [58], but the destruction of coral reefs is affecting coral reef-based tourism and recreation [107]. Coastal ecosystems dependent on wind-based upwelling of deep seawater, like those in East & Southern Africa and the Northwest coast of North America which are popular for tourism are highly vulnerable to future climate scenarios [73,92. 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 [39]. Climate change-driven ocean fish migration could lead to a resurgence or collapse of fisheries depending on latitude [135,149], which could damage the livelihoods of about 3 billion people globally who depend on ocean and coastal biodiversity [140]. 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 [161]. Livelihood and health are inseparably connected, while sound livelihoods are important to maintain the conditions of good

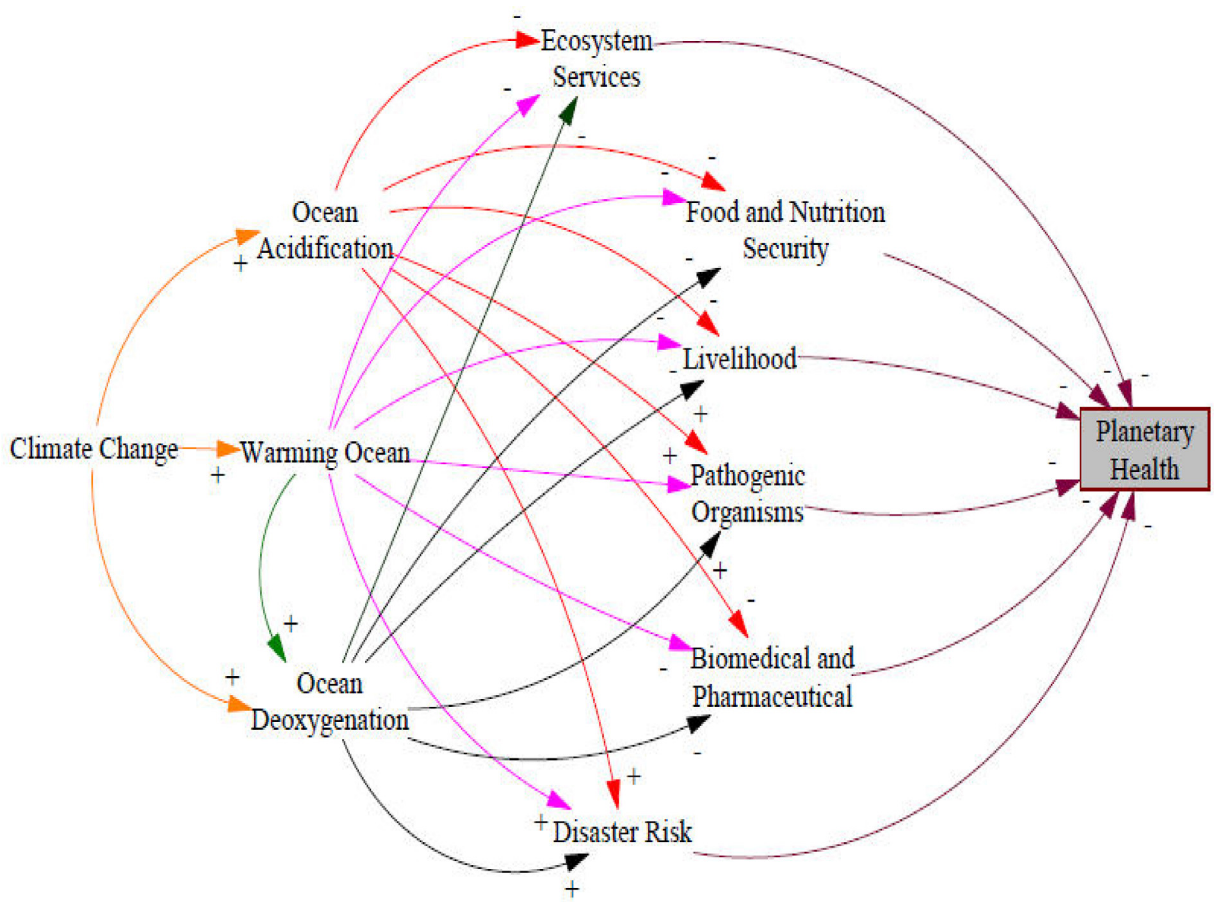

Fig. 5. Causes of ocean biodiversity erosion and their planetary health impacts. Note: "+" = increase; "-" = decrease.

health such as food security, health facilities, and education. Sound livelihoods 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.

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 [38,144,46,69]. 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 [40], 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.

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 [101]. Shoreline erosion caused by accelerating sea-level rise, poses significant threat to coastal cities and communities [23,122]. 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 [152]. Further, there is less natural protection against encroaching salinity caused by sea-level rise [128] 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 [146].

Discussion

The ocean is the planet's primary heat reservoir, oxygen supplier and carbon sink [27,155]. 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 [86]. 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 [64]. In addition, ocean biodiversity erosion will accelerate the decline of the overall biodiversity, one of the nine planetary boundaries [117], 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 [100], 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. [126] 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 [64] 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% [112], 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 [11].

Ramirez et al. [120] 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) [120]. 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. [37] these biodiversity loss hotspots must be protected, and protection measures can be effective. Sala et al. [121] 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. [121] 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 [55] should be further explored [54]. 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 [49], and harnessing host resilience through microbial-host interactions [24]. 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 [68]. Human stakeholder-informed ecosystem modelling strategies have also shown promise in addressing multiple anthropogenic and environmental stressors on complex ocean systems [75]. 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 [136].

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.

Declaration of Competing Interest

The authors declare no conflict of interest.

References

[1] Ashford OS, Kenny AJ, Barrio Froján S, C R, Horton T, Rogers AD, Ashford Oliver, C S. Investigating the environmental drivers of deep-seafloor biodiversity: a case study of peracarid crustacean assemblages in the Northwest Atlantic Ocean. Ecol Evol 2019;9(24):14167–204. doi: 10.1002/ece3.5852.

[2] Asnaghi V, Chiantore M, Mangialajo L, Gazeau F, Francour P, Alliouane S, Gattuso JP. Cascading effects of ocean acidification in a rocky subtidal community. PLoS One 2013;8(4). doi: 10.1371/journal.pone.0061978.

[3] Ateweberhan M, McClanahan TR, Maina J, Sheppard C. Thermal energy and stress properties as the main drivers of regional distribution of coral species richness in the Indian Ocean. J Biogeogr 2018;45(6):1355–66. doi: 10.1111/jbi.13224.

[4] AWI, Lohmann G. Major wind-driven ocean currents are shifting toward. Alfred-Wegener-Institut (AWI); 2020 https://phys.org/news/2020-09-major-wind-driven-ocean-currents-shifting.html.

[5] Babbin AR, Bianchi D, Jayakumar A, Ward BB. Rapid nitrous oxide cycling in the suboxic ocean. Science 2015;348(6239):1127–9. doi: 10.1126/science.aaa8380.

[6] Bahr KD, Tran T, Jury CP, Toonen RJ. Abundance, size, and survival of recruits of the reef coral Pocillopora acuta under ocean warming and acidification. PLoS One 2020;15(2). doi: 10.1371/journal.pone.0228168.

[7] Barbosa V, Maulvault AL, Alves RN, Anacleto P, Pousão-Ferreira P, Carvalho ML, Nunes ML, Rosa R, Marques A. Will seabass (Dicentrarchus labrax) quality change in a warmer ocean? Food Res Int 2017;97:27–36. doi: 10.1016/j.foodres.2017.03.024.

[8] Barker S, Ridgwell A. Ocean acidification. Nat Educ Knowl 2012;3(10):21 https://www.nature.com/scitable/knowledge/library/ocean-acidification-25822734.

[9] Barford E. Rising ocean acidity will exacerbate global warming. Nature 2013. doi: 10.1038/nature.2013.13602.

[10] Backer LC, Fleming LE, Rowan AD, Baden DG. Epidemiology, public health and human diseases associated with harmful marine algae. Man Harmful Marine Microalgae 2003:725–50.

[11] Barnosky AD, Matzke N, Tomiya S, Wogan GO, Swartz B, Quental TB, Ferrer EA. Has the Earth's sixth mass extinction already arrived? Nature 2011;471 (7336):51–7.

[12] Beaugrand G, Rombouts I, Kirby RR. Towards an understanding of the pattern of biodiversity in the oceans. Glob Ecol Biogeogr 2013;22(4):440–9. doi: 10.1111/geb.12009.

[13] Berdalet E, Fleming LE, Gowen R, Davidson K, Hess P, Backer LC, Enevoldsen H. Marine harmful algal blooms, human health and wellbeing: challenges and opportunities in the 21st century. J Marine Biol Assoc UK 2016;96(1):61–91. doi: 10.1017/S0025315415001733.

[14] Bindoff, N.L., W.W.L. Cheung, J.G. Kairo, J. Arístegui, V.A. Guinder, R. Hallberg, N. Hilmi, N. Jiao, M.S. Karim, L. Levin, S. O'Donoghue, S.R. Purca Cuicapusa, B. Rinkevich, T. Suga, A. Tagliabue, and P. Williamson. (2019). Changing ocean, ocean ecosystems, and dependent communities. In: IPCC special report on the ocean and cryosphere in a changing climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. In press.

[15] Boscolo-Galazzo F, Crichton KA, Barker S, Pearson PN. Temperature dependency of metabolic rates in the upper ocean: a positive feedback to global climate change? Glob Planet Chang 2018;170:201–12. doi: 10.1016/j.gloplacha.2018.08.017.

[16] Branch TA, DeJoseph BM, Ray LJ, Wagner CA. Impacts of ocean acidification on marine seafood. Trends Ecol Evol (Amst) 2013;28(3):178–86. doi: 10.1016/j.tree.2012.10.001.

[17] Brito-Morales I, Schoeman DS, Molinos JG, Burrows MT, Klein CJ, Arafeh-Dalmau N, Kaschner K, Garilao C, Kesner-Reyes K, Richardson AJ. Climate velocity reveals

increasing exposure of deep-ocean biodiversity to future warming. Nat Clim Chang 2020;10(6):576–81. doi: 10.1038/s41558-020-0773-5.
[18] Brothers CJ, Van Der Pol WJ, Morrow CD, Hakim JA, Koo H, Mcclintock JB. Ocean warming alters predicted microbiome functionality in a common sea urchin. Proc R Soc B 2018;285 1881. doi: 10.1098/rspb.2018.0340.
[19] Brustolin MC, Nagelkerken I, Ferreira CM, Goldenberg SU, Ullah H, Fonseca G. Future Ocean climate homogenizes communities across habitats through diversity loss and rise of generalist species. Glob Chang Biol 2019;25(10):3539–48. doi: 10.1111/GCB.14745.
[20] Busseni G, Caputi L, Piredda R, Fremont P, Mele Hay, B Campese, L Scalco, E Colomban De Vargas, | Bowler, C Francesco D'ovidio, | Zingone, A Ribera D'alcalà, M, Iudicone D. Large scale patterns of marine diatom richness: drivers and trends in a changing ocean. Global Ecol Biogeogr 2020;29(11):1915–28. doi: 10.1111/geb.13161.
[21] Caldwell GS, Fitzer S, Gillespie CS, Pickavance G, Turnbull E, Bentley MG. Ocean acidification takes sperm back in time. Invertebr Reprod Dev 2011;55(4):217–21. doi: 10.1080/07924259.2011.574842.
[22] Campanati C, Dupont S, Williams GA, Thiyagarajan V. Differential sensitivity of larvae to ocean acidification in two interacting mollusc species. Mar Environ Res 2018;141:66–74. doi: 10.1016/j.marenvres.2018.08.005.
[23] Cantin NE, Cohen AL, Karnauskas KB, Tarrant AM, McCorkle DC. Ocean warming slows coral growth in the central Red Sea. Science 2010;329(5989):322–5. doi: 10.1126/science.1190182.
[24] Cavalcanti GS, Shukla P, Morris M, Ribeiro B, Foley M, Doane MP, Thompson CC, Edwards MS, Dinsdale EA, Thompson FL. Rhodoliths holobionts in a changing ocean: host-microbes interactions mediate coralline algae resilience under ocean acidification. BMC Genom 2018;19(1). doi: 10.1186/s12864-018-5064-4.
[25] CDC. (2017). Harmful Algal Bloom (HAB)-Associated Illness. Marine Environments. Centers p
[26] Cheng L. Improved estimates of ocean heat content from 1960 to 2015. Sci Adv 2017;3(3). doi: 10.1126/sciadv.1601545.
[27] Cherchi A. Connecting AMOC changes. NatCC 2019;9(10):729–30. doi: 10.1038/s41558-019-0590-x.
[28] Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M. A. Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer and A.S. Unnikrishnan. (2013). Sea level change. in: Climate change 2013: the physical science basis. contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change, [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter13_FINAL.pdf
[29] Cochrane SK, Andersen JH, Berg T, Blanchet H, Borja A, Carstensen J, Renaud PE. What is ocean biodiversity? Towards common concepts and their implications for assessing biodiversity status. Front Ocean Sci 2016;3:248. doi: 10.3389/fmars.2016.00248.
[30] Cornwall CE, Hepburn CD, Pritchard D, Currie KI, McGraw CM, Hunter KA, Hurd CL. Carbon-use strategies in macroalgae: differential responses to lowered pH and implications for ocean acidification. J Phycol 2012;48(1):137–44. doi: 10.1111/j.1529-8817.2011.01085.x.
[31] Decarlo TM, Cohen AL, Wong GTF, Shiah F-K, Lentz SJ, Davis KA, Shamberger KEF, Lohmann P. Community production modulates coral reef pH and the sensitivity of ecosystem calcification to ocean acidification. JGR Oceans 2017;122 (1):745–61. doi: 10.1002/2016JC012326.
[32] Deutsch, et al., et al. Climate change tightens a metabolic constraint on marine habitats. Science 2015;348(6239):1132–5. doi: 10.1126/science.aaa1605.
[33] Diaz-Pulido G, Anthony KRN, Kline DI, Dove S, Hoegh-Guldberg O. Interactions between ocean acidification and warming on the mortality and dissolution of coralline algae. J Phycol 2012;48(1):32–9. doi: 10.1111/j.1529-8817.2011.01084.x.
[34] Díaz S, Demissew S, Carabias J, Joly C, Lonsdale M, Ash N, Bartuska A. The IPBES conceptual framework—connecting nature and people. Curr Opin Environ Sustain 2015;14:1–16. doi: 10.1016/j.cosust.2014.11.002.
[35] DiLeone AG, Ainsworth CH. Effects of Karenia brevis harmful algal blooms on fish community structure on the West Florida Shelf. Ecol Model 2019;392:250–67. doi: 10.1016/j.ecolmodel.2018.11.022.
[36] Dixson DL, Munday PL, Jones GP. Ocean acidification disrupts the innate ability of fish to detect predator olfactory cues. Ecol Lett 2010;13(1):68–75. doi: 10.1111/j.1461-0248.2009.01400.x.
[37] Duarte CM, Holmer M, Olsen Y, Soto D, Marba N, Guiu J, Black K, Karakassis I. Will the oceans help feed humanity? Bioscience 2009;59(11):967–76. doi: 10.1525/bio.2009.59.11.8.
[38] Ehrlich H, Krautter M, Hanke T, Simon P, Knieb C, Heinemann S, Worch H. First evidence of the presence of chitin in skeletons of marine sponges. Part II. Glass sponges (Hexactinellida: porifera). J Exp Zool Part B Mol Dev Evol 2007;308 (4):473–83. doi: 10.1002/jez.b.21174.
[39] Eisele MH, Madrigal-Mora S, Espinoza M. Drivers of reef fish assemblages in an upwelling region from the Eastern Tropical Pacific Ocean. J Fish Biol 2020:1–17 2020. doi: 10.1111/jfb.14639.
[40] EU. What is the medical value of marine biodiversity? Science for environmental policy. Thematic issue 36: biodiversity, agriculture and health. European commission dg environment news alert service. SCU, The University of the West of England; 2013. edited byBristol. Retrieved from https://ec.europa.eu/environment/integration/research/newsalert/pdf/36si4_en.pdf.
[41] Falkenberg LJ, Bellerby RG, Connell SD, Fleming LE, Maycock B, Russell BD, Dupont S. Ocean acidification and human health. Int J Environ Res Public Health 2020;17(12):4563. doi: 10.3390/ijerph17124563.
[42] Falkowski P. Ocean science: the power of plankton. Nature 2012;483(7387): S17–20. doi: 10.1038/483S17a.
[43] FAO. State of world fisheries and aquaculture 2020. Food & Agriculture Organization; 2020. Retrieved from http://www.fao.org/3/ca9229en/ca9229en.pdf.
[44] Fitzer SC, Caldwell GS, Close AJ, Clare AS, Upstill-Goddard RC, Bentley MG. Ocean acidification induces multi-generational decline in copepod naupliar production with possible conflict for reproductive resource allocation. J Exp Mar Biol Ecol 2012:30–6 418-419. doi: 10.1016/j.jembe.2012.03.009.
[45] Graham NAJ, Wilson SK, Jennings S, Polunin NVC, Bijoux JP, Robinson J. Dynamic fragility of oceanic coral reef ecosystems. Proc Natl Acad Sci USA 2006;103 (22):8425–9. doi: 10.1073/pnas.0600693103.
[46] Green DW, Lai WF, Jung HS. Evolving marine biomimetics for regenerative dentistry. Mar Drugs 2014;12(5):2877–912. doi: 10.3390/md12052877.
[47] Gregory B, Christophe L, Martin E. Rapid biogeographical plankton shifts in the North Atlantic Ocean. Glob Chang Biol 2009;15(7):1790–803. doi: 10.1111/j.1365-2486.2009.01848.x.
[48] Griffiths HJ, Meijers AJS, Bracegirdle TJ. More losers than winners in a century of future Southern Ocean seafloor warming. Nat Clim Chang 2017;7(10):749–54. doi: 10.1038/nclimate3377.
[49] Groner ML, Burge CA, Cox R, Rivlin ND, Turner MO, Van Alstyne KL, Wyllie-Echeverria S, Bucci J, Staudigel P, Friedman CS. Oysters and eelgrass: potential partners in a high pCO_2 ocean. Ecology 2018;99(8):1802–14. doi: 10.1002/ecy.2393.
[50] Gupta ASen, Brown JN, Jourdain NC, van Sebille E, Ganachaud A, Vergés A. Episodic and non-uniform shifts of thermal habitats in a warming ocean. Deep-sea research part II: topical studies in oceanography, 113; 2015. p. 201559–72. doi: 10.1016/j.dsr2.2013.12.002.
[51] Hale R, Calosi P, McNeill L, Mieszkowska N, Widdicombe S. Predicted levels of future ocean acidification and temperature rise could alter community structure and biodiversity in marine benthic communities. Oikos 2011;120(5):661–74. doi: 10.1111/j.1600-0706.2010.19469.x.
[52] Harvey BP, Kon K, Agostini S, Wada S, Hall-Spencer JM. Ocean acidification locks algal communities in a species-poor early successional stage. Glob Chang Biol 2021:1–14 July. doi: 10.1111/gcb.15455.
[53] Hennige SJ, Wicks LC, Kamenos NA, Perna G, Findlay HS, Roberts JM. Hidden impacts of ocean acidification to live and dead coral framework, 282. Royalsocietypublishing.Org; 2015 1813. doi: 10.1098/rspb.2015.0990.
[54] Henriques R, Potts WM, Santos CV, Sauer WHH, Shaw PW. Population connectivity of an overexploited coastal fish, argyrosomus coronus (Sciaenidae), in an ocean-warming hotspot. Afr J Mar Sci 2018;40(1):13–24. doi: 10.2989/1814232X.2018.1434090.
[55] Hernández ASR, Trull TW, Nodder SD, Flores JA, Bostock H, Abrantes F, Eriksen RS, Sierro FJ, Davies DM, Ballegeer AM, Fuertes MA, Northcote LC. Coccolithophore biodiversity controls carbonate export in the Southern Ocean. Biogeosciences 2020;17(1):245–63. doi: 10.5194/bg-17-245-2020.
[56] Hicks CC, Cohen PJ, Graham NA, Nash KL, Allison EH, D'Lima C, MacNeil, M A. Harnessing global fisheries to tackle micronutrient deficiencies. Nature 2019;574(7776):95–8. doi: 10.1038/s41586-019-1592-6.
[57] Hill SL, Phillips T, Atkinson A. Potential climate change effects on the habitat of Antarctic krill in the Weddell quadrant of the southern ocean. PLoS One 2013;8 (8). doi: 10.1371/journal.pone.0072246.
[58] Honey M, Krantz D. Global trends in coastal tourism. Center on Ecotourism and Sustainable Development; 2007.
[59] Hop H, Vihtakari M, Bluhm BA, Assmy P, Poulin M, Gradinger R, Peeken I, von Quillfeldt C, Olsen LM, Zhitina L, Melnikov IA. Changes in sea-ice protist diversity with declining sea ice in the arctic ocean from the 1980s to 2010s. Front Mar Sci 2020;7. doi: 10.3389/fmars.2020.00243.
[60] Horton R, Beaglehole R, Bonita R, Raeburn J, McKee M, Wall S. From public to planetary health: a manifesto. Lancet N Am Ed 2014;383(9920):847.
[61] Horton R, Lo S. Planetary health: a new science for exceptional action. Lancet N Am Ed 2015;386 (10007)P1921-1922. doi: 10.1016/S0140-6736(15)61038-8.
[62] IPCC. (2019). Summary for policymakers. In: IPCC special report on the ocean and cryosphere in a changing climate [H.O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama, N. Weyer (eds.)]. In press. https://report.ipcc.ch/srocc/pdf/SROCC_FinalDraft_FullReport.pdf
[63] IPCC. (2018). Summary for Policymakers. In: global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press.
[64] IPBES. In: Brondizio ES, Settele J, Díaz S, Ngo HT, editors. Global assessment report on biodiversity and ecosystem services of the intergovernmental science-policy platform on biodiversity and ecosystem services. Bonn, Germany: IPBES secretariat; 2019. (editors)XXX pages.
[65] Isla E, Gerdes D. Ongoing ocean warming threatens the rich and diverse microbenthic. Prog Oceanogr 2019;178:102180. doi: 10.1016/j.pocean.2019.102180.
[66] IUCN. 2017 a. The ocean and climate change. Issue Brief. https://www.iucn.org/sites/dev/files/the_ocean_and_climate_change_issues_brief-v2.pdf

[67] IUCN.(2019). Ocean deoxygenation. Issue Brief. https://www.iucn.org/sites/dev/files/ocean_deoxygenation_issues_brief_-_final.pdf
[68] Jenkins A, Horwitz P, Arabena K. My island home: place-based integration of conservation and public health in Oceania. Environ Conserv 2018;45(2):125–36. doi: 10.1017/S0376892918000061.
[69] Jesionowski T, Norman M, Żółtowska-Aksamitowska S, Petrenko I, Joseph Y, Ehrlich H. Marine spongin: naturally prefabricated 3D scaffold-based biomaterial. Mar Drugs 2018;16(3):88. doi: 10.3390/md16030088.
[70] Jiang Y, Yang EJ, Min JO, Kang SH, Lee SH. Using pelagic ciliated microzooplankton communities as an indicator for monitoring environmental condition under impact of summer sea-ice reduction in western Arctic Ocean. Ecol Indic 2013;34:380–90. doi: 10.1016/j.ecolind.2013.05.026.
[71] Johnson CR, Banks SC, Barrett NS, Cazassus F, Dunstan PK, Edgar GJ, Frusher SD, Gardner C, Haddon M, Helidoniotis F, Hill KL, Holbrook NJ, Hosie GW, Last PR, Ling SD, Melbourne-Thomas J, Miller K, Pecl GT, Richardson AJ, Taw N. Climate change cascades: shifts in oceanography, species' ranges and subtidal marine community dynamics in eastern Tasmania. J Exp Marine Biol Ecol 2011;400(1−2):17–32. doi: 10.1016/j.jembe.2011.02.032.
[72] Johnson KM, Hofmann GE. Combined stress of ocean acidification and warming influence survival and drives differential gene expression patterns in the Antarctic pteropod, Limacina helicina antarctica. Conserv Physiol 2020;8(1). doi: 10.1093/conphys/coaa013.
[73] Jones JM, Passow U, Fradkin SC. Characterizing the vulnerability of intertidal organisms in Olympic National Park to ocean acidification. Elementa 2018;6. doi: 10.1525/elementa.312.
[74] Kaimila Y, Divala O, Agapova SE, Stephenson KB, Thakwalakwa C, Trehan I, Manary MJ, Maleta KM. Consumption of animal-source protein is associated with improved height-for-age Z scores in rural malawian children aged 12–36 months. Nutrients 2019;11(2). doi: 10.3390/nu11020480.
[75] Koenigstein S, Ruth M, Gößling-Reisemann S. Stakeholder-informed ecosystem modeling of ocean warming and acidification impacts in the barents sea region. Front Mar Sci 2016;3 JUN. doi: 10.3389/fmars.2016.00093.
[76] Kroeker, K.J., M.C Gambi, Micheli, F., (2013). Community dynamics and ecosystem simplification in a high-CO2 ocean. Proc Natl Acad Sci USA, 110 (31), 12721−6. 10.1073/pnas.1216464110
[77] Lade SJ, Steffen W, De Vries W, Carpenter SR, Donges JF, Gerten D, Rockström J. Human impacts on planetary boundaries amplified by Earth system interactions. Nat Sustain 2020;3(2):119–28. doi: 10.1038/s41893-019-0454-4.
[78] Laufkötter C, Frölicher TL, Zscheischler J. High-impact ocean heatwaves attributable to human-induced global warming. Science 2020;369(6511). doi: 10.1126/science.aba0690.
[79] Legrand E, Riera P, Bohner O, Coudret J, Schlicklin F, Derrien M, Martin S. Impact of ocean acidification and warming on the productivity of a rock pool community. Mar Environ Res 2018;136:78–88. doi: 10.1016/j.marenvres.2018.02.010.
[80] Lehane L, Lewis RJ. Ciguatera: recent advances but the risk remains. Int J Food Microbiol 2000;61:91–125 2–3. doi: 10.1016/S0168-1605(00)00382-22.
[81] Levin LA, Le Bris N. The deep ocean under climate change. Science 2015;350 (6262):766–8. doi: 10.1126/science.aad0126.
[82] Lewis SL, Maslin MA. A transparent framework for defining the Anthropocene Epoch. Anthr Rev 2015;2(2):128–46. doi: 10.1177/2053019615588792.
[83] Linklater M, Jordan AR, Carroll AG, Neilson J, Gudge S, Brooke BP, Nichol SL, Hamylton SM, Woodroffe CD. Mesophotic corals on the subtropical shelves of Lord Howe Island and Balls Pyramid, south-western Pacific Ocean. Mar Freshw Res 2018;70(1):43–61. doi: 10.1071/MF18151.
[84] Lloyd P, Plaganyi EE, Weeks SJ, Magno-Canto M, Plaganyi G. Ocean warming alters species abundance patterns and increases species diversity in an African sub-tropical reef-fish community. Fish Oceanogr 2011;21(1):78–94. doi: 10.1111/j.1365-2419.2011.00610.x.
[85] López C, Moreno S, Brito A, Clemente S. Distribution of zooxanthellate zoantharians in the Canary Islands: potential indicators of ocean warming. Estuar Coast Shelf Sci 2020;233:106519. doi: 10.1016/j.ecss.2019.106519.
[86] Luypaert T, Hagan JG, McCarthy ML, Poti M. Status of marine biodiversity in the Anthropocene. In youmares 9-the oceans: our research, our future. Cham: Springer; 2020. p. 57–82 https://hdl.handle.net/10.1007/978-3-030-20389-4_4.
[87] Madeira D, Araújo J, Vitorino R, Capelo J, Vinagre C, Diniz M. Ocean warming alters cellular metabolism and induces mortality in fish early life stages: a proteomic approach. Environ Res 2016;148:164–76. doi: 10.1016/j.envres.2016.03.030.
[88] Maharaj RR, Lam VWY, Pauly D, Cheung WWL. Regional variability in the sensitivity of Caribbean reef fish assemblages to ocean warming. Mar Ecol Prog Ser 2018;590:201–9. doi: 10.3354/meps12462.
[89] Marba N, Duarte CM. Mediterranean warming triggers seagrass (Posidonia oceanica) shoot mortality. Glob Chang Biol 2010;16(8):2366–75. doi: 10.1111/j.1365-2486.2009.02130.x.
[90] Martin S, Gattuso JP. Response of Mediterranean coralline algae to ocean acidification and elevated temperature. Glob Chang Biol 2009;15(8):2089–100. doi: 10.1111/j.1365-2486.2009.01874.x.
[91] Martínez B, Radford B, Thomsen MS, Connell SD, Carreño F, Bradshaw CJA, Fordham DA, Russell BD, Gurgel CFD, Wernberg T. Distribution models predict large contractions of habitat-forming seaweeds in response to ocean warming. Divers Distrib 2018;24(10):1350–66. doi: 10.1111/ddi.12767.
[92] McClanahan T, Ateweberhan M, Graham N, Wilson S, Sebastián C, Guillaume M, Bruggemann J. Western Indian Ocean coral communities: bleaching responses and susceptibility to extinction. Mar Ecol Prog Ser 2007;337:1–13. doi: 10.3354/meps337001.
[93] McClanahan TR, Muthiga NA. Oceanic patterns of thermal stress and coral community degradation on the island of Mauritius. Coral Reefs 2021;40(1):53–74. doi: 10.1007/s00338-020-02015-4.
[94] McCormick MI, Watson SA, Munday PL. Ocean acidification reverses competition for space as habitats degrade. Sci Rep 2013;3(1):1–6. doi: 10.1038/srep03280.
[95] Musa SM, Ripley DM, Moritz Timo, Shiels HA. Ocean warming and hypoxia affect embryonic growth, fitness and survival of small-spotted catsharks, Scyliorhinus canicula. J Fish Biol 2020;97(1):257–64. doi: 10.1111/jfb.14370.
[96] Myers SS, Gaffikin L, Golden CD, Ostfeld RS, Redford KH, Ricketts TH, Osofsky SA. Human health impacts of ecosystem alteration. Proc Natl Acad Sci 2013;110 (47):18753–60. doi: 10.1073/pnas.1218656110.
[97] Moher D, Liberati A, Tetzlaff J, Altman DG. Research methodes and reporting. BMJ 2009;8:332–6.
[98] MBARI. Climate change and the ocean. Monterey Bay Aquarium Research Institute; 2019 https://phys.org/news/2019-09-climate-ocean.html.
[99] Nagelkerken I, Russell BD, Gillanders BM, Connell SD. Ocean acidification alters fish populations indirectly through habitat modification. Nat Clim Chang 2016;6 (1):89–93. doi: 10.1038/nclimate2757.
[100] Nash KL, Blythe JL, Cvitanovic C, Fulton EA, Halpern BS, Milner-Gulland EJ, Blanchard JL. To achieve a sustainable blue future, progress assessments must include interdependencies between the sustainable development goals. One Earth 2020;2(2):161–73. doi: 10.1016/j.oneear.2020.01.008.
[101] NCCOS. Assessment of hurricane impacts to coral reefs in Florida and Puerto Rico. National Centres for Coastal Ocean Science; 2017 https://coastalscience.noaa.gov/project/assessment-of-hurricane-impacts-to-coral-reefs-in-florida-and-puerto-rico/.
[102] Newton C, Bracken MES, McConville M, Rodrigue K, Thornber CS. Invasion of the red seaweed Heterosiphonia Japonica spans biogeographic provinces in the Western North Atlantic Ocean. PLoS One 2013;8(4). doi: 10.1371/journal.pone.0062261.
[103] Ng CA, Micheli F. Short-term effects of hypoxia are more important than effects of ocean acidification on grazing interactions with juvenile giant kelp (Macrocystis pyrifera). Sci Rep 2020;10(1):1–11. doi: 10.1038/s41598-020-62294-3.
[104] [Oppenheimer M, Glavovic BC, Hinkel J, van de Wal R, Magnan AK, Abd-Elgawad A, Cai R, Cifuentes-Jara M, DeConto RM, Ghosh T, Hay J, Isla F, Marzeion B, Meyssignac B, Sebesvari Z. Sea level rise and implications for low-lying islands, coasts and communities. In: Pörtner H-O, Roberts DC, Masson-Delmotte V, Zhai P, Tignor M, Poloczanska E, Mintenbeck K, Alegría A, Nicolai M, Okem A, Petzold J, Rama B, Weyer NM, editors. IPCC special report on the ocean and cryosphere in a changing climate. In press; 2019. [(eds.)]Available at https://report.ipcc.ch/srocc/pdf/SROCC_FinalDraft_Chapter4.pdf.
[105] Pazzaglia J, Santillán-Sarmiento A, Helber SB, Ruocco M, Terlizzi A, Marín-Guirao L, Procaccini G. Does warming enhance the effects of eutrophication in the seagrass Posidonia oceanica? Front Mar Sci 2020;7. doi: 10.3389/fmars.2020.564805.
[106] Peirano A, Cocito S, Banfi V, Cupido R, Damasso V, Farina G, Lombardi C, Mauro R, Morri C, Roncarolo I, Saldã Na S, Savini D, Sgorbini S, Silvestri C, Stoppelli N, Torricelli L, Bianchi CN. Phenology of the Mediterranean seagrass Posidonia oceanica (L.) Delile: medium and long-term cycles and climate inferences. Aquat. Bot. 2011;94:77–92. doi: 10.1016/j.aquabot.2010.11.007.
[107] Pendleton L, Hoegh-Guldberg O, Albright R, Kaup A, Marshall P, Marshall N, Fletcher S, Haraldsson G, Hansson L. The Great Barrier Reef: vulnerabilities and solutions in the face of ocean acidification. Reg Stud Mar Sci 2019;31:100729. doi: 10.1016/j.rsma.2019.100729.
[108] Pendleton L, Evans K, Visbeck M. Opinion: we need a global movement to transform ocean science for a better world. Proc Natl Acad Sci 2020;117(18):9652–5. doi: 10.1073/pnas.2005485117.
[109] Poloczanska ES, Brown CJ, Sydeman WJ, Kiessling W, Schoeman DS, Moore PJ, Brander K, Bruno JF, Buckley LB, Burrows MT, Duarte CM, Halpern BS, Holding J, Kappel CV, O'Connor MI, Pandolfi JM, Parmesan C, Schwing F, Thompson SA, Richardson AJ. Global imprint of climate change on marine life. Nat Clim Chang 2013;3(10):919–25. doi: 10.1038/nclimate1958.
[110] Porzio L, Buia MC, Hall-Spencer JM. Effects of ocean acidification on macroalgal communities. J Exp Mar Biol Ecol 2011;400(1−2):278–87. doi: 10.1016/j.jembe.2011.02.011.
[111] Range P, Chícharo MA, Ben-Hamadou R, Piló D, Matias D, Joaquim S, Oliveira AP, Chícharo L. Calcification, growth and mortality of juvenile clams Ruditapes decussatus under increased pCO_2 and reduced pH: variable responses to ocean acidification at local scales? J Exp Mar Biol Ecol 2010;396(2):177–84. doi: 10.1016/j.jembe.2010.10.020.
[112] Rastelli E, Petani B, Corinaldesi C, Dell'Anno A, Lo Martire M, Cerrano C, Danovaro R. A high biodiversity mitigates the impact of ocean acidification on hard-bottom ecosystems. Sci Rep 2020;10(1):1–13. doi: 10.1038/s41598-020-59886-4.
[113] Riebesell U, Aberle-Malzahn N, Achterberg EP, Algueró-Muñiz M, Alvarez-Fernandez S, Arístegui J, Bach LT, Boersma M, Boxhammer T, Guan W, Haunost M, Horn HG, Löscher CR, Ludwig A, Spisla C, Sswat M, Stange P, Taucher J. Toxic algal bloom induced by ocean acidification disrupts the pelagic food web. Nat Clim Chang 2018;8(12):1082–6. doi: 10.1038/s41558-018-0344-1.
[114] Ricevuto E, Vizzini S, Gambi MC. Ocean acidification effects on stable isotope signatures and trophic interactions of polychaete consumers and organic matter

sources at a CO_2 shallow vent system. J Exp Mar Biol Ecol 2015;468:105–17. doi: 10.1016/j.jembe.2015.03.016.
[115] Richardson K, Bendtsen J. Photosynthetic oxygen production in a warmer ocean: the Sargasso Sea as a case study, 375. Royalsocietypublishing.Org; 2017. doi: 10.1098/rsta.2016.0329.
[115] Robinson BJO, Barnes DKA, Morley SA. Disturbance, dispersal and marine assemblage structure: a case study from the nearshore Southern Ocean. Mar Environ Res 2020;160:105025. doi: 10.1016/j.marenvres.2020.105025.
[117] Rockstrom J, Steffen W, Noone K, Persson Å, Chapin FS, Lambin EF, Nykvist B. A safe operating space for humanity. Nature 2009;461(7263):472–5. doi: 10.1038/461472a.
[118] Rodgers GG, Rummer JL, Johnson LK, McCormick MI. Impacts of increased ocean temperatures on a low-latitude coral reef fish – processes related to oxygen uptake and delivery. J Therm Biol 2019;79:95–102. doi: 10.1016/j.jtherbio.2018.12.008.
[119] Rölfer L, Reuter H, Ferse SCA, Kubicek A, Dove S, Hoegh-Guldberg O, Bender-Champ D. Coral-macroalgal competition under ocean warming and acidification. J Exp Mar Biol Ecol 2021;534:151477. doi: 10.1016/j.jembe.2020.151477.
[120] Ramírez F, Afán I, Davis LS, Chiaradia A. Climate impacts on global hot spots of marine biodiversity. Sci Adv 2017;3(2):e1601198. doi: 10.1126/sciadv.1601198.
[121] Sala E, Mayorga J, Bradley D, Cabral RB, Atwood TB, Auber A, Lubchenco J. Protecting the global ocean for biodiversity, food and climate. Nature 2021:1–6. doi: 10.1038/s41586-021-03371-z.
[122] Sandifer PA, Sutton-Grier AE. Connecting stressors, ocean ecosystem services, and human health. Nat Resour Forum 2014;38(3):157–67. doi: 10.1111/1477-8947.12047.
[123] Sands CJ, O'Hara TD, Barnes DKA, Martín-Ledo R. Against the flow: evidence of multiple recent invasions of warmer continental shelf waters by a Southern Ocean brittle star. Front Ecol Evol 2015;3 JUN. doi: 10.3389/fevo.2015.00063.
[124] Santora JA, Hazen EL, Schroeder ID, Bograd SJ, Sakuma KM, Field JC. Impacts of ocean climate variability on biodiversity of pelagic forage species in an upwelling ecosystem. Mar Ecol Prog Ser 2017;580:205–20. doi: 10.3354/meps12278.
[125] Selden RL, Batt RD, Saba VS, Pinsky ML. Diversity in thermal affinity among key piscivores buffers impacts of ocean warming on predator-prey interactions. Glob Chang Biol 2018;24(1):117–31. doi: 10.1111/gcb.13838.
[126] Singh GG, Cisneros-Montemayor AM, Swartz W, Cheung W, Guy JA, Kenny TA, Sumaila R. A rapid assessment of co-benefits and trade-offs among sustainable development goals. Mar Policy 2018;93:223–31. doi: 10.1016/j.marpol.2017.05.030.
[127] Santos C F, Agardy T, Andrade F, Calado H, Crowder L B, Ehler C N, et al. Integrating climate change in ocean planning. Nature Sustainability 2020;3(7):505–16. doi: 10.1038/s41893-020-0513-x.
[128] Smyth K, Elliott M. Effects of changing salinity on the ecology of the marine environment. Stressors in the marine environment: physiological and ecological responses; societal implications; 2016161–74.
[129] Smith JN, Mongin M, Thompson A, Jonker MJ, De'ath G, Fabricius KE. Shifts in coralline algae, macroalgae, and coral juveniles in the Great Barrier Reef associated with present-day ocean acidification. Glob Chang Biol 2020;26(4):2149–60. doi: 10.1111/gcb.14985.
[130] Spicer JI, Morley SA. Will giant polar amphipods be first to fare badly in an oxygen-poor ocean? Testing hypotheses linking oxygen to body size. Philos Trans R Soc B Biol Sci 2019;374 1778. doi: 10.1098/rstb.2019.0034.
[131] Steffen W, Richardson K, Rockström J, Cornell SE, Fetzer I, Bennett EM, Folke C. Planetary boundaries: guiding human development on a changing planet. Science 2015;347(6223):1259855. doi: 10.1126/science.1259855.
[132] Stuart-Smith J, Pecl G, Pender A, Tracey S, Villanueva C, Smith-Vaniz WF. Southernmost records of two Seriola species in an Australian ocean-warming hotspot. Mar Biodivers 2018;48(3):1579–82. doi: 10.1007/s12526-016-0580-4.
[133] Stuart-Smith RD, Barrett NS, Stevenson DG, Edgar GJ. Stability in temperate reef communities over a decadal time scale despite concurrent ocean warming. Glob Chang Biol 2009;16(1):122–34. doi: 10.1111/j.1365-2486.2009.01955.x.
[134] Sunday JM, Fabricius KE, Kroeker KJ, Anderson KM, Brown NE, Barry JP, Connell SD, Dupont S, Gaylord B, Hall-Spencer JM, Klinger T, Milazzo M, Munday PL, Russell BD, Sanford E, Thiyagarajan V, Vaughan MLH, Widdicombe S, Harley CDG. Ocean acidification can mediate biodiversity shifts by changing biogenic habitat. Nat Clim Chang 2017;7(1):81–5. doi: 10.1038/nclimate3161.
[135] Tai TC, Steiner NS, Hoover C, Cheung WW, Sumaila UR. Evaluating present and future potential of arctic fisheries in Canada. Mar Policy 2019;108:103637.
[136] Thistle D, Carman KR, Sedlacek L, Brewer PG, Fleeger JW, Barry JP. Deep-ocean, sediment-dwelling animals are sensitive to sequestered carbon dioxide. Mar Ecol Prog Ser 2005;289:1–4. doi: 10.3354/meps289001.
[137] Thomas CD, Cameron A, Green RE, Bakkenes M, Beaumont LJ, Collingham YC, Hughes L. Extinction risk from climate change. Nature 2004;427(6970):145–8. doi: 10.1038/nature02121.
[138] Todgham AE, Mandic M. Understanding the metabolic capacity of antarctic fishes to acclimate to future ocean conditions. Integr Comp Biol 2020;60 (6):1425–37. doi: 10.1093/icb/icaa121.
[139] UN. (2017 a). UN Atlas of the Oceans: geography. Retrieved from: www.oceansatlas.org/geography/en
[140] UN. Factsheet: people and oceans. In: Proceedings of the Ocean conference. New York: United Nations; 2017 https://www.un.org/sustainabledevelopment/wp-content/uploads/2017/05/Ocean-fact-sheet-package.pdf.
[141] UNEP. Marine and coastal ecosystems and human wellbeing: a synthesis report based on the findings of the millennium ecosystem assessment. UNEP; 2006 76pp.
[142] Uthicke S, Pecorino D, Albright R, Negri AP, Cantin N, Liddy M, Dworjanyn S, Kamya P, Byrne M, Lamare M. Impacts of ocean acidification on early life-history stages and settlement of the coral-eating sea star acanthaster planci. PLoS ONE, 2013;8(12):e82938. doi: 10.1371/journal.pone.0082938.
[143] Valles-Regino R, Tate R, Kelaher B, Savins D, Dowell A, Benkendorff K. Ocean warming and CO_2-induced acidification impact the lipid content of a marine predatory gastropod. Mar Drugs 2015;13(10):6019–37. doi: 10.3390/md13106019.
[144] Venugopal V. Marine products for healthcare: functional and bioactive nutraceutical compounds from the ocean. CRC press; 2008.
[145] Villarino E, Irigoien X, Villate F, Iriarte A, Uriarte I, Zervoudaki S, Carstensen J, O'Brien T, Chust G. Response of copepod communities to ocean warming in three time-series across the North Atlantic and Mediterranean Sea. Mar Ecol Prog Ser 2020;636:47–61. doi: 10.3354/meps13209.
[146] Vineis P, Chan Q, Khan A. Climate change impacts on water salinity and health. J Epidemiol Glob Health 2011;1(1):5–10.
[147] Watts N, Adger WN, Agnolucci P, Blackstock J, Byass P, Cai W, Cox PM. Health and climate change: policy responses to protect public health. Lancet N Am Ed 2015;386:1861–914 10006. doi: 10.1016/S0140-6736(15)60854-6.
[148] Ward RD, Friess DA, Day RH, MacKenzie RA. Impacts of climate change on mangrove ecosystems: a region by region overview. Ecosystem Health Sustain 2016;2(4):e01211. doi: 10.1002/ehs2.1211.
[149] Weatherdon LV, Magnan AK, Rogers AD, Sumaila UR, Cheung WW. Observed and projected impacts of climate change on marine fisheries, aquaculture, coastal tourism, and human health: an update. Front Mar Sci 2016;3:48. doi: 10.3389/fmars.2016.00048.
[150] Wernberg T, Russell BD, Thomsen MS, Gurgel CFD, Bradshaw CJA, Poloczanska ES, Connell SD. Seaweed communities in retreat from ocean warming. Curr Biol 2011;21(21):1828–32. doi: 10.1016/j.cub.2011.09.028.
[151] Whitehead H, McGill B, Worm B. Diversity of deep-water cetaceans in relation to temperature: implications for ocean warming. Ecol Lett 2008;11(11):1198–207. doi: 10.1111/j.1461-0248.2008.01234.x.
[152] Wilkinson C, Salvat B. Coastal resource degradation in the tropics: does the tragedy of the commons apply for coral reefs, mangrove forests and seagrass beds. Mar Pollut Bull 2012;64(6):1096–105.
[153] Wilkinson C. Status of coral reefs of the world: 2008. Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre; 2008. p. 296 https://www.sprep.org/att/IRC/eCOPIES/Global/213.pdf.
[154] Winder M, Sommer U. Phytoplankton response to a changing climate. Hydrobiologia 2012;698(1):5–16. doi: 10.1007/s10750-012-1149-2.
[155] Winton M. On the climatic impact of ocean circulation. J Clim 2003;16 (17):2875–89. doi: 10.1175/1520-0442(2003)016≤2875:OTCIOO≥2.0.CO;2.
[156] Wisshak M, Schönberg CHL, Form A, Freiwald A. Effects of ocean acidification and global warming on reef bioerosion-lessons from a clionaid sponge. Aquat Biol 2013;19(2):111–27. doi: 10.3354/ab00527.
[157] Whitmee S, Haines A, Beyrer C, Boltz F, Capon AG, de Souza Dias BF, Horton R. Safeguarding human health in the Anthropocene epoch: report of The Rockefeller Foundation–Lancet Commission on planetary health. Lancet N Am Ed 2015;386(10007):1973–2028. doi: 10.1016/S0140-6736(15)60901-1.
[158] WHO. Operational framework for building climate resilient health systems. World Health Organization; 2015. Available at https://apps.who.int/iris/bitstream/handle/10665/189951/9789241565073_eng.pdf.
[159] WHO. WHO calls for urgent action to protect health from climate change – sign the call. World Health Organization; 2018. Available at http://www.who.int/globalchange/global-campaign/cop21/en/.
[160] WWF-ZSL. (2015). Living blue planet report–species, habitats and human wellbeing. https://c402277.ssl.cf1.rackcdn.com/publications/817/files/original/Living_Blue_Planet_Report_2015_Final_LR.pdf?1442242821
[161] Yamasaki M, Aono M, Ogawa N, Tanaka K, Imoto Z, Nakamura Y. Drifting algae and fish: implications of tropical Sargassum invasion due to ocean warming in western Japan. Estuar Coast Shelf Sci 2014;147:32–41. doi: 10.1016/j.ecss.2014.05.018.
[162] Yang H, Lohmann G, Lu J, Gowan EJ, Shi X, Liu J, Wang Q. Tropical expansion driven by poleward advancing midlatitude meridional temperature gradients. J Geophys Res Atmos 2020;125(16) e2020JD033158. doi: 10.1029/2020JD033158.
[163] Yang H, Lohmann G, Wei W, Dima M, Ionita M, Liu J. Intensification and poleward shift of subtropical western boundary currents in a warming climate. J Geophys Res Oceans 2016;121(7):4928–45. doi: 10.1002/2015JC011513.
[164] Yeruham E, Shpigel M, Abelson A, Rilov G. Ocean warming and tropical invaders erode the performance of a key herbivore. Ecology 2020;101(2):e02925. doi: 10.1002/ecy.2925.